2023 Annual Meeting

Seismological Society of America
Technical Sessions
17–20 April • San Juan, Puerto Rico

The SSA 2023 Annual Meeting will convene at the Puerto Rico Convention Center and feature more than 860 technical oral and poster presentations as well as plenary sessions, workshops, special interest groups and field trips.

The following schedule of events and abstracts are valid until 1 March 2023 and subject to change.

Annual Meeting Co-Chairs

The Society is grateful to SSA's 2023 Co-chairs Xyoli Pérez-Campos, Universidad Nacional Autónoma de México, and Elizabeth Vanacore, University of Puerto Rico at Mayagüez.

Contact

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Technical Program

Plenary Sessions

Keynote Address: Development of an Alternative Elastic Design Spectra for Some Municipalities in Puerto Rico

Monday, 17 April, 6:30-7:30 PM

José A. Martinez-Cruzado, University of Puerto Rico at Mayagüez

The keynote lecture by José A. Martinez-Cruzado will discuss the seismic hazard map being used in the current building code in Puerto Rico (IBC, 2018) that dates from 2003. The Puerto Rico Seismic Network has recorded thousands of earthquakes within the island that highlight the existence of several faults not included in the 2003 map. The United States Geological Survey has begun the process to update the map, a process that will probably end by 2026. However, the Commonwealth of Puerto Rico has received billions of federal funds for reconstruction due to the damage caused by Hurricane Maria (2017), the 2020 Southwestern Puerto Rico Mw 6.4 earthquake and seismic sequence and Hurricane Fiona (2022), a reconstruction that has begun. The engineers are preparing the structural designs of the new infrastructure based on the current building code (2018). In this presentation, an alternative is presented for the use of elastic design spectra that consider faults not included in the 2003 seismic hazard map.

Volcanism in the Eastern Caribbean: Hazards, Monitoring, Challenges and Lessons Learnt

Tuesday, 18 April, 11:30 AM-12:30 PM

Erouscilla P. Joseph, The University of West Indies

The UWI Seismic Research Centre (SRC) is the agency responsible for monitoring earthquakes and volcanoes in the English-speaking islands of the Eastern Caribbean, spanning ~850 km along the arc. The Centre operates the largest volcano and earthquake monitoring network in the Caribbean and has been doing so for almost 70 years. The SRC provides the governments of its nine contributing territories with accurate and up-to-date information about earthquake, volcanic and other geologic activity, including 19 live volcanoes.

Volcanic eruptions have resulted in loss of life and have had significant economic impact on some islands. Despite this, governments in the Eastern Caribbean are generally more prepared and aware of other hazards (e.g. hurricanes) than of volcanic eruptions. To manage the volcanic threat, the SRC maintains a continuously recording seismic network and continuous and campaign-style GPS networks as well as monitors hydrothermal fluids in the islands of their responsibility. This is complemented by a program of hazard mapping and basic geologic investigation designed to improve understanding of volcanic systems in the region. The high volatility of key government establishments and low frequency of volcanic eruptions presents further challenges to sustaining a high level of volcanic hazard awareness and dictates the need for a variety of techniques to get the message across. Several volcano-seismic crises and volcanic eruptions during the past 70 years have served to illustrate the challenges of delivering timely and appropriate information to the civil authorities and public. Experience has shown the need to maintain an active Education and Outreach program and the Centre uses a variety of techniques (such as public lectures, stakeholder workshops and meetings, press interviews, web tools, exhibitions) to communicate accurate information on volcanic hazard and risk to local civil authorities and the public in the Eastern Caribbean. Reaching out to vulnerable island communities has been challenging and issuing early warnings to governments in different islands at various stages of nation building has required adaptation and change.

Like many monitoring agencies in resource-constrained settings, continuing to fund and sustain this level of monitoring and communication is a continuous strain, made more complicated in this context by the need to engage with nine different governments and disaster management agencies. This talk presents some of the challenges faced by SRC in hazard mitigation and in the dissemination of volcanic hazard and risk information to vulnerable populations, particularly as it relates to small states with fragile economies.

The Future of Tsunami Hazards and Readiness Research (Panel Discussion)

Tuesday, 18 April, 6-7 PM

Panelists: Diego Melgar, University of Oregon (moderator); Christa von Hillebrandt-Andrade, National Oceanic and Atmospheric Administration; Rocky Lopes, NOAA Tsunami Science & Technology Advisory Panel; Alberto Lopez, University of Puerto Rico at Mayagüez

SSA President's Address and Awards Ceremony

Wednesday, 19 April, 11:30 AM-12:30 PM

SSA President Ruth Harris will preside over the awards ceremony and provide an update on the Society. Immediate Past President Peggy Hellweg (2022-23) will deliver the presidential address. The 2023 honorees:

- Brian L. N. Kennett, Harry Fielding Reid Medal
- Daniel Trugman, Charles F. Richter Early-Career Award
- Susan Hough, Frank Press Public Service Award
- Mitch Withers, Distinguished Service to SSA Award
- José Martinez-Cruzado, Bruce Bolt Medal

Joyner Lecture: Spatial Correlation in Ground Motion Intensities: Measurement, Prediction and Seismic Risk Implications

Wednesday, 19 April, 6-7 PM

Jack Wesley Baker, Stanford University

The amplitude of ground shaking during an earthquake varies spatially, due to location-to-location differences in wave propagation, attenuation, and source- and site-effects. These variations have important implications for impacts to infrastructure systems and other distributed assets. This presentation will provide an overview of efforts to quantify spatial correlations in amplitudes, via past earthquakes and numerical simulations. Fitting of traditional empirical models will be discussed, followed by the introduction of new techniques to account for soil conditions and other site-specific effects. The role of numerical simulations and new measurement technologies will also be introduced. Finally, some regional risk analysis results will be presented to demonstrate the potential role of spatial correlations on impacts to the built environment.

Machine Learning for Real-time Monitoring

Thursday, 20 April, 11:30 AM-12:30 PM

Panelists: Greg Beroza, Stanford University (moderator); Kristine Pankow, University of Utah; Lise Retailleau, Institut de Physique du Globe de Paris; Frederik Tilmann, GFZ Potsdam; Weiqiang Zhu, Caltech

The implementation of machine learning in real-time monitoring offers a novel way to process data sets and extract and analyze signals. This panel will investigate advantages and disadvantages of this emerging technology, the challenges of implementation and the future possibilities.

Workshops

SSA offers workshops for members to help advance their skills.

Post-earthquake Reconnaissance: Turning Disasters into Knowledge Workshop

Monday, 17 April, 8 AM-5 PM

Instructors: Ashly Cabas, North Carolina State University; Christine Beyzaei, National Institute of Standards and Technology; Alessandra Morales, University of Puerto Rico at Mayagüez; Estefan Garcia, University of Michigan; Cristina Lorenzo Velazquez, North Carolina State University; and the NHERI RAPID facility

Post-earthquake reconnaissance missions play a key role in the advancement of earthquake science and engineering, as well as in community resilience. The NSF-sponsored Geotechnical Extreme Events Reconnaissance (GEER) Association responds to extreme natural events nationally and internationally aiming to systematically collect perishable post-disaster data and develop well-documented case histories that have the potential to advance research and engineering practice. More recently, the vulnerability of communities affected by the convergence of multiple natural hazards (e.g., earthquakes and hurricanes) while seeking recovery from other socio-political and economic stressors (e.g., the COVID19 pandemic) has been highlighted by events such as the 2021, Nippes, Haiti earthquake, and the 2019-2020 Puerto Rico earthquake sequence.

The goal of this workshop is to share GEER's best practices and tools for post-earthquake reconnaissance missions, providing training modules, hands-on exercises and opportunities for community engagement. Attendees will also learn about conducting ethical reconnaissance safely and effectively, GEER's standard measurement and reporting protocols, best practices for virtual reconnaissance missions and the incorporation of important social dimensions.

Optimizing Seismic Hazard Assessments for Improved Policy Decision Making, Compliance and Individual Safety Actions in Puerto Rico and the U.S. Virgin Islands

Monday, 17 April, 10 AM-4 PM

Instructors: Christa von Hillebrandt-Andrade, National Oceanic and Atmospheric Administration; Victor Huerfano, Puerto Rico Seismic Network; José Martinez Cruzado, University of Puerto Rico at Mayagüez; Allison Shumway, U.S. Geological Survey

Earthquake scientists, engineers, policymakers, emergency managers and social scientists from and interested in Puerto Rico, the U.S. Virgin Islands, Latin America and the Caribbean are invited to a transdisciplinary discussion on seismic hazard assessment, implementation, education and compliance. The findings and recommendations will inform the United States Geological Survey 2025 Puerto and U.S. Virgin Islands seismic hazard assessment activities, its timely implementation in Puerto Rico and the U.S. Virgin Islands and identify areas of interest for future national, regional and international collaboration and engagement.

Getting Published—Writing Papers, Working with Editors, Responding to Reviews

Monday, 17 April, 2-5 PM

Instructors: Allison Bent, editor-in-chief of Seismological Research Letters (SRL); John Ebel, Boston College and founding editor-in-chief of SRL; Brent Grocholski, editor at Science

Learn what makes an excellent peer-reviewed paper and how to handle constructive—and not so constructive—reviews from those who know—editors at Science and SRL. This SSA workshop is geared toward students and early-career seismologists but is open to all Annual Meeting attendees.

DAS Workshop

Monday, 17 April, 2-5 PM

Instructors: Zack Spica, University of Michigan; Eileen Martin, Colorado School of Mines; Jonathan Ajo-Franklin, Rice University

During this three-hour workshop, we will provide a short introduction on how to acquire, manage and process seismic data recorded by DAS. It targets students and early-career scientists who are interested in working with DAS data but have no prior or limited experience.

Field Trips

2020 Southwestern Puerto Rico Seismic Sequence

Friday, 21 April, 7 AM-10 PM

Trip Leaders: Elizabeth Vanacore, University of Puerto Rico at Mayagüez; Stephen Hughes, University of Puerto Rico at Mayagüez

Hardy participants will travel to the southwestern portion of the island to learn about the 2020 Puerto Rico Seismic Sequence. Along the way, the group will make stops to learn about the island's geology, see the local impact of the sequence and visit the Puerto Rico Seismic Network. This trip's itinerary includes visits to:

- The Guayanilla River Bluff, where the group will have special access to a bedrock landslide and rock fall triggered by the 2020 shaking events.
- The Punta Ventana collapsed sea arch will bring attendees as close as one can be on land to the epicenter of the M6.4 event.
- At the Punta Montalva fault, the group will observe deformed limestone layers and the fault trace, discussing its role in the seismic sequence.
- La Parguera overview gives attendees the opportunity to discuss the micro-tsunami generated by the M6.4 earthquake.
- The trip will conclude with a visit to the Puerto Rico Seismic Network in Mayagüez.
- Depending on time, the group may also stop at the Great Southern Puerto Rico fault zone, Guánica Bay overlook and Lajas Valley overlook.

Old San Juan Walking Tour

Friday, 21 April, 8 AM-Noon

Trip Leaders: José Izquierdo-Encarnación, Porticus Ingenieria; Andy Rivera, Puerto Rico Historic Buildings Drawings Society

Explore the walled city of Old San Juan and discover hidden gems that go unnoticed to the casual visitor. Led by a local architect and a local earthquake engineer, attendees will learn the historical significance, construction methods and earthquake technologies found in the Spanish colonial buildings and defensive structures. The group will walk the blue cobblestoned streets, venture into local crypts and climb rooftops to explore hidden towers.

TsunamiReady Program

Friday, 21 April, 8 AM-Noon

Trip Leaders: Christa G. von Hillebrandt-Andrade, International Tsunami Information Center; Roy Ruiz Velez, Puerto Rico Seismic Network; Wildaomaris González Ruiz, Puerto Rico Seismic Network

Get an inside perspective on Puerto Rico's TsunamiReady® Program and the work being done to prepare communities to respond to the next tsunami. The first stop on this four-hour field trip around the San Juan area will be at Isla de Cabras park in Toa Baja to learn about the tsunami sirens and signage and have a beautiful view of El Morro fortress from across the bay. Then, the group will travel to the mayor's office in Cataño to visit an evacuation site with the emergency management team. Departing Cataño, attendees will ride the ferry across the San Juan Bay, arriving in Old San Juan, where the group will walk along an evacuation route from the Paseo de la Princesa to Plaza Colón and discuss tsunami preparedness and evacuation procedures.

SSA Meetings Code of Conduct

SSA is committed to fostering the exchange of scientific ideas by providing a safe, productive and welcoming environment for all SSA-sponsored meeting participants, including attendees, staff, volunteers and vendors. All participants at SSA meetings are expected to be considerate and collaborative, communicating openly with respect for others and critiquing ideas rather than individuals. Behavior that is acceptable to one person may not be acceptable to another, so use discretion to be sure that respect is communicated. For a detailed description of the ethics and code of conduct policies, please visit the SSA website: seismosoc.org/meetings/code-of-conduct.

Technical Sessions

2025 Puerto Rico and the U.S. Virgin Islands National Seismic Hazard Model Update

The National Seismic Hazard Model Project (NSHMP) will publish a new Puerto Rico and U.S. Virgin Islands (PRVI) NSHM in 2025. The last update was in 2003, therefore the new update will include over 20-years of new science and engineering data, models and methods. The NSHMP has requested the scientific community bring our attention to published earthquake source and ground motion models (GMMs) that could be included in this update by December 31, 2022. Planned updates for the 2025 PRVI NSHM include new seismicity models, based on an improved Puerto Rico Seismic Network seismicity catalog, updated geologic and geodetic deformation models, NGA-West2 and NGA-Subduction GMMs, site response models and uncertainty estimates.

NSHMs are community- and consensus-based models that are constantly aiming to incorporate the latest data, models and methods available to evaluate and validate hazard assessments as we undertake this updating process. This session will outline the plan and timeline for the 2025 PRVI NSHM Update, feature new source and ground motion data and models that will be considered in the 2025 model, as well as showcase current work being performed in the region that may impact future PRVI NSHM updates. We invite abstracts on new sources and GMMs, risk assessments, building code applications and other policy uses. We also invite abstracts from end users on applications and needs of NSHMs in end user products.

Conveners: Alberto M. López-Venegas, University of Puerto Rico Mayagüez, alberto.lopez3@upr.edu; Allison M. Shumway, U.S. Geological Survey, ashumway@usgs.gov; Jessica A. Thompson Jobe, U.S. Geological Survey, jjobe@usgs.gov; Thomas L. Pratt, U.S. Geological Survey, tpratt@usgs.gov; Victor Huérfano, University of Puerto Rico Mayagüez, victor.huerfano@upr.edu

Above the Seismogenic Zone: Fault Damage and Healing in the Shallow Crust

Fault damage zones provide a window into the inelastic processes and products that result from coseismic stress changes. The spatial extent of fault damage during earthquakes is greatest in the upper-most kilometers of the crust, above the seismogenic zone. Inelastic processes within this volume modify the bulk long-term properties of the shallow crust, increasing local seismic hazard through enhanced shaking. Fault damage zones have attracted the interest of a broad range of geoscientists because of their relevance to fundamental earthquake physics problems, i.e., the earthquake energy balance, strong ground motions and near fault fluid flow. Higher resolution datasets, a growing number of observations and increased computational power have advanced our understanding of the spatial extent, physical properties and time-integrated evolution of the shallow portion of damage zones. Our understanding of fault damage zones, the processes that form them and their feedbacks with various phases of the earthquake cycle is improving; however, there remain many unanswered questions such as the mechanism and rate of fault healing above the seismogenic zone, the role of subsidiary faults on earthquake nucleation and a complete model that extends damage observed at the surface to seismogenic depth. In this session, we welcome contributions and recent advances in the quantitative understanding of the shallow properties of fault damage zones. We are particularly interested in contributions that explore and combine observations, laboratory experiments, numerical modeling and theoretical studies.

Conveners: Ahmed Elbanna, University of Illinois Urbana-Champaign, elbanna2@illinois.edu; Alba M. Rodríguez Padilla, University of California, Davis, arodriguezpadilla@ucdavis.edu; Ashley W. Griffith, Ohio State University, griffith.233@osu.edu; Prithvi Thakur, University of Michigan, prith@umich.edu; Travis Alongi, University of California, Santa Cruz, talongi@ucsc.edu

Active Faults in the Caribbean and Central America

The Caribbean - Central America region is tectonically complex and diverse including convergent, divergent and transform plate boundaries. Numerous damaging historical earthquakes and tsunamis demonstrate the high level of earthquake hazard in the region, yet in many areas the specifics necessary for accurate hazard analysis and earthquake forecasting, such as fault slip rates, fault rupture history, earthquake chronologies and recurrence intervals, and even fault locations remain uncertain. We invite presentations of studies that elucidate any of these factors, including those employing terrestrial or subaqueous earthquake geology, geomorphology, paleoseismology, paleogeodesy or instrumental geodesy, paleotsunami studies, geophysics or seismology, or efforts to map active faults using any technique. Additionally, we accept presentations of work on the interface between earthquake science and society, including risk management, citizen science, and public policy. Submissions emphasizing the contribution of geoscience research to stakeholders in the evaluation of infrastructure resilience in the region are encouraged. Presentations that highlight cutting-edge methods are particularly welcome.

Conveners: Daniel A. Laó-Dávila, Oklahoma State University, daniel.lao_davila@okstate.edu; Belle Philibosian, U.S. Geological Survey, bphilibosian@usgs.gov; Kate Scharer, U.S. Geological Survey, kscharer@usgs.gov; Lorna G. Jaramillo-Nieves, University of Puerto Rico, Rio Piedras, lorna.jaramillo@upr.edu; Alberto M. López Venegas, University of Puerto Rico, alberto.lopez3@upr.edu; Carol Prentice, U.S. Geological Survey, cprentice@usgs.gov; Nathalie Feuillet, Institut de Physique du Globe de Paris, feuillet@ipgp.fr

Advances in Characterizing Seismic Hazard and Forecasting Risk in Hydrocarbon Systems

Unprecedented seismic activity near hydrocarbon development sites has raised questions regarding the physical mechanisms causing induced seismicity and spurred the expansion of hazard mitigation strategies over the past two decades. Adaptive and data-driven strategies for mitigating seismic hazard associated with hydrocarbon production, rely on real-time monitoring of earthquakes, identification of faults, and accurate timely reporting of operational data like downhole pressure. Different kinds of injection and production in operational fields change the reservoir and subsurface stress in space and time. Necessary ancillary data (e.g., sonic logs, 3D seismic data, fault maps, and subsurface pressure) are not always publicly available or reported in near-real time. Recent advancements in seismic and geodetic data availability and processing afford opportunities for developing high resolution catalogs and monitoring programs. Such data can be used to drive stress simulations and forecasting scenarios for induced seismicity and the real-time characterization of the evolving seismic hazard that enables stakeholders to make informed decisions on mitigation.

We seek diverse contributions focusing on hazard mitigation and risk assessment that span disciplines, including insight into the physics of induced earthquakes, the evolution of host faults and rocks, and case studies of successful mitigation. We encourage submissions that showcase innovative datasets made of deep learning, distributed acoustic sensing and large-N arrays, 3D imaging of faults, and integrated hydrologic and geomechanical modeling linked to production and injection operational data (including carbon capture sites). Presentations on computational, laboratory, and in-situ experiments for understanding fault behavior and fault slip modes under undrained/drained conditions are also encouraged to shed light on hydro-mechanical processes governing the spatiotemporal evolution of micro-seismicity.

Conveners: Alexandros Savvaidis, University of Texas at Austin, alexandros.savvaidis@beg.utexas.edu; Asiye Aziz Zanjani, Southern Methodist University, aazizzanjani@smu.edu; Heather R. DeShon, Southern Methodist University, hdeshon@smu.edu; Jake Walter, University of Oklahoma, Oklahoma Geological Survey, jwalter@ou.edu; Nadine Igonin, University of Texas at Austin, nadine.igonin@beg.utexas.edu

Advances in Marine Seismoacoustics

On land, we are seeing increasing interdependence between seismic and infrasonic or acoustic observations for many important research applications. Continued expansion of seismoacoustic research into the oceans has given rise to a vast expansion of our geophysical reach, sensing and observational capabilities. Both autonomous deep ocean sensing and nearshore cabled arrays have provided significant advances not only for geodynamic modeling but also earthquake and tsunami early warning, extension of global geophysical models and new appreciation of the complex and coupled problem of hydroacoustic and seafloor seismic interactions and phenomena. We invite contributions surrounding all relevant studies addressing marine seismoacoustic issues, including sensor and communications developments, oceanic noise (both hydroacoustic and seismic), marine mammal vocalization and acoustic tomography, propagation and phase conversion, spreading center, transform system and subduction models and observations and fusion of relevant geophysical observations to augment new and existing seafloor seismic data.

Conveners: Charlotte Rowe, Los Alamos National Laboratory, char@lanl.gov; Ethan Williams, Caltech, efwillia@caltech.edu; Kasey Aderhold, Incorporated Research Institutions for Seismology, kasey@iris.edu; Nishath Rajiv Ranasinghe, Los Alamos National Laboratory, ranasinghe@lanl.gov

Advances in Probabilistic Seismic Hazard Analysis and Applications

Probabilistic seismic hazard analysis (PSHA) was established a half-century ago and has since been used for seismic hazard, as the basis for building codes and seismic risk analysis. Significant improvements have been made in both seismic source and ground motion modeling. The modeling of epistemic uncertainty through logic-trees and other tools has allowed modelers to combine diverse ideas to produce more informative hazard estimates.

However, several challenges remain. Despite considerable progress made in the latest decade (e.g., UCERF3), combining different information in the seismic source characterization (e.g., historical seismicity, geodesy, tectonics and paleoseismology) remains problematic. Assumptions about, for example, magnitude scaling, earthquake rates on faults and Mmax are necessary due to incomplete data and lack of understanding and oversimplification of complex earthquake phenomena. On the ground-motion modeling side, an increasing number of hazard analyses incorporate regional and local properties through partially- and non-ergodic models and account for epistemic uncertainties with advanced approaches, such as the ones based on backbone models.

We invite presentations on the developing or updating of national or regional hazard models including site specific hazard studies, as well as the application of them, including but not limited to their application in the building code community and insurance sectors. We also welcome studies on model evaluation such as impact on hazard result by different modeling assumptions. Please note that papers specifically on seismic source modeling should be submitted to "Opportunities and Challenges in Source Modeling for Seismic Hazard Analysis" session.

Conveners: Elliot Klein, FM Global, elliot.klein@fmglobal.com; Harold Magistrale, FM Global, harold.magistrale@fmglobal.com; Marco Pagani, GEM Foundation, marco.pagani@globalquakemodel.org; Matt Gerstenberger, GNS Science, m.gerstenberger@gns.cri.nz; Richard Styron, GEM Foundation, richard.styron@globalquakemodel.org; Sanjay Bora, GNS Science, s.bora@gns.cri.nz; Yufang Rong, FM Global, yufang.rong@fmglobal.com

Advancing Science with Global Seismological and Geophysical Networks

Four decades of globally distributed and openly available very broadband seismic recordings have enabled significant advances in characterizing earthquake sources, mapping the deep structure of the Earth, and understanding the behavior of the atmosphere, hydrosphere, and cryosphere. Long-term deployment has illuminated time-dependent processes and allowed subtle signals to be enhanced and utilized through stacking. At the same time, establishing real-time telemetry at these stations has revolutionized the monitoring capability for large and potentially destructive earthquakes. Central to these activities have been the international partnerships, infrastructure investments, and technological developments that have facilitated, grown, and maintained the availability of low-noise and high-fidelity seismic recordings from almost anywhere in the world. This session will be a forum to highlight impactful current science being done with globally distributed real-time networks, to understand how technological developments can optimize existing resources, to share ideas for expanding networks like the Global Seismographic Network, GeoScope, and others to include other geophysical and environmental observations, to recognize how increased partnerships and collaboration can further grow high-quality station coverage around the world, and to reflect on the common challenges to operating and sustaining these scientific resources. We encourage contributions from the international community of seismologists and related disciplines, instrumentation developers, network and station operators, and other stakeholders.

Conveners: Andrew M. Frassetto, Incorporated Research Institutions for Seismology, andy.frassetto@iris.edu; Colleen Dalton, Brown University, colleen_dalton@brown.edu; David Wilson, Albuquerque Seismological Laboratory, United States Geological Survey, dwilson@usgs.gov; Frederik Tilmann, Helmholtz Center Potsdam, tilmann@gfz-potsdam.de; Martin Vallée, Institut de Physique du Globe de Paris, vallee@ipgp.fr; Robert Busby, Incorporated Research Institutions for Seismology, busby@iris.edu

Collective Impact in Earthquake Science

The earthquake science and engineering community has the opportunity to apply leading edge earthquake research to improve resilience from seismic hazards in an equitable, accessible and sustainable manner. One way to do this is by adopting a collective impact model, which develops a network of community members, organizations and institutions by adopting a common agenda, centralized support, continuous communication, mutually reinforcing activities and shared measurement. In this session, we invite presentations highlighting research from any disciplines with the potential to respond to the needs of vulnerable populations that have been historically underserved by current earthquake science, engineering and public policy. Topics could include 1) community-driven or community-based research results, 2) discoveries advancing our understanding of seismic hazards in areas of low probability but high impact earthquakes (including intraplate and induced earthquakes), 3) strategies for implementing practical, research-inspired solutions for communities, 4) research engaging low-resourced communities or historically marginalized populations, 5) existing efforts to coordinate research and projects for broader community benefits and 6) integration of social science with seismology. We encourage presenters to highlight strategies and efforts to improve inclusivity, diversity, equity and accessibility in seismology.

Conveners: Aaron A. Velasco, University of Texas at El Paso, aavelasco@utep.edu; Alexandros Savvaidis, Bureau of Economic Geology, alexandros.savvaidis@beg.utexas.edu; Manuel Mendoza, University of Colorado, mame3278@colorado.edu; Marianne S. Karplus, University of Texas at El Paso, mkarplus@utep.edu; Michael R. Brudzinski, Miami University, brudzimr@miamioh.edu; Steven Jaume, College of Charleston, jaumes@cofc.edu; Susan Bilek, New Mexico Tech, sbilek@nmt.edu

Constraining Seismic Hazard in the Cascadia Subduction Zone

The Cascadia Subduction Zone is host to a range of significant earthquake and tsunami-related hazards, which have the potential to impact major population centers and coastal communities. Due to the historically low seismicity in this region, it has been difficult to constrain the hazard and risk to nearby communities from earthquakes and their cascading effects. However, in recent years, our understanding of seismic hazard in Cascadia has progressed thanks to advances in instrumentation and modeling and interdisciplinary collaborations. For example, the M9 Project and Cascadia Coastal Hazards Research Coordination Network have integrated geosciences and structural engineering with social science and public policy planning. These have helped to better characterize CSZ seismic hazards, both from great megathrust earthquakes and from the more frequent low-to-moderate magnitude seismicity occurring on nearby crustal faults and in the subducting slab. Additional multidisciplinary efforts are anticipated over the next few years: the draft SZ4D implementation plan calls for additional long-term instrumentation in the Cascadia Subduction Zone and collaborations resulting from a nascent earthquake science center proposal (Cascadia Region Earthquake Science Center, CRESCENT) aim to understand hazards from an interdisciplinary perspective, with stakeholder input. This session welcomes presentations that address all aspects of earthquake and tsunami hazard in Cascadia, including seismic or geodetic modeling efforts, offshore and onshore observational studies, statistical seismology, probabilistic hazard estimation, early warning and communication and policy planning. We encourage contributions related to intraslab and crustal earthquakes as well as megathrust events.

Conveners: Diego Melgar, University of Oregon, dmelgarm@uoregon.edu; Erin A. Wirth, U.S. Geological Survey, emoriarty@usgs.gov; Leah Langer, U.S. Geological Survey, llanger@usgs.gov; Max Schneider, U.S. Geological Survey, mschneider@usgs.gov; Valerie Sahakian, University of Oregon, vjs@uoregon.edu

Coseismic Ground Failure: Advances in Modeling, Impacts and Communication

Landslides and liquefaction triggered by earthquakes are a diverse set of phenomena that can cause significant impacts and losses across wide areas affected by earthquake shaking. Advances in our ability to model the initiation, displacement or runout, and impacts of ground failure of all types are needed to improve our ability to quantify the magnitude and uncertainty of hazard and risk, as well as predict near-real-time losses for emergency response. To be most useful, these hazard and risk models also need to be effectively communicated to a wide range of technical and general audiences across a wide range of contexts. All coseismic ground failure advances depend on a basis of strong high-quality datasets, both in terms of susceptibility and loading factors and detailed documentation of the occurrence of ground failure in past earthquakes. We welcome all submissions relating to coseismic ground failure, including but not limited to contributions on: regional scale assessment; characterizing uncertainty, or developing ensemble model predictions; studies on the impacts, losses and risk modeling for coseismic ground failure; research or case histories on the best practices and advances in engagement and communication with diverse stakeholder groups; as well as case histories and lessons from recent and historic earthquakes.

Conveners: Alex R. Grant, U.S. Geological Survey, agrant@usgs.gov; Eric Thompson, U.S. Geological Survey, emthompson@usgs.gov; Kate E. Allstadt, U.S. Geological Survey, kallstadt@usgs.gov; Laurie G. Baise, Tufts University, laurie.baise@tufts.edu

Crustal Deformation and Seismic Hazard in Western Canada, Cascadia and Alaska

It is well known that a component of plate boundary deformation is distributed along fault sources located 10s to 100s of km away from the plate interface. However, in many systems the locations, geometries, kinematics and rates of deformation along these faults, and how they interact with the plate interface, are poorly understood. This information is necessary both to understand how plate boundary strain is accommodated across the system and to evaluate the seismic hazard these fault sources pose. This is particularly true of the Cascadian upper plate, Canadian Cordillera and Alaskan margins of western North America, where dense vegetation, rugged terrain, limited instrumentation and locally slow strain rates make assessing fault rupture potential challenging. Over the past decade, there has been significant advances in understanding the deformational and paleoseismic histories of fault structures in Oregon, Washington, Vancouver Island, eastern British Columbia and southeastern Alaska. Much of the most recent work builds upon several decades of prior research — but not all of this work is published or publicly available to researchers and hazard modelers. For this reason, we aim to develop a session to bring researchers together to discuss known and suspected crustal faults in this complex plate boundary zone. In this session, we hope to discuss the current state of knowledge of known or suspected active faults using data sets including but not limited to paleoseismology, seismology, geodesy and modeling of shallow faults in northwestern North America. We aim to bring researchers together to not only share knowledge, but also to help build a community of practice, developing ideas and workflows that can be applied to quantify the deformation rates and hazard of crustal fault in similar tectonic and climatic settings.

Conveners: Christine Regalla, Northern Arizona University, christine.regalla@nau.edu; Lydia Staisch, U.S. Geological Survey, lstaisch@usgs.gov; Richard H. Styron, GEM Foundation, richard.styron@globalquakemodel.org; Tiegan Hobbs, Geological Survey of Canada, thobbs@eoas.ubc.ca

Crustal Imaging of High Seismic Hazard Regions

In high seismic hazard areas, imaging both the elastic and anelastic properties of the medium is key for evaluating deformation processes and the impact of complex fault systems on ground motion amplification. Characterizing crustal features is especially challenging when wave focusing and conversions, or fluid interactions occur such as in geothermal and volcanic areas. Combining attenuation and velocity models is crucial for predicting site response and seismic wavefield amplitudes. This session aims at providing an overview of techniques and applications related to the imaging and validation of seismic velocity and attenuation across various scales ranging from laboratory samples to basin and plate boundary scales. We welcome onshore and offshore passive and active-source seismic studies and studies based on gravity and magnetic data that discuss the characterization of crustal structures, including faults, volcanic and geothermal areas. We aim to gather contributions from velocity and attenuation tomography (t^* method, direct wave attenuation, coda waves) and other imaging techniques (e.g., using ambient noise and converted waves). We welcome studies aimed at including these models and other multidisciplinary geophysical and geological data in ground motion modeling, seismic hazard assessments and site response analysis. We also encourage submissions from early-career researchers and studies using innovative methodologies (e.g., machine learning).

Conveners: Chiara Nardoni, Louisiana State University, cnardoni@lsu.edu; Simona Gabrielli, Istituto Nazionale di Geofisica e Vulcanologia, simona.gabrielli@ingv.it; Patricia Persaud, University of Arizona, ppersaud@lsu.edu; Eric Sandvol, University of Missouri, SandvolE@missouri.edu

Deciphering Earthquake Clustering for the Better Understanding of Crustal Deformation Mechanisms

When is the occurrence of earthquakes random and when is it not? How do earthquakes interact and why are interactions stronger in some places? Which physical processes enhance clustering and which do not? More than a century after the first quantitative description of earthquake clustering in aftershock sequences by Omori, clustering has been recognized as the consequence of stress redistribution accompanying deformation in the crust (for example, after a large earthquake). However, high resolution catalogs, application of advanced statistical analyses and numerical modeling in complex fault analogues have started to reveal how earthquake clustering can also emerge from the interplay between fault complexity and physical processes occurring in the lithosphere. The role of transient creep and fault heterogeneity are for example nowadays key factors in controlling the occurrence of time and space synchronization of seismicity. However, much remains to discover about the relationship between the observed spatio-temporal clustering of earthquakes and the driving mechanisms, as well as the host rock properties. In this session we welcome observational, experimental, numerical and theoretical studies tackling the issue of earthquake clustering at different spatial and temporal scales, and which provide interpretation in terms of fault and other crustal mechanisms. Studies focusing on different tectonics settings, and on volcanoes, are welcome, with the aim of shedding new light on the physics of earthquake clustering and understanding the dynamics of complex crustal processes better.

Conveners: Eric Beauce, Lamont-Doherty Earth Observatory, Columbia University, ebeauce@ldeo.columbia.edu; Patricia Martínez Garzón, GFZ Potsdam, patricia@gfz-potsdam.de; Piero Poli, Università di Padova, pieropoli85@gmail.com

De-Risking Deep Geothermal Projects: Geophysical Monitoring and Forecast Modeling Advances

Geothermal energy is an emerging renewable energy source and as a green and sustainable energy can make a significant contribution to the current worldwide challenge to reduce the net atmospheric emissions of greenhouse gases to zero. Geothermal heat extracted from depth in excess of 400 m is defined as deep geothermal energy or Enhanced Geothermal Systems (EGS). EGS usually employ hydraulic fracturing to increase the rock permeability and favor a more efficient exploitation of deep geothermal reservoirs when local geology does not favor natural pathways for fluid circulation. Induced micro-earthquakes in EGS are not therefore undesired by-products but a necessary tool to create effective pathways for fluid migration and heat exchange. Thus, to develop EGS, adaptive, data-driven real-time monitoring and risk analysis of potential seismicity triggered by EGS operations is crucial for assessing the geothermal stimulation effects and demonstrate that safe and sustainable development of deep geothermal energy projects is possible. A current research-oriented EGS laboratory is being developed at the FORGE (Frontier Observatory for Research in Geothermal Energy) geothermal site in Utah, USA. We encourage contributions from FORGE and other different geothermal energy projects and field test sites that focus on geophysical technologies applied to geothermal energy, such as real-time monitoring and characterization of induced seismicity, distributed acoustic sensing, large-N array, active surface seismic, vertical seismic profiling, seismic imaging of faults and fracture zones, laboratory experiments and novel instrumentation. We also welcome submission of abstracts on modelling studies at all scales, seismicity forecasting models, hazard and risk analysis studies as well as presentations dealing with good-practice guidelines and risk assessment procedures that would help in reducing commercial costs and enhancing the safety of future geothermal projects.

Conveners: Annemarie Muntendam-Bos, Delft University of Technology A.G., Muntendam-Bos@tudelft.nl; David Eaton, University of Calgary, eatond@ucalgary.ca; Federica Lanza, Swiss Seismological Service, ETH Zurich, federica.lanza@sed.ethz.ch; Kristine Pankow, University of Utah, kris.pankow@utah.edu; Nori Nakata, Lawrence Berkeley National Laboratory, nnakata@lbl.gov; Ryan Schultz, Stanford University, rjs10@stanford.edu

Detecting, Locating, Characterizing and Monitoring Non-Earthquake Seismoacoustic Sources

Non-earthquake seismoacoustic sources, such as landslides, avalanches, lahars, glacial events, blasts and bolide impacts, are commonly recorded by seismoacoustic monitoring networks. Although most of these sources are not routinely monitored in real-time like earthquakes, the recent surge in seismoacoustic data and ground-based, airborne and satellite imagery makes these post-event detections and characterizations possible. Furthermore, regional networks increasingly incorporate acoustic instrumentation, making acoustic measurements of these events more common. This session focuses on methods that aim to better understand and characterize these sources and to better monitor and mitigate their associated hazards. We encourage presentations that study all types of non-earthquake seismic sources by utilizing seismoacoustic, geodetic and remote sensing techniques on local, regional, and global scales. Relevant topics may include but are not limited to source detection, location, characterization, modeling and classification (including machine learning approaches); precursory signal analysis; monitoring; and hazard mitigation.

Conveners: Ezgi Karasözen, Alaska Earthquake Center, Geophysical Institute, University of Alaska Fairbanks, ekarasozen@alaska.edu; Kate Allstadt, U.S. Geological Survey, kallstadt@usgs.gov; Liam Toney, Alaska Volcano Observatory and Wilson Alaska Technical Center, University of Alaska Fairbanks, ldtoney@alaska.edu

Earth's Structure from the Crust to the Core

Several science priority questions in the community report "A Vision for NSF Earth Sciences 2020-2030" rely on progress in seismological research of Earth's deep interior. This session will cover all aspects of "structural seismology." In particular, we encourage submissions that discuss new or new combinations of seismological data types, as well as advances in global and regional-scale seismic tomography, 3D waveform modeling, array-based approaches and the analysis of correlation wavefields. We hope that this session will highlight new contributions from seismologists to interdisciplinary research of core and mantle dynamics, the role of the mantle transition zone in mantle convection, volcanism in different settings around the world, the structure of subducting slabs, deep lithospheric deformation and processes, lithosphere-asthenosphere interactions and their feedbacks into geohazards.

Conveners: Jeroen Ritsema, University of Michigan, jritsema@umich.edu; Keith Koper, University of Utah, kkoper@gmail.com; Vera Schulte-Pelkum, University of Colorado, vera.schulte-pelkum@colorado.edu

Earthquake Early Warning Optimization and Efficacy

Several elements contribute to the optimization of an Earthquake Early Warning (EEW) system's performance, including: the design of the network, choice of sensors, algorithm refinement and means of communications. The processing of data and the accuracies and latencies this introduces also require analysis to ensure warnings are timely and meaningful. For example, the inclusion of site amplification in estimating intensities and the extent of the potentially impacted region should improve the accuracy of the EEW system; it may, however, slow the distribution of alerts. Additionally, EEW systems can only be effective if people and systems respond appropriately. Technical recipients must have automated systems in place to initiate protective measures, and people need to take safe response actions, such as to Drop, Cover and Hold on. To establish the necessary culture of awareness and preparedness, EEW organizations must work with others, including emergency measures organizations, to ensure a broad, consistent and authoritative EEW education and outreach effort. Such initiatives should include engagement with critical infrastructure operators and take special care to address particularly vulnerable populations, such as low income, new immigrants, Indigenous and elderly. This session invites abstracts on all aspects of optimizing EEW systems, including sensor and communication developments, optimizing methodologies and system assessment and abstracts related to Education, Outreach and Engagement for EEW.

Conveners: Alison L. Bird, Natural Resources Canada, Sidney, alison.bird@nrcan-rncan.gc.ca; Claire Perry, Natural Resources Canada, claire.perry@NRCan-RNCan.gc.ca; Danielle Sumy, Incorporated Research Institutions for Seismology, danielle.sumy@iris.edu; Sara K. McBride, U.S. Geological Survey, skmcbride@usgs.gov

Earthquake Preparation Across Scales: Reconciling Geophysical Observations with Laboratory and Theory

Observing and understanding the physical processes occurring before large earthquakes is fundamental for both scientific purposes and to advance our ability to forecast these catastrophic events. Current physical models of earthquake initiation mainly focus on laboratory experiments and theoretical work. While these studies often describe a distinct nucleation phase, direct field observations of similar preparatory processes based on seismological or geodetic data are still lacking. Nevertheless, recent improvements in monitoring capabilities, density of recording stations, data quality and the development of novel data analysis methods, have increased the spectrum of available observations of processes occurring before large earthquakes. These recent observations, often spanning several spatial and temporal scales, can provide insights into the physical conditions promoting or inhibiting a detectable earthquake preparatory process or fault unrest. In this session we welcome (but we are not limited to) (i) contributions focusing on the observation, analysis and modeling of earthquake preparatory processes from seismological and/or geodetic data covering different spatial and temporal scales, (ii) studies focusing on laboratory scale, theoretical analysis and numerical modeling. For both, we welcome presentations providing novel observations and new insights into the complexities involved in earthquake preparation and initiation and new data analysis (e.g., machine learning, big data, unsupervised analysis) which shed light on earthquake preparation.

Conveners: Gregory McLaskey, Cornell University, gcm8@cornell.edu; Patricia Martinez-Garzon, GFZ Potsdam, patricia@gfz-potsdam.de; Piero Poli, Università di Padova, piero.poli@unipd.it

Earthquake Source Parameters: Theory, Observations and Interpretations

Understanding origin and spatio-temporal evolution of seismicity needs a careful quantitative analysis of earthquake source parameters for large sets of earthquakes in studied seismic sequences. Accurate determination of earthquake hypocenters, focal mechanisms, seismic moment tensors, static stress drop, apparent stress and other earthquake source parameters provides an insight into tectonic stress and crustal strength in the area under study, fault material properties, fault roughness and prevailing fracturing mode (shear/tensile) in the focal zone, and allows investigating earthquake source processes in greater details. In addition, studying relations between static and dynamic source parameters and earthquake size is essential for understanding the self-similarity of rupture processes and scaling laws and for improving our knowledge on ground motion prediction equations.

This session focuses on methodological as well as observational aspects of earthquake source parameters of natural or induced earthquakes in broad range of scales from large natural earthquakes through reservoir scale microseismicity, to pico- and femto-seismicity from in-situ laboratories and laboratory experiments on rock samples. Presentations of new approaches and methodologies for determination of source characteristics as well as case studies related to analysis of earthquake source parameters in the context of earthquake physics are welcome. We also invite contributions related to scaling of static and dynamic source parameters, to self-similarity of earthquakes and inversions for stress and other physical parameters in the focal zone.

Conveners: German A. Prieto, Universidad Nacional de Colombia, gaprietogo@unal.edu.co; Grzegorz Kwiatek, Deutsches GeoForschungsZentrum, GFZ, grzegorz.kwiatek@gfz-potsdam.de; Pavla Hrubcova, Institute of Geophysics of the Czech Academy of Sciences, pavla@ig.cas.cz; Satoshi Ide, The University of Tokyo, ide@eps.s.u-tokyo.ac.jp; Vaclav Vavrycuk, Institute of Geophysics of the Czech Academy of Sciences, vv@ig.cas.cz

Emerging Developments in Operational Monitoring Systems and Products

Software tools for processing and analyzing geophysical data have continued to evolve along with advancements in monitoring instrumentation and technology. The broad seismic monitoring, assessment and research community must keep up with these advancements in order to quickly and reliably detect events, derive scientific products and distribute this scientific information to a wide array of consumers. In this session we invite presentations that explore emerging developments in operational monitoring systems, interfaces and products. This scope includes, but is not limited to, how various technologies (e.g., cloud-based, orchestration, web services, data streaming) and algorithms or methodologies (e.g., AI/ML, parallel processing) are improving operational monitoring systems for near-real-time processing or rapid delivery of information to human or machine consumers. Abstracts detailing enhancements to code or infrastructure used in the near real-time generation of data products are encouraged. Examples of advancements in monitoring systems via the integration of multiple kinds of data (e.g., geodetic, seismic, DAS, social media, etc.) as well as making software/code, models and interfaces FAIR (findable, accessible, interoperable, and reusable) to a broader scientific community are also important topics of interest.

Conveners: Ellen Yu, Southern California Earthquake Data Center, Caltech, eyu@caltech.edu; Kirstie Haynie, Geologic Hazards Science Center, U.S. Geological Survey, khaynie@usgs.gov; Michelle Guy, Geologic Hazards Science Center, U.S. Geological Survey, mguy@usgs.gov

Exploiting Explosion Sources: Advancements in Seismic Source Physics

Underground, near-surface and/or above ground explosion sources can be used to illuminate the subsurface geologic structure and understand seismo-acoustic signal propagation. Recent work using template matching, waveform modeling for moment tensors, and combining seismo-acoustic data has shown great success in characterizing explosions and discriminating them from earthquakes and other sources. In regions of low natural background seismicity, mine blasting can dominate monitoring catalogs, and identifying and separating these sources from tectonic earthquakes is critical for hazard assessment. The seismo-acoustic signals from intentional and accidental explosions can be used in forensic analysis to study propagation anomalies. Recordings of surface explosions illuminate the geologic structures in aseismic regions and aid in better characterization of the velocity structure. The wavefields that delineate the subsurface structure are being acquired in unprecedented detail with the advent of dense arrays and multi-phenomenology instrumentation. We welcome abstracts in explosion source physics, wave propagation, seismic array design, distributed acoustic sensing (DAS), new sensor technologies, multi-physics data fusion and advanced processing and characterization techniques applied to explosion sources.

Conveners: Catherine M. Snelson, Los Alamos National Laboratory, snelsonc@lanl.gov; Christian Stanciu, Sandia National Laboratories, astanci@sandia.gov; Cleat P. Zeiler, Nevada National Security Site, zeilercp@nv.doe.gov; Colin Pennington, Lawrence Livermore National Laboratory, pennington6@llnl.gov; Elizabeth A. Silber, Sandia National Laboratories, esilbe@sandia.gov; Jenna L. Faith, Los Alamos National Laboratory, jfaith@lanl.gov; William R. Walter, Lawrence Livermore National Laboratory, walter5@llnl.gov

From Earthquakes to Plate Boundaries: Insights into Fault Behavior Spanning Seconds to Millennia

The processes of strain accumulation and release and related topographic evolution happen over disparate timescales – from seconds to millennia and longer. Quantifying and understanding the earthquake cycle in the continental crust and how tectonic strain is expressed at the surface in the landscape thus requires integrating methods that measure deformation at a range of timescales. While geodetic methods record regional infinitesimal strain accumulation over decadal timescales and finite coseismic deformation from individual large events, paleoseismology and tectonic geomorphology measure site-specific or regional-scale strain release over thousands to millions of years. Numerical modeling and analog experiments attempt to replicate processes that can span multiple temporal scales, but they must be validated with observations to ensure they are physically meaningful. In this session, we invite abstracts that integrate observations and methods from different temporal and/or spatial scales to address topics such as: surface rupture and slip distribution patterns in space and time; variations in earthquake timing and recurrence; fault growth, linkage, and scaling; (dis)agreement of geologic and geodetic rates; and tectonic landscape evolution. We welcome contributions from geodesy, earthquake geology, tectonic geomorphology, numerical modeling, analog experiments, and especially contributions with novel approaches to integrating multiple data sources that help further our understanding of strain accumulation and release spanning coseismic to geologic timescales.

Conveners: Austin Elliott, U.S. Geological Survey, ajelliott@usgs.gov; Chris Milliner, California Institute of Technology, milliner@caltech.edu; Nadine Reitman, U.S. Geological Survey, nreitman@usgs.gov; Marion Thomas, Earth Sciences Institute of Paris, Sorbonne Univeristé, marion.thomas@sorbonne universite.fr; Solene Antione, NASA Jet Propulsion Lab, solene.antoine@jpl.nasa.gov

From Sensors and Networks to Site Characterization and Site Response: Coming Full Circle

Recent advances in the fields of site characterization and seismic instrumentation (in terms of sensors and analysis) have introduced a wide range of new approaches that improve our ability to model the influence of near-surface soil and rock formations on ground motion. However, these new approaches are associated with challenges with how to best use and interpret these data. Decisions affecting the quality and quantity of useful ground motion data, encompassing the sensors on which they were recorded, data processing methods, and the choice of site characterization methods at various scales, all affect the accuracy of and uncertainty in the determination of seismic site parameters. These parameters describe the geometry and distribution of earth materials and their properties and are used to predict the "site effect" component of ground motion models used in seismic hazard assessment. Often, however, these downstream applications take for granted the provenance and quality of recorded waveform data and their derivatives, be they earthquake ground motions from seismic networks or site parameters derived from geophysical field campaigns. Our session aims to explore how variation in these operational and analytical decisions affects the modeling of seismic site conditions, site response and ground motion modeling and their uncertainties. We welcome presentations on each stage of ground motion data collection and analysis, from acquisition to analysis, including: recording stations, fieldwork, regional and temporary deployments, assessment of material properties and earth structure, choice of methodologies for carrying out site response analyses and the relationship between uncertainty in site characterization and site response. We encourage submissions from across the globe and at various geospatial scales, especially those pertaining to Puerto Rico and the greater Caribbean/Latin America regions.

Conveners: Albert Kottke, Pacific Gas & Electric, Co., arkk@pge.com; Lisa S. Schleicher, U.S. Geological Survey, Earthquake Science Center, lschleicher@usgs.gov; Olga-Joan Ktenidou, National Observatory of Athens, olga.ktenidou@noa.gr; Sean Ahdi, U.S. Geological Survey, Geologic Hazards Science Center, sahdi@usgs.gov

Future Directions in Physics-Based Ground-Motion Modeling in Preparation for the Fall 2023 Meeting

Modern ground-motion modeling for improved source physics and hazard understanding has been investigated from both simulation-based and data-driven perspectives for quantitative prediction. Significant recent advances in empirical modeling move towards spatially varying, non-ergodic models, while physics-based simulations are broadening their applicability to regions or faults not previously considered. The community needs to move forward together to ensure that these models are realistic and applicable to a larger range of magnitudes of different types of events. To this end, SSA, joint with SSJ, will host a topical meeting entitled "Modern Global Ground-Motion Modeling: Future Directions in Physics-Based Ground-Motion Modeling" in fall 2023. At this meeting, we will bring together international researchers to exchange ideas, compare approaches, and delineate new directions of research for the next decade in the field of physics-based ground-motion modeling and prediction. The conference will be held in Vancouver, Canada on October 9 to 12, 2023. This session is designed as an opportunity to discuss the current status of research on ground motion modeling and make the most effective foci for the discussion during the Fall 2023 Ground Motion meeting. Therefore, this session seeks contributions that elucidate the impact of the new approaches for source and site effects representation on the ground motions and the associated seismic hazard evaluations. Example topics of interest/areas of study include, but are not limited to: evolution and limitations of complex kinematic and dynamic source modeling; new approaches to the modeling of the empirical source characteristics; physical and empirical modeling of side effects; comparisons of physics-based and empirical data-driven approach on the overall prediction accuracy; and, statistical evaluation of the variability of our evaluations and predictions.

Conveners: Annemarie Baltay, Earthquake Science Center, USGS, abaltay@usgs.gov; Hiroshi Kawase, Disaster Prevention Research Institute, Kyoto University, kawase@zeisei.dpri.kyoto-u.ac.jp; Zhigang Peng, Earth and Atmospheric Sciences, Georgia Institute Technology, zpeng@gatech.edu

Geophysical Data Analysis in Cloud Computing Environments

Advancements in instrumentation are increasing the variety, complexity and volume of geophysical datasets. Improvements in cyber infrastructure have been helping to reduce the effort and cost in collecting, storing and sharing large datasets. Utilization of cloud compute and storage resources has the potential to make large temporal and spatial analyses more tractable and for a larger audience. Furthermore, with more data center facilities providing access to datasets in the cloud, the opportunity to process data without transferring it across the internet significantly reduces the operational burden, and potentially cost, of research computation. Cloud computing services, like distributed messaging queues, serverless functions, object storage and container orchestration, expand the options for how research at very large scales can be performed. Open frameworks that can be used in the cloud such as Apache Spark, xarray and Dask, Ray, etc. provide even more options. In this session, we invite researchers, data producers and data providers to share their experiences deploying resources in cloud environments to support or conduct data collection, transformation, analysis, storage and distribution at scale.

Conveners: Chad Trabant, Incorporated Research Institutions for Seismology, chad.trabant@iris.edu; Henry Berglund, UNAVCO, henry.berglund@unavco.org

Ground Truthing Multidimensional Site Response Analyses at Borehole Array Sites

A significant amount of seismic site response research over the past decade has focused on our abilities to replicate recorded ground motions at borehole array sites, where both the input (rock) and output (surface) ground motions are known. When viewed in aggregate, these studies have found that approximately 50% of borehole array sites are poorly modeled using 1D ground response analyses (GRAs). While multidimensional (i.e., 2D and 3D) GRAs are theoretically plausible, 1D GRAs remain by far the most widely used approach for simulating site effects in practice and research. This is partly due to a lack of well-documented and openly accessible case histories that ground truth multidimensional GRAs at borehole array sites. The availability of multidimensional GRA validation studies at borehole array sites could serve as a benchmark for practitioners and researchers to calibrate their own analyses and achieve more reliable seismic hazard assessment and risk mitigation. A current research study is being conducted with collaborators from research and industry to ground truth multidimensional GRAs at the Treasure Island Downhole Array (TIDA). A large-scale, site-specific 3D subsurface model is now available for this site and multidimensional GRAs have proven that site response recorded in the borehole array is influenced by subsurface spatial variability at distances over 1 km away. Several teams have performed multidimensional GRAs for the TIDA site using different commercial and open-source software (e.g., OpenSees, Sesimo-VLab, FLAC, LS-DYNA). We strongly encourage contributions from the different collaborators on this project, as well as from other studies on any aspect of ground truthing multidimensional GRAs. This session will provide an opportunity for researchers and engineers to discuss and constructively compare modeling strategies, boundary conditions, computational time and ground truthing of the numerical results against recorded ground motions.

Conveners: Brady R. Cox, Utah State University, brady.cox@usu.edu; Mohamad M. Hallal, University of California, Berkeley, mhallal@utexas.edu

High-frequency Ground Motion Measurements, Assessments and Predictions

High-frequency ground motion is critical for both seismologists, who can understand the source process, and engineers, who need to design structures with high natural frequency or structures hosting safety-related equipment sensitive to high frequency shaking (e.g., nuclear power plant). Although seismologists consider that high-frequency ground motions include frequencies larger than 1 Hz, while engineers are more interested in frequencies larger than 10 Hz, measuring, analyzing and modeling high-frequency ground motions are necessary for advancing the simulation of ground motions at broader ranges of frequencies and improving ground motion models. Particularly, high-frequency seismic waves tend to be affected by near-surface deposits significantly, hence the appropriate modeling and interpretation of high-frequency ground motions are essential to understand site effects more holistically. Thus, this session invites investigations on an aspects of the assessment of high-frequency ground motions and the improvement of current practices in site response estimations, which may include: (1) the variability in observations of high frequency ground motions, (2) the simulation of high-frequency ground motion, (3) the search of optimal site proxies to characterize site effects affected by shallow or deeper geologic structures, (4) numerical or empirical studies on 2D/3D site effects and the integration of the corresponding results into seismic hazard assessment, (5) site-specific ground motion prediction at high frequencies and its associated uncertainties, (6) in-situ characterization of attenuation, (7) ground motion models with explicit consideration of site attenuation and (8) near-surface and regional attenuation of seismic waves modeled with attenuation parameters such as the high-frequency spectral decay parameter kappa or the seismic quality factor, Q.

Conveners: Albert Kottke, Pacific Gas and Electric Company, albert.kottke@gmail.com; Ashly Cabas, North Carolina State University, amcabasm@ncsu.edu; Chunyang Ji, North Carolina State University, cji3@ncsu.edu; Kenneth Campbell, CoreLogic, ken.w.campbell@comcast.net; Marco Pilz, German Research Center for Geosciences, pilz@gfz-potsdam.de

It's All About Relocation, Relocation, Relocation

The current capability to locate smaller seismic events has been boosted by unprecedented numbers of nodal networks and improved local monitoring throughout the world, yet the challenge still remains to accurately estimate an earthquake's hypocenter. Many relocation algorithms and processing techniques have been implemented to determine absolute and relative locations. The methods of measuring events have not changed significantly but the modern tools and higher sample rates introduce a new opportunity to refine our error estimates. The quantification of error in a location and the tradeoffs between site corrections, velocity model and other constraints applied to the location algorithm are rarely compared across multiple techniques or catalogs. The comparison of historical events and modern relocated events is made more difficult by the changing methods and data availability with time. The quantification of how modern studies deal with such divergence is one that has yet to be strongly examined. As we continue to look at the future of locating smaller seismic events, we want to accurately estimate the hypocenter location while improving our understanding of the historical context of earthquake locations. In this session we invite contributions that are pushing the science of locating earthquakes through new measurement techniques, the development of new location algorithms, the comparison of different methods and comparisons or combinations of the locations of historical and modern catalogs. The goal is to look at the accuracy of modern techniques and understand the errors associated with locating targeted events or event clusters.

Conveners: Cleat Zeiler, Nevada National Security Site, zeilercp@nv.doe.gov; Leiph Preston, Sandia National Laboratory, lpresto@sandia.gov; Michelle Scalise, Nevada National Security Site, scalisme@nv.doe.gov; Moira Pyle, Lawrence Livermore National Laboratory, pyle4@llnl.gov; Ting Chen, Los Alamos National Laboratory, tchen@lanl.gov

Legacy Seismic Data Collections: The Present State of and Future Outlook for Data from the Past

Legacy seismic data were recorded from the late 19th century until the end of the analogue recording era in the late 20th century. Many of these records are still extant today in film and/or paper formats and cover a significant part of the history of seismology. With these data, scientific questions necessitating long-running data such as the “great” earthquakes of the 1960s, above-ground nuclear tests, the earthquake cycle and the effect of climate change can be investigated. However, finding storage to retain this analogue data, making inroads into scanning and extracting digital waveforms and facilitating accessibility continue to be challenges. Due to the diversity of collections and the records which they hold (e.g., media types, number of stations, local vs. global scope), exchanging information about the ways in which data are organized, stored and/or scanned is a prime opportunity for the community. In this way, experiences with one collection that are relevant to others can be identified, plans for the future can be better developed and a more accurate picture of data available globally can be put together.

Conveners: Adam Ringler, USGS Albuquerque Seismological Laboratory, aringler@usgs.gov; Allison Bent, Natural Resources Canada, allison.bent@nrcan-rncan.gc.ca; Paul G. Richards, Columbia University Lamont-Doherty Earth Observatory, richards@ldeo.columbia.edu; Thomas A. Lee, Harvard University, thomasandrewlee@g.harvard.edu

Monitoring Climate Change with Seismology

Climate change is the most pressing global-scale challenge of the coming century. Examples of the immediate and long-term consequences include the intensification of tropical cyclones (as Puerto Rico has experienced in the past several years), accelerated erosion of coastlines, changes in annual precipitation and runoff patterns and the collapse of glaciers and ice caps. Many of these processes are observable with seismology. With decades of archival data predating the satellite era and a globally increasing density of seismic networks, environmental seismology is poised for significant contributions to the modeling and monitoring of climate change. Realizing this largely untapped potential requires formal and persistent monitoring campaigns, accessible data products (including the digitization of legacy seismic datasets) and multi-disciplinary collaborations with the broader climate change research community. This session is seeking abstracts showcasing the implementation or application of environmental seismology to climate change modeling and monitoring. We welcome seismoacoustic studies from all domains impacted by climate change, including processes occurring in the atmosphere, hydrosphere, cryosphere or biosphere. Presentations are also encouraged on the effects of climate change on seismic instrumentation, network operation, velocity structures, ambient noise or other concerns. Also of interest are discussions on how additional data streams could be incorporated at global seismic stations to improve climate monitoring capabilities.

Conveners: Allison Bent, Natural Resources Canada, allison.bent@nrcan-rncan.gc.ca; Michael G. Baker, Sandia National Laboratories, mgbaker@sandia.gov; Robert Anthony, U.S. Geological Survey, Albuquerque Seismic Laboratory, reanthony@usgs.gov; Robert Mellors, Scripps Institution of Oceanography, University of California, San Diego, rmellors@ucsd.edu; Siobhan Niklasson, New Mexico Institute of Mining and Technology, sniklasson@lanl.gov

Multi-Scale Models for Seismic Hazard Analysis

Seismic hazard analysis often requires multi-scale models to capture both regional and local effects at a given site, such as smaller, high-resolution features imbedded in larger-scale structures. Examples include analysis of dam structures, fault damage low-velocity zones and sedimentary basins inside regional models with outer length scales determined by seismic source location or extent of hazard maps. In order to obtain unbiased hazard estimates in the multi-scale models, the smaller-scale features must be merged with the regional models in an optimal fashion. We invite contributions that describe imaging of high-resolution crustal features, methods (including machine learning) for seamless merging of such features with regional models and application/validation of multi-scale models in seismic hazard analysis (e.g., dynamic rupture modeling and wave propagation simulations).

Conveners: Evan Hirakawa, U. S. Geological Survey, ehirakawa@usgs.gov; Kim Olsen, San Diego State University, kbolsen@mail.sdsu.edu; William Stephenson, U. S. Geological Survey, wstephens@usgs.gov

Network Seismology: Recent Developments, Challenges and Lessons Learned

Seismic monitoring is not only an essential component of earthquake response but also forms the backbone of a substantial amount of research into seismic hazards, volcanic processes, the earthquake process and seismotectonics. As such, it is important to continue to develop monitoring networks’ abilities to accurately and rapidly catalog earthquakes to ensure networks best serve the public, government and academic communities. Due to the operational environment of seismic monitoring, seismic networks encounter many unique challenges not seen by the research community. In this session, we highlight the unique observations and challenges of monitoring agencies and look to developments that may improve networks' ability to fulfill their missions. Seismic operation centers play a crucial role in collecting seismic data, generating earthquake products including catalogs, warnings and maps of ground shaking. The purpose of the session is to foster collaboration between network operators, inform the wider seismological community of the interesting and challenging problems within network seismology and look to the future on how to improve monitoring capabilities. This session is not only an opportunity for monitoring agencies to highlight new developments in their capabilities, but we also encourage submissions describing new techniques that would benefit network operations for detecting, locating and characterizing earthquakes, particularly in a near real-time environment.

Conveners: Dmitry Storchak, ISC, dmitry@isc.ac.uk; Kris Pankow, University of Utah Seismograph Stations, kris.pankow@utah.edu; Ranate Hartog, PNSN, jrhartog@uw.edu; William Barnhart, U.S. Geological Survey, wbarnhart@usgs.gov; William L. Yeck, U.S. Geological Survey, wyeck@usgs.gov

New Methods and Models for More Informative Earthquake Forecasting

The increasing availability and quality of geophysical datasets, including high-resolution earthquake catalogs, fault information and interseismic strain data, has enabled the creation of statistical and physics-based seismicity models that underpin probabilistic seismic hazard analyses (PSHA). Beyond PSHA, new methods developed by the statistical and machine learning (ML) communities have been shown to add predictive skill for forecasting large earthquakes and aftershock activity. These new methods, hypotheses and models can be prospectively tested and compared within the framework of the Collaboratory for the Study of Earthquake Predictability (CSEP). We invite contributions that develop novel methodology or applications in analyzing and modeling seismicity datasets. In particular, we encourage contributions from researchers who are developing and testing models for long-term earthquake forecasting, Operational Earthquake Forecasting (OEF) and Operational Aftershock Forecasting (OAF). Example submissions may include models based on ML-derived catalogs, new hypotheses explaining what controls earthquake probabilities, quantitative analyses evaluating the predictive abilities of seismicity models or new approaches to evaluating probabilistic earthquake forecasts.

Conveners: Leila Mizrahi, ETH Zurich, leila.mizrahi@sed.ethz.ch; Jose A. Bayona, University of Bristol, jose.bayona@bristol.ac.uk; Max Schneider, United States Geological Survey, mschneider@usgs.gov; Nicholas J. van der Elst, United States Geological Survey, nvanderelst@usgs.gov; William H. Savran, Southern California Earthquake Center, wsavran@usc.edu

New Observations and Modeling of Triggered Seismicity

After a large earthquake occurs the seismic rate increases in its epicenter's surroundings in the form of aftershocks. This is the most recognized form of triggered seismicity. However, many questions still remain open regarding the physics of aftershocks, including the aftershock's maximum magnitude, their spatio temporal distribution, the effects of fluid in the aftershock region, and the role of the stress changes caused by previous mainshocks. Furthermore, observations show that other forms of seismicity can be also triggered, including slow-slip events, tectonic tremor, volcanic seismicity and icequakes. In addition, seismicity – both slow and fast – can be triggered dynamically thousands of kms from the source event.

In this session we invite contributions focused on new observations and the numerical or theoretical modeling of the different types of triggering of seismicity, in the near-field and the far-field (remote triggering). Understanding the different processes that can trigger seismicity, as well as the type of seismic events that can be triggered, is essential towards gaining a better understanding of the physics of earthquakes.

Conveners: Abhijit Ghosh, University of California, Riverside, aghosh@ucr.edu; Debi Kilb, University of California, San Diego, dkilb@ucsd.edu; Esteban J. Chaves, OVSICORI, Universidad Nacional, Costa Rica, estevan.j.chaves@una.cr; Hector Gonzalez-Huizar, CICESE, Mexico, hgonzalez@cicese.mx

Normal Faults: From Source to Surface

High-resolution earthquake-related surface displacement measurements from optical data or field studies are useful to determine co-seismic off-fault deformation. These data serve as an input into fault-slip inversion studies and to validate dynamic rupture models, rendering the measurements of surface displacement a proxy for the fault structure at depth. While this approach can be valid in the strike-slip setting, many earthquakes occur on basin-bounding normal faults where most of the damage is concealed by the sedimentary deposits. In addition, inherent asymmetry of normal dipping faults has been shown to lead to distinct dynamic rupture behaviours, such as reduced or enhanced shallow coseismic slip. The resulting surface deformation may, therefore, reflect the propagation of the rupture through the basin-fill rather than the basement rocks, potentially altering the style and the magnitude of the final displacement. To relate the surface deformation to the subsurface structure of normal faults, we aim to explore the connection between the surface deformation created by large-magnitude normal events and the geometry of the associated subsurface structures. In this session, we would like to bring together studies which collect high-resolution measurements of surface displacement from remote sensing, subsurface geophysics, as well as kinematic and dynamic rupture models and laboratory experiments. We hope to address the question of how representative the surface deformation created during normal earthquakes is of the subsurface structure of normal fault zones.

Conveners: Alice-Agnes Gabriel, University of California San Diego, LMU Munich, alice-agnes.gabriel@geophysik.uni muenchen.de; Lucia Andreuttiova, University College London, lucia.andreuttiova.16@ucl.ac.uk; Thomas M. Mitchell, University College London, tom.mitchell@ucl.ac.uk; Zachary E. Ross, Caltech, zross@caltech.edu

Numerical Modeling in Seismology: Developments and Applications

We equally invite both contributions to numerical-modeling methods/algorithms and applications. Progress in seismology is unthinkable without continuous developments of theory and numerical-modeling methods. Recent developments include faithful rheological and geometrical complexity of the Earth's interior, earthquakes and other important seismological phenomena, time-space discretization, optimizations of computational algorithms and computer codes, optional balance between accuracy and efficiency. Recent methodological progress in numerical modeling in seismic exploration poses a useful challenge for numerical modeling also in earthquake seismology.

New observations and data from local dense networks make it possible for numerical modeling to considerably contribute to our understanding of rupture dynamics, seismic wave propagation, earthquake ground motion including non-linear behavior, seismic noise and earthquake hazard. We especially welcome applications to compelling observational issues in seismology.

Conveners: Alice-Agnes Gabriel, Scripps Institution of Oceanography, UC San Diego, algabriel@ucsd.edu; Emmanuel Chaljub, Université Grenoble Alpes, emmanuel.chaljub@univ-grenoble-alpes.fr; Jozef Kristek, Comenius University in Bratislava, kristek@fmph.uniba.sk; Martin Galis, Comenius University in Bratislava, martin.galis@uniba.sk; Peter Moczo, Comenius University Bratislava, moczo@fmph.uniba.sk; Wei Zhang, Southern University of Science and Technology, zhangwei@sustech.edu.cn

Opportunities and Challenges for Machine Learning Applications in Seismology

Owing to the increase in the availability of large amounts of high-quality open-source data, in recent years, we observed a successful surge in Machine Learning (ML) applications in Seismology. For instance, ML has largely been adopted in earthquake detection; seismic phase picking, in generating high-resolution earthquake catalogs, in discrimination and classification of seismic events, in earthquake early warning, in seismicity forecasting, in ground motion modeling and simulation, as well as in seismic inversion. Today, traditional ML techniques, such as CNN and LSTM networks trained over very large datasets, are successfully employed in operational conditions. Nonetheless, efficient training with small and imbalanced datasets, as well as extrapolation to new data are among the challenges that are still unresolved. On one hand, advanced ML techniques such as attention layers, autoencoders and transformers provide accurate and faster alternatives. On the other hand, physics-informed learning attempts to solve the mathematical problem using neural networks or kernel-based approaches, nourished by real world data. Moreover, ML techniques are adopted to improve existing predictive tools, in a non-intrusive way. However, a thorough investigation of those data driven techniques is demanded, in both existing and new research branches of seismology, before their deployment as operational models. In this session, we invite contributions that explore the potential of ML for seismology. In particular, we are interested in studies focusing on developing state-of-the-art ML models for seismology and earthquake engineering, ML investigations of new research areas, and works highlighting issues related to methodologies in ML, data quantity and quality. Furthermore, we welcome contributions on research topics including null hypothesis testing, open databases for collaborative research, architecture framework, software packages and development of research capabilities.

Conveners: Claudia Q. Cartaya, Frankfurt Institute for Advanced Studies, quinteros@fias.uni-frankfurt.de; Filippo Gatti, CentraleSupélec, Université Paris-Saclay, filippo.gatti@centralesupelec.fr; Florent Aden, GNS Science, f.aden@gns.cri.nz; Kiran k. Thingbaijam, GNS Science, k.thingbaijam@gns.cri.nz; Nishtha Srivastava, Frankfurt Institute for Advanced Studies, FIAS, srivastava@fias.uni-frankfurt.de; Quentin Brissaud, NORSAR Norwegian Seismic Array, quentin@norsar.no

Opportunities and Challenges in Source Modeling for Seismic Hazard Analysis

Evaluating earthquake rates is critical to assess seismic hazards for a variety of applications including national building codes, catastrophe risk modeling and site-specific studies for critical facilities. To accomplish this, recent national and regional seismic hazard models have used interdisciplinary approaches that combine geological, geodetic and seismological models. Often, fault-based models are complemented with distributed (or smoothed) seismicity models derived from earthquake catalogs, especially in regions where knowledge of the fault network is largely incomplete. Some efforts have begun to incorporate physics-based (dynamic) earthquake models, which produce synthetic catalogs spanning hundreds of thousands of years. In active areas, there are complicated cases where different seismotectonic regimes are present, such as subduction zones (interface and intraslab sources) juxtaposed with crustal sources. Some other frontiers include complex multi-fault ruptures, models for earthquake occurrences (Poissonian versus non-Poissonian rates) and region-specific source scaling properties. In this context, there is an impetus for integrated approaches that take advantage of different datasets to deliver a consistent model of earthquake rates, their spatial distribution and potential rupture mechanisms. In this session, we welcome contributions that are focused on the advancements in the development of source models, with new methods, datasets and/or hypotheses. Research topics pertinent to this session include but are not limited to: distributed seismicity models, magnitude-frequency distributions, models for earthquake occurrences, time-dependent seismicity, active fault models, region-specific source scaling properties, inversion of slip-rates, simulated seismicity and synthetic catalogs and subduction sources. We also look forward to region-specific investigations that provide useful case studies.

Conveners: Andrea L. Llenos, U.S. Geological Survey, allenos@usgs.gov; Andrew J. Michael, U.S. Geological Survey, ajmichael@usgs.gov; Andy Nicol, University of Canterbury, andy.nicol@canterbury.ac.n; Chris Rollins, GNS Science, c.rollins@gns.cri.nz; Delphine Fitzenz, Risk Management Solutions Inc., delphine.fitzenz@rms.com; Kiran Kumar S. Thingbaijam, GNS Science, k.thingbaijam@gns.cri.nz; Marco Pagani, GEM Foundation, marco.pagani@globalquakemodel.org; Matt C. Gerstenberger, GNS Science, m.gerstenberger@gns.cri.nz

Seismology for the Energy Transition

The energy transition can help mitigate climate changes by progressively shifting from fossil-based energies to low- or zero-carbon energies, such as wind, solar, hydropower, hydrogen, geothermal, nuclear and marine energies, etc. Decarbonization of the energy sector is crucial for achieving the net-zero goal. Approaches such as geologic carbon storage can enable decarbonization of some energy sources, such as coal- and natural gas-fired power plants, oil refineries, cement plants and bioenergy production facilities. The development of new seismic technologies will play a crucial role in the energy transition. We invite contributions from research exploring applications of advanced seismic approaches and techniques to the energy transition process, particularly for subsurface characterization, monitoring and infrastructure surveillance. We welcome submissions of abstracts on computational, laboratory experimental and field-scale studies.

Conveners: Erkan Ay, Shell, erkan.ay@shell.com; Lianjie Huang, Los Alamos National Laboratory, ljh@lanl.gov; Ting Chen, Los Alamos National Laboratory, tchen@lanl.gov; Verónica R. Rodríguez, Lawrence Berkeley National Laboratory, vrodrigueztribaldos@lbl.gov; Yingcai Zheng, University of Houston, yzheng24@central.uh.edu

Seismology's Role in Assessing Volcanic Hazard at Multiple Time Scales

Dangerous volcanoes not only pose an ongoing threat to nearby settlements, but also to regional economies and global connectivity. Inter-eruption repose periods vary by orders of magnitude and can directly impact the perceived monitoring requirements. Seismology has always been arguably the greatest monitoring tool during active eruption cycles, but can also contribute to change detection in times of repose, offering a potential alarm bell well in advance of a new eruptive cycle. We invite contributions of your research into volcanic seismicity at all time scales, in the context of contributing to interdisciplinary, dynamic hazard assessments for volcanoes of concern.

Conveners: Charlotte A. Rowe, Los Alamos National Laboratory, char@lanl.gov; Francisco Nunez-Cornu, Universidad de Guadalajara, pacornu77@gmail.com; Glenn Thompson, University of South Florida, thompsong@usf.edu; Jolante van Wijk, Los Alamos National Laboratory, jolantevanwijk@lanl.gov; Wendy McCausland, U.S. Geological Survey, wmccausland@usgs.gov

ShakeMap-Related Research, Development, Operations, Applications and Uses

ShakeMap-related research and development encompass a wide range of ground motion, macroseismic, path and site, spatial sampling, finite fault, directivity and various other innovations. All these efforts are crucial for recovering the most accurate ground motion field. Critical uses of the shaking estimates include earthquake response, loss estimation, engineering forensics, financial decision-making, ground failure and loss model calibration and communication of earthquake effects to the public. This session explores and encourages contributions concerning ShakeMap-related research and development, such as GMM selection and development, validation of ground motion and intensity relations, site amplification and geospatial analyses (along with uncertainties) pertinent to ShakeMap. We also encourage updates on innovative operational tools, APIs, and web pages, and presentations on new ShakeMap-related applications and products, formats and web rendering. We also urge presentations on more general research, operations or applications related to ShakeMap. Such applications include but are not limited to earthquake scenarios, risk assessment, loss estimation, earthquake response tools, engineering and other analyses utilizing ShakeMap ground motion estimates and associated uncertainty information.

Conveners: Bruce Worden, U.S. Geological Survey, cbworden@contractor.usgs.gov; Carlo Cauzzi, ORFEUS & SED@ETH Zürich, carlo.cauzzi@sed.ethz.ch; David J. Wald, U.S. Geological Survey, wald@usgs.gov; Eric Thompson, U.S. Geological Survey, emthompson@usgs.gov; Hadi Ghasemi, Geoscience Australia, hadi.ghasemi@ga.gov.au; Nick Horspool, GNS Science, n.horspool@gns.cri.nz

Single-Station Passive Exploration Methods: Status and Perspectives

The physical conditions of subsoil are related to the surface seismic response and may control it. To understand and mitigate the effects that cause damage, it is necessary to characterize the velocity structure in tens or hundreds of meters. To do this, it is required to analyze and confront the results of different geophysical methods together since the distribution of physical properties in depth occurs at different scales. Ambient seismic noise methods can be ideally suited as exploration methods. So far, there are many advances using station arrays and case studies using a single station are quickly emerging. In this session, all those works showing the advantages of high-resolution ambient seismic noise techniques for the subsoil velocity structure are welcome. We will discuss the advancement of microtremor arrays to the limitations and advantages of the HVSR method. Comparing results with other geophysical techniques will enrich the definition of application and development perspectives. We encourage presentations that illustrate the solution to problems related to seismic amplification, terrain subsidence, landslides, the presence of discontinuities, etc.

Conveners: José Francisco Sánchez Sesma, Universidad Nacional Autónoma de México, sesma@unam.mx; José Piña Flores, Universidad Nacional Autónoma de México, jpf@unam.mx; Martín Cárdenas Soto, Universidad Nacional Autónoma de México, martinc@unam.mx

Site-Specific Modeling of Seismic Ground Response: Are We Quantitative Enough to Predict?

The effects of shallow geological layers and interfaces (within the upper 1-2 km) on the seismic-induced ground motion recorded at the ground surface have been the focus of numerous stud-ies over the past few decades. Though the physics governing the main aspects of site effects (also referred to as "site response" or simply "site amplification") is relatively well understood, amplification at many actual sites is too complex to be fully described by a set of differential equations under certain initial conditions. Also, ergodic amplification equations, embedded in ground motion models, can only provide average estimates of amplification, and bias is expected in a site-specific posterior application.

This session encompasses a broad range of approaches used in site characterization and their downstream effects on site response analyses and seismic hazard and risk assessments. Topics of interest include active- /passive-source geophysical surveys (e.g., single-/multi-station surface-based array methods, down-/cross hole methods, seismic interferometry, etc.), soil nonlinearity, numerical or empirical studies on 2D/3D site effects. Studies comparing data collection techniques at the same site and those integrating a variety of datasets are also encouraged. We also invite contributions on the development and/or implementation of state-of-the-art methods in inverse problems, statistical interference techniques and uncertainty and variability quantification, to improve the characterization of near-surface site conditions. Studies on improving our current practice in ground response assessment through the use of Artificial Intelligence (AI) (e.g., database development, benchmarking different AI models and model transferability) are particularly welcome.

Conveners: Andres Olivar Castano, University of Potsdam, andres.olivar-castano@uni-potsdam.de; Chuanbin Zhu, Department of Civil and Natural Resources Engineering, University of Canterbury, chuanbin.zhu@gfz-potsdam.de; Hiroshi Kawase, Disaster Prevention Research Institute, University of Kyoto, kawase.hiroshi.6x@kyoto-u.ac.jp; Marco Pilz, German Research Center for Geosciences – GFZ, pilz@gfz-potsdam.de

Structure and Properties of Subducting Slabs and Deep Earthquakes

Subduction zones are among the most seismically active regions on Earth. Subducting slabs can affect the convection of the Earth's mantle and the geochemical evolution of the Earth. However, subducting slabs have complex structures and dynamics in terms of their geometry, age, deformation history, stress state, volatile content, thermal structure and seismicity behavior. Most deep earthquakes (depth > 70 km) in the mantle occur in subducting slabs. They are further categorized as intermediate-depth earthquakes (70-350 km depth) and deep-focus earthquakes (350-700 km depth). The cause of deep earthquakes is still a major scientific puzzle. In this session, we invite contributions that address the structure and properties of subducting slabs and deep earthquakes. We seek to bring together researchers from a wide range of studies including observations, laboratory experiments, numerical modeling and theoretical analyses. Novel ideas/models/approaches and/or unusual datasets/observations are especially welcome.

Broader scientific issues to be addressed may include slab structure, the distribution of volatile content and stress state in subducting slabs and deep seismogenesis, as well as interactions between these topics.

Conveners: German Prieto, Universidad Nacional de Colombia, gaprietogo@unal.edu.co; Man Xu, The University of Chicago, mxu@cars.uchicago.edu; Shanna Chu, U.S. Geological Survey, schu@usgs.gov; S. Sindhusuta, The University of Illinois Chicago, sindh2@uic.edu; Qiushi Zhai, California Institute of Technology, qzhai@caltech.edu

Subduction Zone Structure from Trench to Arc

Subduction zones are dynamic tectonic environments that generate destructive natural hazards, produce large orogenic systems, create and modify continental crust, recycle volatiles and sediments into the interior and drive mantle convection. Many of these processes occur at depths of < 120 km, roughly from the oceanic trench to the magmatic arc - a key focus area of the broader Earth Science community as evidenced by community-driven programs such as EarthScope, GeoPRISMS and SZ4D. Our understanding of these processes is predicated on direct observations through increasingly more refined and comprehensive seismic images of the incoming plate, the downgoing slab, the mantle wedge and the overriding plate, which we can use to infer subsurface properties such as rock composition, in situ melt percentage and water content. For this session, we invite contributions from the broadly defined seismic imaging community at the basin scale to the crustal and mantle scale. Seismic imaging techniques can include, but are not limited to tomographic techniques, including refraction, surface wave, teleseismic, full waveform and adjoint tomography, as well as active source reflection imaging, distributed acoustic sensing, noise interferometry, attenuation studies, and scattered wave imaging. In particular, we invite contributions that integrate across scales and across shorelines, jointly interpret multiple techniques and/or focus on improving our interpretation of seismic wavespeeds in the crust and mantle to better understand tectonic processes and geologic structures in subduction zone settings.

Conveners: Daniel E. Portner, Arizona State University, dportner@asu.edu; Harm Van Avendonk, University of Texas at Austin, harm@ig.utexas.edu; Jonathan R. Delph, Purdue University, jdelph@purdue.edu; Lindsay L. Worthington, University of New Mexico, lworthington@unm.edu

Tectonics and Seismicity of Stable Continental Interiors

Earthquakes in stable continental interiors far from active plate boundaries, such as in central and eastern North America, northern Europe, Australia and parts of Asia, are perhaps the least understood. Nevertheless, advances in intraplate seismicity are being achieved through a variety of approaches. Examples include local and national-scale seismic monitoring efforts that increase completeness of earthquake catalogs, detection algorithms that identify ever-smaller earthquakes from existing data, imaging of subsurface faults using relocated seismicity and seismic tomography, studies that constrain historical slip on such faults, quantification of geodetic, geomorphologic and elevation changes and through improved measurements of local stresses. In parallel with these efforts, ongoing ground motion studies continue to improve our understanding of source, path, and site response characteristics unique to intraplate regions.

This session seeks diverse contributions related to intraplate earthquake hazards with goals of describing seismicity, identifying and characterizing active faults and/or deformation in stable continental interiors, deciphering long-term earthquake histories, assessing potential ground motion impacts, constraining models of kinematics and geodynamic properties and understanding the mechanisms that cause enigmatic intraplate earthquakes. Contributions regarding recent earthquake sequences in stable continental interiors, such as those in South Carolina, are especially welcome.

Conveners: Anji Shah, USGS, ashah@usgs.gov; Jessica T. Jobe, USGS, jjobe@usgs.gov; Miguel Neves, Georgia Tech, mjgfgn3@gatech.edu; Oliver S. Boyd, USGS, olboyd@usgs.gov; Will Levandowski, Tetra Tech, Inc., bouldergeophysics@gmail.com; Zhigang Peng, Georgia Tech, zpeng@gatech.edu

The 2020-2021 Southwest Puerto Rico Seismic Sequence: Current State of Knowledge and Implications

The island of Puerto Rico is situated in the northeastern corner of the Caribbean basin, where active geological features around the island reflect the current tectonic environment of an oblique collision between the Caribbean and North American plates. Although microseismic activity occurs daily, only occasional small events are felt by the general population. In Puerto Rico, for exactly 102 years prior to the year 2020, the people of Puerto Rico were unaware of what was to live in a seismically prone area. The January 7th, 2020 Mw6.4 earthquake and ensuing seismic aftershock activity in Southwestern Puerto Rico served as a wake-up call to the entire population, forcing them to realize how vulnerable the island is to seismic activity. Seismic monitoring and research carried out in the region for the past decades were instrumental to classify the seismic risk and provided limited knowledge of the tectonics of the region. However, it was all the co/post-seismic activity, geodetically-determined crustal monitoring, and marine geophysical surveys performed during the past couple of years that allowed us to learn more about the rupture process, the current kinematics, and related effects. With this session, we seek to unite all efforts and contributions related to the January 7th, 2020 earthquake and layout all the findings with the goal of providing the current state of knowledge and a venue to discuss a seismic sequence known for releasing a complex rupture process and an atypical aftershock behavior. We look forward to all contributions on seismic assessment of the rupture process, relocations, aftershock forecasts, post-seismic deformation, and secondary triggered phenomena such as landslides, liquefaction, and tsunami that are related to the Southwest Puerto Rico 2020-2021 seismic sequence.

Conveners: Alberto M. Lopez, University of Puerto Rico, Mayagüez, alberto.lopez3@upr.edu; Christa von Hillebrandt, International Tsunami Information Center, christa.vonh@noaa.gov; Daniel A. Laó-Dávila, Oklahoma State University, daniel.lao_davila@okstate.edu; Elizabeth Vanacore, Puerto Rico Seismic Network – UPRM, elizabeth.vanacore@upr.edu; Gisela Baéz-Sánchez, Puerto Rico Seismic Network – UPRM, gisela.baez1@upr.edu; James Joyce, University of Puerto Rico – Mayagüez, james.joyce@upr.edu; Margarita Solares-Colón, University of Oregon, msolares@uoregon.edu; Stephen K. Hughes, University of Puerto Rico – Mayagüez, kenneth.hughes@upr.edu; Victor Húerfano, Puerto Rico Seismic Network, victor@prsnmail.uprm.edu

The Future of Tsunami Science, Preparedness and Response

Significant advances in observations, modeling, response, and communication of tsunamis have taken place over the last two decades, often as part of the assessment and improvement process following damaging events. Optimizing risk reduction from future tsunami events requires a full community effort across many disciplines. Much work remains to better characterize global tsunami hazards, both in advance for mitigation and preparedness and in real time with improved observation and forecasting systems. At all stages, hazards need to be translated into potential risk and impacts. Here, we highlight improvements in tsunami science and their pairing with equally important improvements in tsunami preparedness, risk communication, and decision support. Looking forward, the community aims to utilize technical expertise from social scientists and work with an emphasis on social equity to better serve historically marginalized populations. Contributions to this session can span the full spectrum of tsunami work and include: improvements in modeling, assessments of past events, estimation of vulnerabilities and exposure, new measurement techniques, communication of hazards and risk, early warning and rapid or real-time forecasts, and any other relevant tsunami science, engineering, operations, preparedness, or outreach topics.

Conveners: Diego Melgar, University of Oregon, dmelgarm@uoregon.edu; Summer J. Ohlendorf, National Oceanic and Atmospheric Administration, summer.ohlendorf@noaa.gov; Yajie Lee, ImageCAT, yjl@imagecatinc.com; Elyssa Tappero, Washington Emergency Management Division, elyssa.tappero@mil.wa.gov

Transforming Our Seismological Community Through Inclusive Mentorship and Diverse Narratives

Future generations, responsible for moving the field of geosciences forward, should be envisioned from a social and gender equality perspective, reflecting and embracing diversity to build capacities and novel solutions beyond current schemas. The Seismological Society of America Annual meeting provides an extraordinary platform for connecting scientists from diverse backgrounds to students interested in a research career that will have an impact in making the seismology community more inclusive. This session aims to (1) foster a just, equitable and inclusive research community within the SSA, (2) expose underrepresented minorities (URM) to careers in geophysics and seismology and (3) form a mentorship network for URM students and early-career professionals. This session will focus on connecting individuals across a wide range of backgrounds to support the SSA and engage with URMs and marginalized groups to promote career growth and the advancement of geophysics and seismology, establishing sustainable and long-term connections between individuals in the community by creating an environment that facilitates the building of collaborative mentor-mentee relationships and career-pathways. We invite researchers and students interested in networking/mentoring to present their research and/or career path to engage with the SSA community. We encourage presentations from all career levels to present their scientific research that are also interested in providing and adding their narrative about their experiences with mentorship and/or working with under-represented groups and/or individuals or how they navigated their research and/or career path in their field.

Conveners: Aaron A. Velasco, University of Texas at El Paso, aavelasco@utep.edu; Esteban J. Chaves, Volcanological and Seismological Observatory of Costa Rica, esteban.j.chaves@una.ac.cr; Katherine Scharer, US Geological Survey, kscharer@usgs.gov; Kevin Kwong, Los Alamos National Lab, kbkwong@lanl.gov; Richard A. Alfaro-Diaz, Los Alamos National Laboratory, raalfarodiaz@lanl.gov

Understanding and Managing Induced Seismicity

Earthquakes caused by anthropogenic operations pose serious risks: either in terms of their potential for economic/human losses or their ability to place moratoriums on resource development. While induced seismicity is one of the major impediments for many resource/energy projects, to date, limited attention has been paid to improving the management of induced earthquakes. Solutions to induced seismicity will be multi-disciplinary and require an approach that includes monitoring the development of induced seismicity, characterizing the geophysical principles involved in fault reactivation, assessing the geological conditions for fault susceptibility, testing operational mitigatory actions, designing regulatory controls, and clear communication of stakeholder concerns. In this spirit, our session invites abstract submissions from all facets of induced seismicity. These studies could include physical/statistical modeling that delve into describing how/why these events occur, laboratory measurements that infer analogs between modeling and observation, hazard/risk assessments that provide management strategies or regulatory/industry perspectives on successful mitigation/avoidance strategies. Overall, the successful management of induced earthquakes will require an integrated understanding of all these aspects. Toward this goal of better understanding and managing induced seismicity, we welcome studies from various scales and regions that could facilitate an integrated understanding of the above aspects.

Conveners: Margaret Glasgow, University of New Mexico, mglasgow@unm.edu; Mohammad J. A. Moein, Freie Universität Berlin, mohammad.moein@fu-berlin.de; Ruijia Wang, Southern University of Science and Technology, ruijia.wang@ualberta.ca; Ryan Schultz, Stanford University, rjs10@stanford.edu

Understanding and Modeling the Uncertainties in Earthquake Ground Motions

Understanding and modeling uncertainties in earthquake ground motions are significant tasks of scientific interest and societal relevance. Variability in earthquake rupture and the physical mechanisms controlling it, as well as linear and nonlinear effects on seismic wave propagation from source to site, are fundamental scientific questions that have not been fully answered, and which may vary across regions. Ground-motion uncertainty is of significant interest for many earthquake hazard applications, though it is not always accounted for consistently. Perhaps the most sophisticated treatment of uncertainty occurs for probabilistic seismic hazards analysis, which partitions uncertainty into two components—a natural (aleatory) variability and knowable (epistemic) uncertainty that can be determined with more information. As the increasing number of available ground-motion records and simulations are utilized in the development of nonergodic ground-motion models, key questions addressing uncertainty have arisen: What is the natural variability of earthquake rupture, what controls it and can we identify repeatable features for use in predictive models? What source parameters (e.g., stress drop, rupture speed) and mechanisms relating to wave propagation (e.g., site and path effects including attenuation and amplification) are well constrained and appropriate for predictive models? Can physics-based modeling reproduce observed ground-motion variabilities? How should hazard analyses partition epistemic uncertainty and aleatory variability? How should approaches to partly or fully nonergodic seismic hazard analyses differ at different spatial scales (local, regional, national)? We encourage abstract submissions relating to fundamental and applied research or case studies in engineering and policy regarding the causes and treatment of earthquake ground-motion uncertainties.

Conveners: Fabrice Cotton, GFZ Potsdam, fcotton@gfz-potsdam.de; Grace Parker, U.S. Geological Survey, gparker@usgs.gov; Morgan P. Moschetti, U.S. Geological Survey, mmoschetti@usgs.gov; Olga-Joan Ktenidou, National Observatory of Athens, olga.ktenidou@gmail.com

Understanding Earth Systems with Fiber-Optic Cables

In the last decade, significant technological advances have been made in distributed sensing. This technology turns fiber-optic cables into arrays of sensors recording physical signals with an unprecedented spatio temporal resolution. In the Earth sciences, Distributed Acoustic

Sensing (DAS, measuring seismic and acoustic waves), Distributed Temperature Sensing (DTS, measuring temperature), and Distributed Strain Sensing (DSS, measuring deformation) have been widely used to better understand and monitor the solid Earth, glaciers, rivers, oceans, ecosystems, and urban environments. We invite contributions on any recent development in the fields of application, instrumentation, and theory of distributed optical fiber geophysics. These may include, but are not limited to, theoretical and methodological aspects of fiber-optic sensing, comparison and analysis of DAS/DTS/DSS records with other types of seismological/geophysical measurements, potential combination of distributed sensing with conventional geophysical networks, applications for imaging and monitoring the solid Earth and the hydrosphere, detection and characterization of natural and anthropological signals, and algorithms/techniques to handle and process the large amounts of data recorded by DAS/DTS.

Conveners: Brad Lipovsky, University of Washington, bpl7@uw.edu; Ettore Biondi, California Institute of Technology, ebiondi@caltech.edu; Loïc Viens, Los Alamos National Lab, lviens@lanl.gov; Xiaowei Chen, Texas A&M, xiaowei.chen@tamu.edu

Understanding the Variability in Earthquake Stress Drop Measurements

Stress drop is a fundamental earthquake source parameter that in theory relates the average slip on a fault to rupture area, and in practice characterizes the high frequency seismic radiation.

It is a key parameter in earthquake ground motion modeling, rupture simulation and source physics analysis. However, stress drops are notoriously variable and difficult to measure; estimates by different researchers using different methods or datasets yield inconsistent values which mask physical trends. We seek to bring together all interested researchers to compare and validate stress drop estimates, source characterization and high-frequency ground motion. We particularly encourage studies of the 2019 Ridgecrest Earthquake Sequence, any studies focused on the comparison of multiple methods, and studies aimed at quantifying the uncertainties in stress drop estimates. We hope to understand the physical controls and methodological reasons for similarity or differences in stress drops, so that they can be used reliably by the earthquake science community.

Conveners: Annemarie Baltay, USGS Earthquake Science Center, abaltay@usgs.gov; Colin N. Pennington, Lawrence Livermore National Laboratory, pennington6@llnl.gov; Ian Vandevert, Scripps Institution of Oceanography, ivandevert@ucsd.edu; Kevin Mayeda, Air Force Technical Applications Center, kevin.mayeda@us.af.mil; Meichen Liu, University of Michigan, meichenl@umich.edu; Rachel Abercrombie, Boston University, rea@bu.edu; Shanna Chu, USGS Earthquake Science Center, schu@usgs.gov; Taka'aki Taira, University of California, Berkeley, taira@berkeley.edu; Trey Knudson, Stanford University, trey05@stanford.edu

USGS National Seismic Hazard Models: 2023 and Beyond

The USGS National Seismic Hazard Models (NSHMs) are a bridge between best-available earthquake science and public policy. By the end of 2023, the National Seismic Hazard Model Project (NSHMP) will publish a 50-State NSHM, focusing on updates to the conterminous U.S., Alaska and Hawaii. The Puerto Rico and U.S. Virgin Islands NSHM will be updated by the end of 2025 (see 2025 Puerto Rico and the U.S. Virgin Islands National Seismic Hazard Model Update Technical Session), and updates to the Guam and Northern Mariana Islands and American Samoa and Neighboring South Pacific Islands NSHMs are tentatively scheduled to be completed by the end of 2026. Looking ahead to all future NSHM updates, we would like to consider new data, methods and models. For this session, we invite contributions on topics that will influence future seismic hazard models, including but not limited to: seismicity catalogs, declustering and smoothed seismicity models, geologic and geodetic deformation models, multi-fault ruptures, improved representation and quantification of epistemic uncertainty, new ground motion models (GMMs), including non-ergodic models, incorporation of physics-based (3D simulation) GMMs, basin effects, site response, directivity and time dependence. We also invite contributions on the use of NSHMs for scenario development, risk assessment for both buildings and infrastructure, and other applications of risk mitigation including those within the insurance industry. We are also interested in contributions that highlight potential impacts of hazard modeling uncertainties on downstream applications.

Conveners: Emel Seyhan, Risk Management Solutions (RMS), emel.seyhan@rms.com; Jason M. Altekruse, USGS Geologic Hazards Science Center, jaltekruse@usgs.gov; Kishor S. Jaiswal, USGS Geologic Hazards Science Center, kjaiswal@usgs.gov; Mark D. Petersen, USGS Geologic Hazards Science Center, mpetersen@usgs.gov; Peter M. Powers, USGS Geologic Hazards Science Center, pmpowers@usgs.gov; Sanaz Rezaeian, USGS Geologic Hazards Science Center, srezaeian@usgs.gov

Overview of Technical Program

Monday 17 April

- 8 AM–5 PM: Workshop: Post-earthquake Reconnaissance: Turning Disasters into Knowledge
- 10 AM–4 PM: Workshop: Optimizing Seismic Hazard Assessments
- 2–5 PM: Workshop: Getting Published—Writing Papers, Working with Editors, Responding to Reviews
- 2–5 PM: Workshop: DAS
- 3–7 PM: Registration Open
- 5–6:30 PM: Opening Reception
- 6:30–7:30 PM: *Keynote Plenary*: José A. Martinez-Cruzado

Tuesday 18 April

- 8–9:15 AM: Oral Sessions
- 9:15–10 AM: Poster Break
- 10–11:15 AM: Oral Sessions
- 11:30 AM–12:30 PM: *Plenary*: Erouscilla P. Joseph
- 12:30–2 PM: Lunch Break
- 2–3:15 PM: Oral Sessions
- 3:15–4:30 PM: Poster Break
- 4:30–5:45 PM: Oral Sessions
- 6–7 PM: *Plenary:* Tsunami Hazards (panel)
- 7–8 PM: Student/Early-Career Reception

Wednesday 19 April

- 8–9:15 AM: Oral Sessions
- 9:15–10:30 AM: Poster Break
- 10:30–11:45 AM: Oral Sessions
- 12:00 NOON–2:00 PM: Awards Luncheon
- 12:30–2 PM: Lunch Break
- 2–3:15 PM: Oral Sessions
- 3:15–4:30 PM: Poster Break
- 4:30–5:45 PM: Oral Sessions
- 6–7 PM: Joyner Lecture
- 7–8 PM: Joyner Reception

Thursday 20 April

- 8–9:15 AM: Oral Sessions
- 9:15–10 AM: Poster Break
- 10–11:15 AM: Oral Sessions
- 11:30 AM–12:30 PM: Machine Learning (panel)
- 12:30–2 PM: Lunch Break
- 2–3:15 PM: Oral Sessions
- 3:15–4:30 PM: Poster Break
- 4:30–5:45 PM: Oral Sessions

Friday 21 April

- 7 AM–10 PM: 2020 Southwestern Puerto Rico Seismic Sequence
- 8 AM–Noon: Old San Juan Walking Tour
- 8 AM–Noon: TsunamiReady Program

Tuesday, 18 April

Oral Sessions

Time	*202B/C*	*203*	*204*	*208A*	*208B*
8:00–9:15 AM	Earthquake Source Parameters: Theory, Observations and Interpretations	TBA	Collective Impact in Earthquake Science	USGS National Seismic Hazard Models: 2023 and Beyond	Seismology's Role in Assessing Volcanic Hazard at Multiple Time Scales
9:15–10:00 AM	Poster Break				
10:00–11:15 AM	Earthquake Source Parameters: Theory, Observations and Interpretations	TBA	Monitoring Climate Change With Seismology	USGS National Seismic Hazard Models: 2023 and Beyond	Seismology's Role in Assessing Volcanic Hazard at Multiple Time Scales
11:30 AM–12:30 PM	Erouscilla P. Joseph, The University of West Indies: Volcanism in the Eastern Caribbean: Hazards, Monitoring, Challenges and Lessons Learnt				
12:30–2:00 PM	Lunch Break				
2:00–3:15 PM	Earthquake Source Parameters: Theory, Observations and Interpretations	TBA	Transforming our Seismological Community through Inclusive Mentorship and Diverse Narratives	USGS National Seismic Hazard Models: 2023 and Beyond	Advances in Characterizing Seismic Hazard and Forecasting Risk in Hydrocarbon Systems
3:15–4:30 PM	Poster Break				
4:30–5:45 PM	Earthquake Source Parameters: Theory, Observations and Interpretations	TBA	Seismology for the Energy Transition	2025 Puerto Rico and the U.S. Virgin Islands National Seismic Hazard Model Update	Advances in Characterizing Seismic Hazard and Forecasting Risk in Hydrocarbon Systems
6:00–7:00 PM	The Future of Tsunami Hazards and Readiness Research Panel Discussion				
7:00–8:30 PM	Student/Early-Career Reception				

Poster Sessions

- The 2020-2021 Southwest Puerto Rico Seismic Sequence: Current State of Knowledge and Implications
- 2025 Puerto Rico and the U.S. Virgin Islands National Seismic Hazard Model Update
- Advances in Characterizing Seismic Hazard and Forecasting Risk in Hydrocarbon Systems
- Advances in Marine Seismoacoustics
- Advancing Science With Global Seismological and Geophysical Networks
- Collective Impact in Earthquake Science
- De-risking Deep Geothermal Projects: Geophysical Monitoring and Forecast Modeling Advances
- Earth's Structure From the Crust to the Core
- Earthquake Source Parameters: Theory, Observations and Interpretations
- Emerging Developments in Operational Monitoring Systems and Products
- From Sensors and Networks to Site Characterization and Site Response: Coming Full Circle
- Future Directions in Physics-based Ground-motion Modeling in Preparation for the Fall 2023 Meeting

Time	*208C*	*209A*	*209B*	*209C*
8:00–9:15 AM	High-frequency Ground Motion Measurements, Assessments and Predictions	The 2020-2021 Southwest Puerto Rico Seismic Sequence: Current State of Knowledge and Implications	Earth's Structure From the Crust to the Core	De-risking Deep Geothermal Projects: Geophysical Monitoring and Forecast Modeling Advances
9:15–10:00 AM	Poster Break			
10:00–11:15 AM	From Sensors and Networks to Site Characterization and Site Response: Coming Full Circle	The 2020–2021 Southwest Puerto Rico Seismic Sequence: Current State of Knowledge and Implications	Earth's Structure From the Crust to the Core	De-risking Deep Geothermal Projects: Geophysical Monitoring and Forecast Modeling Advances
11:30 AM–12:30 PM	Erouscilla P. Joseph, The University of West Indies: Volcanism in the Eastern Caribbean: Hazards, Monitoring, Challenges and Lessons Learnt			
12:30–2:00 PM	Lunch Break			
2:00–3:15 PM	From Sensors and Networks to Site Characterization and Site Response: Coming Full Circle	Advances in Marine Seismoacoustics	Earth's Structure From the Crust to the Core	Legacy Seismic Data Collections: The Present State of and Future Outlook for Data from the Past
3:15–4:30 PM	Poster Break			
4:30–5:45 PM	Future Directions in Physics-based Ground-motion Modeling in Preparation for the Fall 2023 Meeting	Single-station Passive Exploration Methods: Status and Perspectives	Emerging Developments in Operational Monitoring Systems and Products	Advancing Science With Global Seismological and Geophysical Networks
6:00–7:00 PM	The Future of Tsunami Hazards and Readiness Research Panel Discussion			
7:00–8:30 PM	Student/Early-Career Reception			

- General Seismology
- Geophysical Data Analysis in Cloud Computing Environments
- High-frequency Ground Motion Measurements, Assessments and Predictions
- Legacy Seismic Data Collections: The Present State of and Future Outlook for Data from the Past
- Monitoring Climate Change With Seismology
- Normal Faults: From Source to Surface
- Seismology for the Energy Transition
- Seismology's Role in Assessing Volcanic Hazard at Multiple Time Scales
- Single-station Passive Exploration Methods: Status and Perspectives
- Transforming our Seismological Community through Inclusive Mentorship and Diverse Narratives
- USGS National Seismic Hazard Models: 2023 and Beyond

Wednesday, 19 April

Oral Sessions

Time	*202B/C*	*203*	*204*	*208A*
8:00–9:15 AM	Site-specific Modeling of Seismic Ground Response: Are We Quantitative Enough to Predict?	New Methods and Models for More Informative Earthquake Forecasting	Understanding and Managing Induced Seismicity	Advances in Probabilistic Seismic Hazard Analysis and Applications
9:15–10:30 AM	Poster Break			
10:30–11:45 AM	Site-specific Modeling of Seismic Ground Response: Are We Quantitative Enough to Predict?	New Methods and Models for More Informative Earthquake Forecasting	Understanding and Managing Induced Seismicity	Advances in Probabilistic Seismic Hazard Analysis and Applications
Noon–2:00 PM	Awards Luncheon and Presidential Address			
2:00–3:15 PM	ShakeMap-related Research, Development, Operations, Applications and Uses	Exploiting Explosion Sources: Advancements in Seismic Source Physics	Understanding and Managing Induced Seismicity	Advances in Probabilistic Seismic Hazard Analysis and Applications
3:15–4:30 PM	Poster Break			
4:30–5:45 PM	ShakeMap-related Research, Development, Operations, Applications and Uses	Exploiting Explosion Sources: Advancements in Seismic Source Physics		New Observations and Modeling of Triggered Seismicity
6:00–7:00 PM	Joyner Lecture			
7:00–8:00 PM	Joyner Reception			

Poster Sessions

- Above the Seismogenic Zone: Fault Damage and Healing in the Shallow Crust
- Detecting, Locating, Characterizing and Monitoring Non-earthquake Seismoacoustic Sources
- Exploiting Explosion Sources: Advancements in Seismic Source Physics
- New Methods and Models for More Informative Earthquake Forecasting
- New Observations and Modeling of Triggered Seismicity
- Opportunities and Challenges for Machine Learning Applications in Seismology
- ShakeMap-related Research, Development, Operations, Applications and Uses
- Site-specific Modeling of Seismic Ground Response: Are We Quantitative Enough to Predict?
- Structure and Properties of Subducting Slabs and Deep Earthquakes
- Subduction Zone Structure From Trench to Arc
- Tectonics and Seismicity of Stable Continental Interiors
- The Future of Tsunami Science, Preparedness and Response
- Understanding and Managing Induced Seismicity
- Understanding Earth Systems with Fiber-optic Cables

Time	*208B*	*208C*	*209A*	*209B*	*209C*
8:00–9:15 AM	Subduction Zone Structure From Trench to Arc	Understanding Earth Systems with Fiber-optic Cables			Detecting, Locating, Characterizing and Monitoring Non-earthquake Seismoacoustic Sources
9:15–10:30 AM	Poster Break				
10:30–11:45 AM	Subduction Zone Structure From Trench to Arc	Understanding Earth Systems with Fiber-optic Cables	Tectonics and Seismicity of Stable Continental Interiors	Opportunities and Challenges for Machine Learning Applications in Seismology	Detecting, Locating, Characterizing and Monitoring Non-earthquake Seismoacoustic Sources
Noon–2:00 PM	Awards Luncheon and Presidential Address				
2:00–3:15 PM	Structure and Properties of Subducting Slabs and Deep Earthquakes		Tectonics and Seismicity of Stable Continental Interiors	Opportunities and Challenges for Machine Learning Applications in Seismology	Detecting, Locating, Characterizing and Monitoring Non-earthquake Seismoacoustic Sources
3:15–4:30 PM	Poster Break				
4:30–5:45 PM	The Future of Tsunami Science, Preparedness and Response	Above the Seismogenic Zone: Fault Damage and Healing in the Shallow Crust	Tectonics and Seismicity of Stable Continental Interiors	Opportunities and Challenges for Machine Learning Applications in Seismology	
6:00–7:00 PM					
7:00–8:00 PM					

Thursday, 20 April

Oral Sessions

Time	*202B/C*	*204*	*208A*	*208B*
8:00–9:15 AM	Network Seismology: Recent Developments, Challenges and Lessons Learned	Crustal Deformation and Seismic Hazard in Western Canada, Cascadia and Alaska	Opportunities and Challenges in Source Modeling for Seismic Hazard Analysis	Coseismic Ground Failure: Advances in Modeling, Impacts and Communication
9:15–10:00 AM	Poster Break			
10:00–11:15 AM	Network Seismology: Recent Developments, Challenges and Lessons Learned	Understanding and Modeling the Uncertainties in Earthquake Ground Motions	Opportunities and Challenges in Source Modeling for Seismic Hazard Analysis	Coseismic Ground Failure: Advances in Modeling, Impacts and Communication
11:30 AM–12:30 PM	Panel: Machine Learning			
12:30–2:00 PM	Lunch Break			
2:00–3:15 PM	Earthquake Early Warning Optimization and Efficacy	Understanding the Variability in Earthquake Stress Drop Measurements	Constraining Seismic Hazard in the Cascadia Subduction Zone	Deciphering Earthquake Clustering for the Better Understanding of Crustal Deformation Mechanisms
3:15–4:30 PM	Poster Break			
4:30–5:45 PM	Earthquake Early Warning Optimization and Efficacy		Constraining Seismic Hazard in the Cascadia Subduction Zone	Deciphering Earthquake Clustering for the Better Understanding of Crustal Deformation Mechanisms

Poster Sessions

- Active Faults in the Caribbean and Central America
- Advances in Probabilistic Seismic Hazard Analysis and Applications
- Constraining Seismic Hazard in the Cascadia Subduction Zone
- Coseismic Ground Failure: Advances in Modeling, Impacts and Communication
- Crustal Deformation and Seismic Hazard in Western Canada, Cascadia and Alaska
- Crustal Imaging of High Seismic Hazard Regions
- Deciphering Earthquake Clustering for the Better Understanding of Crustal Deformation Mechanisms
- Earthquake Early Warning Optimization and Efficacy
- From Earthquakes to Plate Boundaries: Insights Into Fault Behavior Spanning Seconds to Millennia
- Ground Truthing Multidimensional Site Response Analyses at Borehole Array Sites
- It's All About Relocation, Relocation, Relocation
- Multi-scale Models for Seismic Hazard Analysis
- Network Seismology: Recent Developments, Challenges and Lessons Learned
- Numerical Modeling in Seismology: Developments and Applications
- Opportunities and Challenges in Source Modeling for Seismic Hazard Analysis
- Understanding and Modeling the Uncertainties in Earthquake Ground Motions
- Understanding the Variability in Earthquake Stress Drop Measurements

Time	*208C*	*209A*	*209B*	*209C*
8:00–9:15 AM	Active Faults in the Caribbean and Central America		Crustal Imaging of High Seismic Hazard Regions	Earthquake Preparation Across Scales: Reconciling Geophysical Observations With Laboratory and Theory
9:15–10:00 AM	Poster Break			
10:00–11:15 AM	Active Faults in the Caribbean and Central America	From Earthquakes to Plate Boundaries: Insights Into Fault Behavior Spanning Seconds to Millennia	Crustal Imaging of High Seismic Hazard Regions	Earthquake Preparation Across Scales: Reconciling Geophysical Observations With Laboratory and Theory
11:30 AM–12:30 PM	Panel: Machine Learning			
12:30–2:00 PM	Lunch Break			
2:00–3:15 PM	Active Faults in the Caribbean and Central America	From Earthquakes to Plate Boundaries: Insights Into Fault Behavior Spanning Seconds to Millennia	Multi-scale Models for Seismic Hazard Analysis	Numerical Modeling in Seismology: Developments and Applications
3:15–4:30 PM	Poster Break			
4:30–5:45 PM	It's All About Relocation, Relocation, Relocation	From Earthquakes to Plate Boundaries: Insights Into Fault Behavior Spanning Seconds to Millennia	Ground Truthing Multidimensional Site Response Analyses at Borehole Array Sites	Numerical Modeling in Seismology: Developments and Applications

Tuesday, 18 April 2023—Oral Sessions

Presenting author is indicated in bold.

Time	*202B/C*	*204*	*208A*	*208B*
	Earthquake Source Parameters: Theory, Observations and Interpretations (see page 1174)	**Collective Impact in Earthquake Science (see page 1130)**	**USGS National Seismic Hazard Models: 2023 and Beyond (see page 1300)**	**Seismology's Role in Assessing Volcanic Hazard at Multiple Time Scales (see page 1253)**
8:00 AM	Leveraging the Iran Regional Moment Tensor Database to Estimate Parameter Uncertainties in 1D and 3D Earth Models. **Braunmiller, J.**, Rodríguez Cardozo, F., Ghods, A., Sawade, L.	Learning Past Disasters and Forecasting Future Earthquakes on the 100th Anniversary of the 1923 Kanto Earthquake. **Satake, K.**	2023 U.S. 50-State National Seismic Hazard Model. **Petersen, M. D.**, Shumway, A. M., Powers, P. M., Field, E. H., Moschetti, M. P., *et al.*	INVITED: Analysis of the Seismicity Recorded Before the May 22, 2021 Eruption of Nyiragongo Volcano, Democratic Republic of the Congo. **Sadiki, A.**
8:15 AM	INVITED: Time-Domain Determination of Regional Wave Propagation Characteristics and Earthquake Source Spectra: Application to the Ridgecrest, California Earthquakes. Al-Ismail, F., **Ellsworth, W. L.**, Beroza, G. C.	Developing Guidance to Communicate Global Aftershock Forecasts. **McBride, S. K.**, Schneider, M., van der Elst, N., Hardebeck, J. L., Michael, A. J., *et al.*	Overview of the Final Earthquake Rupture Forecasts for the 2023 USGS NSHM. **Field, E. H.**	Precursory Seismicity and Explosion Seismoacoustics of the Recent Phreatomagmatic Eruption of Semisopochnoi Volcano, Alaska. **Lyons, J. J.**, Hotovec-Ellis, A., Iezzi, A., Haney, M., Fee, D.
8:30 AM	STUDENT: Use of the Second Seismic Moments to Estimate Source Parameters and Rupture Directivity of Moderate Earthquakes in Central Italy. **Cuius, A.**, Meng, H., Saraò, A., Costa, G.	Improving Family Resilience for Earthquakes in Hispaniola. **Espinal, D.**, Rodgers, J., Mentor-William, G., Pierre, J., Dévilmé, G., *et al.*	Hazard Implications and Epistemic Uncertainties of the Updated Fault-System Inversion Model for the 2023 U.S. National Seismic Hazard Model. **Milner, K. R.**, Field, E. H.	Temporal and Spatial Evolution of Cabeza De Vaca 2021 Rift Eruption (Cumbre Vieja Volcano, La Palma, Canary Islands) From Geophysical and Geodesic Paramethers Analyses. **Benito Oterino, M.**, Alvarado, G. E., *et al.*
8:45 AM	Duration and Dynamic Stress Drop During the Initial Rupture "Breakaway" Stage of Ridgecrest Earthquakes. **Ji, C.**, Archuleta, R. J., Peyton, A.	Using a Collective Impact Framework in SZ4D to Build Equity and Capacity With Geoscience. **Brudzinski, M. R.**	A Fault-Based Crustal Deformation Model With Deep Driven Dislocation Sources for the 2023 Update to the US National Seismic Hazard Model. **Zeng, Y.**	The February 2018 Seismic Swarm in the Island of São Miguel, Azores. Soares, A., **Custodio, S.**, Cesca, S., Silva, R., Vuan, A., *et al.*
9:00 AM	STUDENT: Early Parameters of Seismograms: What Influences Them and Are They Useful in Understanding Earthquake Determinism? **Colquhoun, R.**, Hawthorne, J. C.	Dealing With the Unexpected: South Carolina's Response to the 2021-2022 Elgin-Lugoff Earthquake Sequence. **Jaume, S.**, Howard, S., Becker, D.	The 2023 Update of the Alaska National Seismic Hazard Model. **Powers, P. M.**, Altekruse, J. M.	Precursory Seismic Signals Before Two Catastrophic Landslides at Irazú Volcano, Costa Rica. **Chaves, E. J.**, Pacheco, J. F., Schwartz, S. Y., Finnegan, N., Higman, B.
9:15–10:00 AM	Poster Break			

Time	*208C*	*209A*	*209B*	*209C*
	High-frequency Ground Motion Measurements, Assessments and Predictions (see page 1212)	**The 2020-2021 Southwest Puerto Rico Seismic Sequence: Current State of Knowledge and Implications (see page 1101)**	**Earth's Structure From the Crust to the Core (see page 1160)**	**De-risking Deep Geothermal Projects: Geophysical Monitoring and Forecast Modeling Advances (see page 1147)**
8:00 AM	INVITED: A Model for Small-Strain Damping for the Groningen Field Constrained by Vertical Array Measurements. **Rodriguez-Marek, A.**, Ruigrok, E., Edwards, B., Kruiver, P. K., Dost, B., *et al.*	A Detailed View of the 2020-2021 Southwestern Puerto Rico Seismic Sequence With Deep Learning. **Yoon, C. E.**, Cochran, E. S., Vanacore, E. A., Huerfano, V. A., Báez-Sánchez, G., *et al.*	STUDENT: Teleseismic P Wave Travel Times on Dense Nodal Networks Across the Kilauea East Rift Zone Reveal Two High-Speed Intrusive Cores. **Wei, X.**, Shen, Y.	Assessing the Relative Contributions of Fluid Pressure and Elastic Stress to Induced Seismicity. **Goebel, T. H. W.**, Koirala, R., Guo, H., Schuster, V., Brodsky, E. E.
8:15 AM	High Frequency Attenuation of Seismic Waves Due to the Heterogeneous Nature of the Crust : Theoretical Developments and Numerical Investigations. **Colvez, M.**, Lopez-Caballero, F., Cottereau, R.	Ground Failure Triggered by the 2020 M6.4 Puerto Rico Earthquake. **Allstadt, K.**, Thompson, E. M., Bayouth García, D., Irizarry Brugman, E., Hughes, K., *et al.*	Crustal Structure of the Caucasus. **Godoladze, T.**, Nabelek, J.	The Effect of Correlated Permeability on Fluid-Induced Seismicity. **Davidsen, J.**, Khajehdehi, O., Karimi, K.
8:30 AM	Empirical Correlations of Response Spectral Ordinates, Arias Intensity (AI) and Cumulative Absolute Velocity (CAV) With Fourier Spectral Ordinates of Ground-Motion and Associated Variabilities. **Bora, S.**	INVITED: Finding Fault With Earthquakes. **Joyce, J.**	STUDENT: High-Resolution Crustal Attenuation Model in Southeastern Tibetan Plateau and Its Implications for Regional Tectonic Deformation. **Li, R.**, Zhao, L., Xie, X., Yao, Z.	INVITED: STUDENT: Transient Evolution of the Relative Size Distribution of Earthquakes as a Risk Indicator for Induced Seismicity. **Ritz, V. A.**, Rinaldi, A. P., Wiemer, S.
8:45 AM	Broadband Ground Motion Synthesis via Generative Adversarial Neural Operators. Shi, Y., **Lavrentiadis, G.**, Ross, Z. E., Asimaki, D.	Insar Measurement of the Coseismic and Postseismic Displacements From the 2020 Southwest Puerto Rico Seismic Sequence. **Fielding, E. J.**, Vanacore, E. A., López-Venegas, A. M.	STUDENT: A High-Resolution Phase Velocity Inversion for the Crustal Structure of the Southeastern US Using a Double-Sided Hankel Transform. **Barman, D.**, Pulliam, J.	An Ensemble Approach to Characterizing Trailing Induced Seismicity. **Schultz, R.**, Ellsworth, W. L., Beroza, G. C.
9:00 AM	Rupture Directivity Effects Observed in Ground Motions From the 2022 M5.1 Alum Rock Earthquake. **Parker, G. A.**, Hirakawa, E., Baltay, A. S., Hanks, T. C.	Mature Diffuse Tectonic Block Boundary Revealed by the 2020 Southwestern Puerto Rico Seismic Sequence. **ten Brink, U. S.**, Vanacore, E. A., Fielding, E. J., Chaytor, J. D., López-Venegas, A. M., *et al.*	STUDENT: New Images of the Radially Anisotropic Uppermost Mantle Beneath the Continental US. **Hariharan, A.**, Dalton, C. A.	Assessing Potential Hazard and Risk from EGS Projects in Nevada and Oregon. **Wong, I. G.**, Bubeck, A., Gray, B., Lewandowski, N., McGregor, I., *et al.*
9:15–10:00 AM	Poster Break			

Time	*202B/C*	*204*	*208A*	*208B*
	Earthquake Source Parameters: Theory, Observations and Interpretations (see page 1174)	**Monitoring Climate Change With Seismology (see page 1219)**	**USGS National Seismic Hazard Models: 2023 and Beyond (see page 1300)**	**Seismology's Role in Assessing Volcanic Hazard at Multiple Time Scales (see page 1253)**
10:00 AM	INVITED: Challenges in Quantifying Small Earthquakes. **Herrmann, R. B.**, Benz, H. M.	INVITED: Climate Change Seismology. **Aster, R. C.**	Towards Regionalized Earthquake Source Models of Subduction Interface Earthquakes. **Skarlatoudis, A.**, Condon, S., Thio, H., Somerville, P.	STUDENT: A Look Under the Hood: Characterizing the Spatiotemporal Evolution of Mount Hood Seismicity Through Data Mining and High Precision Relocation. **Johnson, B. N.**, Hartog, R.
10:15 AM	On the Limitations of Spectral Source Parameter Estimation for Minor and Microearthquakes. **Parolai, S.**, Oth, A.	Vertical-Slice Ocean Tomography Using CTBTO Hydrophones. **Wu, W.**, Shen, Z., Peng, S., Zhan, Z., Callies, J.	Incorporating the M9 Project Simulations Into Non-Ergodic Site and Path Terms for the Cascadia Region Outside the Seattle Region. **Sung, C.**, Abrahamson, N. A.	INVITED: Solid Earth–atmosphere Interaction Forces During the 15 January 2022 Tonga Eruption. **Garza-Giron, R.**, Lay, T., Pollitz, F. F., Kanamori, H., Rivera, L.
10:30 AM	Effects of Failure Parameterization on Pre- and Co-Seismic Earthquake Rupture. **Bolotskaya, E.**, Hager, B. H.	STUDENT: Deciphering Climate Information From Array Ambient Noise in Groningen. **Zhong, Y.**, Gu, C., Fehler, M., Prieto, G. A., Wu, P., *et al.*	PSHA Study for the State of Hawai'i Based on Regionalized Seismic Source Characterization and Ground Motion Characterization Models. **Gregor, N.**, Beutel, J., Hunt, D., Hoeft, J., *et al.*	STUDENT: Temporal Velocity Variations Associated With the 2020 Eruption of Kīlauea Volcano in Hawai'i, Revealed by Ambient Noise Cross-Correlation. **Vinarski, E.**, Lin, G., *et al.*
10:45 AM	STUDENT: Yielding and Fracture in the Nucleation of Frictional Fault Slip. **Castellano, M.**, Lorez, F., Kammer, D.	Seasonal Change at Shallow Depth in the Permafrost Region of Alaska From Seismic Noise. **Tanimoto, T.**, Anderson, A.	STUDENT: Update of NGA-East Database to Include Central and Eastern North America Events Since November 2011. **Ramos-Sepulveda, M. E.**, Parker, G. A., *et al.*	STUDENT: High-Resolution Passive Imaging Beneath Valles Caldera. **Pradhan, K. K.**, Chaput, J. A., Schmandt, B.
11:00 AM	Four Granites in the Lab: Acoustic Emission During the Uniaxial Loading. **Jechumtálová, Z.**, Šílený, J., Petružálek, M., Lokajíček, T., Kolář, P.	INVITED: Seismic Network Hardening Against Tropical Systems: A Tale of Two Hurricanes. **Vanacore, E. A.**, Rivera-Torres, J. M., Friberg, P., Huerfano-Moreno, V., Baez-Sanchez, G., *et al.*	STUDENT: Development of a Site Response and Hazard Model for the U.S. Atlantic and Gulf Coastal Plains With a Geology-Based Shear Wave Velocity Model. **Gann-Phillips, C.**, Cabas, A., *et al.*	Rapid Strengthening of the La Soufriere Volcano Monitoring During Eruption, Covid-19 and Dengue Fever Threats. **Lynch, L. L.**, Robertson, R.
11:30 AM–12:30 PM	*Plenary:* Volcanism in the Eastern Caribbean: Hazards, Monitoring, Challenges and Lessons Learnt.			
12:30–2:00 PM	Lunch Break			

Time	208C	209A	209B	209C
	From Sensors and Networks to Site Characterization and Site Response: Coming Full Circle (see page 1198)	**The 2020-2021 Southwest Puerto Rico Seismic Sequence: Current State of Knowledge and Implications (see page 1101)**	**Earth's Structure From the Crust to the Core (see page 1160)**	**De-risking Deep Geothermal Projects: Geophysical Monitoring and Forecast Modeling Advances (see page 1147)**
10:00 AM	INVITED: Site Characterization by Means of Geophysical MASW Method at Designated Instrumented Sites of the Puerto Rico Strong Motion Program Seismic Network. **Huerta-López, C. I.**, Herrera-Laverde, G. D., López-Fajardo, J., Rodríguez-Jiménez, M. A., Martínez-Cruzado, J. A., *et al.*	New Insights Into the 2019 Puerto Rico Sequence - a Combined Study Based on Correlation Fractal Dimension and Static Stress Changes. **Mangalagiri, T.**, Chandriyan, H., Singha Roy, P.	Upper-Lithospheric Structure of Northeastern Venezuela From Joint Inversion of Surface-Wave Dispersion and Receiver Functions. **Cabieces, R.**, Arnaiz-Rodriguez, M., Vilaseñor, A., Berg, E. M., Olivar-Castaño, A., *et al.*	INVITED: Factors Characterizing Stable Seismic Energy Release During Hydraulic Stimulations: Egs Helsinki and Experimental Perspective. **Kwiatek, G.**, Martinez-Garzon, P., Bohnhoff, M., Dresen, G.
10:15 AM	STUDENT: Noise-Based Estimation of Local Seismic Amplification in an Industrialized Area of the French Rhone Valley. **Gisselbrecht, L.**, Froment, B., Boué, P.	A Three-Year Update on the Performance of the USGS Aftershock Forecasts for the 2020 SW Puerto Rico Sequence. **van der Elst, N.**, Hardebeck, J. L., Michael, A. J.	INVITED: Anisotropic and Anelastic Global Adjoint Tomography. **Bozdag, E.**, Örsvuran, R., Espindola Carmona, A., Peter, D.	De-risking Enhanced Geothermal Energy Projects: Insights from the DEEP Project. **Wiemer, S.**, Lanza, F.
10:30 AM	Empirical Site Response of Mexico City Developed From Regional Customization of Global Subduction Ground Motion Models. **Contreras, V.**, Stewart, J. P., Pérez-Campos, X., *et al.*	Insights Into the 2019-2022 Southwest Puerto Rico Seismic Swarm and Broader Caribbean Seismo-tectonics With an Automatic Workflow Aided by Machine-learning Pickers. **Walter, J.**	Radial Reference Models: Core Structure and Spin Transition Effects. **Kennett, B. L. N.**	Clustering Analysis of Microseisms Generated During Hydraulic Fracturing Recorded by Downhole Geophones. **Qiu, H.**, Nakata, N., Qin, L., White, M.
10:45 AM	Achieving Deep Site Characterization in Greater Vancouver, British Columbia, Canada. **Molnar, S.**, Bilson Darko, A., Kapron, M.	INVITED: Lessons Learned as a Geoscience Communicator During the 2020-2021 Southwest Puerto Rico Seismic Sequence. **Jaramillo-Nieves, L. G.**	Revisit Smsks Differential Traveltime Data and the Inferred Stratification at Earth's Outermost Outer Core. **Niu, F.**, Zhou, Y.	Noise Characterization of Surface DAS in Monitoring the April 2022 Stimulation at Utah FORGE. **Mendoza, M. M.**, Sheehan, A. F., Jin, G., Titov, A.
11:00 AM	The Activities of the Emersito Ingv Emergency Task Force During the Marchigiana-Pesarese Offshore Seismic Sequence (Central Italy): Directional Amplification and Polarization Analyses. **Pischiutta, M.**, Ladina, C., Puglia, R., Marzorati, S., *et al.*	Behavioral Responses to the 2020-2021 Southwest Puerto Rico Earthquake Sequence: Information-Seeking, Rumors, and Protective Action Decision-Making. **Santos-Hernández, J. M.**, Campbell, N. M., McBride, S. K., *et al.*	The UPFLOW Experiment: Peeking from the Sea Floor to the Deep Mantle with an ~1,500 km Aperture Array of 49 Ocean Bottom Seismometers in the Mid-Atlantic. MG Ferreira, A., Miranda, M., Baranbooei, S., **Cabieces, R.**, *et al.*	Towards Best Practices for Egs Seismic Monitoring: Insights Gained at Utah Forge. **Pankow, K. L.**, Dyer, B., Rutledge, J., Bethmann, F., Eaton, D. W., *et al.*
11:30 AM–12:30 PM	*Plenary:* Volcanism in the Eastern Caribbean: Hazards, Monitoring, Challenges and Lessons Learnt.			
12:30–2:00 PM	Lunch Break			

Time	*202B/C*	*204*	*208A*	*208B*
	Earthquake Source Parameters: Theory, Observations and Interpretations (see page 1174)	**Transforming our Seismological Community through Inclusive Mentorship and Diverse Narratives (see page 1282)**	**USGS National Seismic Hazard Models: 2023 and Beyond (see page 1300)**	**Advances in Characterizing Seismic Hazard and Forecasting Risk in Hydrocarbon Systems (see page 1116)**
2:00 PM	INVITED: Review of the Seismicity of Mars. **Clinton, J.**, Ceylan, S., Stähler, S. C., Giardini, D., Charalambous, C., *et al.*	INVITED: Geophysical and Sea Level Monitoring in Puerto Rico, an Inclusive Experience. **Huerfano, V. A.**, Gomez, G., Baez Sanchez, G.	STUDENT: Bias of NGA-East GMMs and Site Amplification Models Relative to Supplemented Cena Ground Motion Database. **Ramos-Sepulveda, M. E.**, Parker, G. A., Buckreis, T. E., Moschetti, M. P., *et al.*	Detecting an Enormous Number of Small-Magnitude Earthquakes Using EQCCT. **Chen, Y.**, Saad, O. M., Chen, Y., Siervo, D., Zhang, F., *et al.*
2:15 PM	The 2017 Pohang, Korea, Earthquake and its Largest Aftershocks: Stress Drop and Source Complexity Suggestive of Fluid-faulting Interaction. **Son, M.**, Chaves, E. J., Cho, C.	INVITED: From Academia to Industry: How an Underrepresented Seismologist Became a Data Scientist. **Holt, M. M.**	Evaluating Bias of NGA-EAST GMMs and Site Factors for Ground Motions From Natural and Potentially Induced Earthquakes in Texas, Oklahoma, and Kansas. **Li, M.**, Rathje, E. M., *et al.*	Discriminating Natural and Injection-Induced Earthquakes in the Presence of Uncertainty: A Case Study in Alberta, Canada. **Eaton, D. W.**, Salvage, R. O., Furlong, C., Kao, H., Dettmer, J.
2:30 PM	STUDENT: Shallow Serpentinization Promoted the Up-dip High-Frequency Seismic Wave Radiation During the 2021 Mw8.1 Kermadec Megathrust Earthquake. **Zeng, H.**, Wei, S.	Trying. Failing. and Trying Again. and Again. An Informal Case Study on the Path to Figuring Out What You Want to Do for a Job and Help Others Do the Same. **Reusch, M.**	STUDENT: A Framework for Incorporating Epistemic Uncertainty in Site Effects in National Building Codes. **Anbazhagan, B.**, Rodriguez-Marek, A.	Cascading and Multi-Segment Rupture of a Mw 5.3 Injection-Induced Earthquake. **Glasgow, M. E.**, Schmandt, B., Bilek, S.
2:45 PM	New Empirical Source Scaling Laws for Crustal Earthquakes Incorporating the Fault Dip Angle and Seismogenic Thickness Effects. **Huang, J.**, Abrahamson, N. A., *et al.*	Perspectives on the Inaugural Resess Satellite Program at University of Washington. **Crowell, B. W.**, Condit, C., Schmidt, D., Ghent, J., Ott, J., *et al.*	An Update to FEMA P366: Estimating Annualized Earthquake Loss Estimates in the United States. **Jaiswal, K.**, Bausch, D., Rozelle, J.	Characteristics of a Complex Rupture Zone System Associated With the m5.4 Coalson (West Texas) Earthquake. **Savvaidis, A.**, Huang, D., Chen, Y., Dommisse, R., Breton, C., *et al.*
3:00 PM	Slow Earthquake Scaling Revisited. **Ide, S.**, Beroza, G. C.	Evolving NOAA's Tsunami Warning Center Workforce Towards Improved Service Equity. **Ohlendorf, S. J.**, Snider, D. J., Gridley, J.	STUDENT: Earthquake Hazard Prediction Software for South Carolina Considering Local Geology and Seismicity. **Jella, V.**, Ravichandran, N., Carlson, C. P., *et al.*	Investigating the Influence of Extraction on Seismicity in Areas of Injection Induced Seismicity. **Brudzinski, M. R.**, Blake, D., Currie, B. S., Dzubay, A. J., Fasola, S. L., *et al.*
3:15 PM–4:30 PM	Poster Break			

Time	*208C*	*209A*	*209B*	*209C*
	From Sensors and Networks to Site Characterization and Site Response: Coming Full Circle (see page 1198)	**Advances in Marine Seismoacoustics (see page 1119)**	**Earth's Structure From the Crust to the Core (see page 1160)**	**Legacy Seismic Data Collections: The Present State of and Future Outlook for Data from the Past (see page 1218)**
2:00 PM	Estimating Cross-Coupling in Site Response by Seismic Noise Interferometry: An Example From an Alpine Valley (Northeastern Italy). **Parolai, S.**, Laurenzano, G., Garbin, M.	Acoustic Detection of Volcanic Gas Seeps Using Underwater Distributed Acoustic Sensing. **Spica, Z.**, Caudron, C., Miao, Y., Wollin, C., Jousset, P., *et al.*	Imaging Deep Mantle Plumbing Beneath La Réunion and Comores Hotspots: Vertical Plume Conduits and Horizontal Ponding Zones. **Dongmo Wamba, M.**, Montagner, J., Romanowicz, B. A., Simons, F. J., Irving, J. C. E.	INVITED: Historical Seismograms of the South Pacific - Preserving and Utilizing a Unique 100-Year Continuous Record of Earth Observations. **Viskovic, P.**, Christophersen, A., Hanson, J. B., O'Hagan, S.
2:15 PM	STUDENT: Regional Seismic Site Characterization Maps of Massachusetts using a Depth to Bedrock and a Surficial Geology Map. **Pontrelli, M. A.**, Baise, L. G., Mabee, S., Clement, W. P., Ebel, J. E., *et al.*	INVITED: Submarine Volcano Seismoacoustics: Why Multi-Modal Data Is Important. **Tepp, G.**, Dziak, R. P.	A Seismic Investigation of Lithospheric Seismic Structure Beneath the Shillong Plateau and Adjoining Regions in N-E India by Jointly Fitting of Receiver Functions and Dispersion Curves. Agrawal, M., **Das, M. K.**, *et al.*	INVITED: European Efforts for Legacy Seismograms Preservation and Use: The Esc Wg on Seismological Legacy Data and the Seismostorm Project. **De Plaen, R. S. M.**, Batlló, J., Lecocq, T.
2:30 PM	USGS SmartSolo Seismometer Arrays in the Upper Mississippi Embayment. **Boyd, O. S.**, Pratt, T. L., Lindberg, N. S., Sarker, K., Bhattarai, R. R., *et al.*	Non-Linear Seismoacoustic Responses of Explosions in Different Rock Types and Water: Comparisons With Experimental Data. **Ezzedine, S. M.**, Cashion, A., Laintz, K., Vorobiev, O., Walter, W. R.	Effects of Partial Melt in the Uppermost Mantle on SK(K)S Splitting: Global Wavefield Simulations and Potential Applications. **Loeberich, E.**, Wolf, J., Long, M. D.	The Electronic Archive of Printed Station/Network Bulletins at the ISC. Di Giacomo, D., **Storchak, D. A.**
2:45 PM	Seismic Monitoring of Fragile Geologic Features Near Avila Beach, California. **Steidl, J.**, Hegarty, P., Kottke, A.	Exploring the Potential of Low-cost Hydrophones in Constraining Subsea Faults and Seismic Early Warning for the San Francisco Bay Region. **Salaree, A.**, Spica, Z.	INVITED: Post-Seismic Deformation Following a Deep (~560-km) Earthquake Reveals Weak Base of the Upper Mantle. **Park, S.**, Avouac, J., Zhan, Z., Gualandi, A.	The Air Force Technical Application Center Efforts to Collect, Preserve and Integrate Historic Geophysical Data. **Soto-Cordero, L.**, Jezard, M. F., Poffenberger, A.
3:00 PM	STUDENT: Capturing Spatial Variability of Site Effects: from Geology to Proxy Considerations to inform Spatial Ground Motion Correlation Models. **Lorenzo-Velazquez, C.**, Cabas, A.	INVITED: New Constraints on the Factors That Control the Lithosphere-Asthenosphere Transition and the Driving Forces of Plate Motions From the Pi-Lab Experiment. **Rychert, C.**, Harmon, N., Agius, M., Bogiatzis, P., *et al.*	The Mantle Transition Zone Seismic Discontinuities Beneath NW South America From P-Wave Receiver Function Analysis. **Vargas, C. A.**, Cubillos, J. E.	STUDENT: An Update on the Development of the Digitseis Software. **Lee, T. A.**, Ishii, M., Ishii, H.
3:15 PM–4:30 PM	Poster Break			

Time	202B/C	204	208A	208B
	Earthquake Source Parameters: Theory, Observations and Interpretations (see page 1174)	**Seismology for the Energy Transition (see page 1251)**	**2025 Puerto Rico and the U.S. Virgin Islands National Seismic Hazard Model Update (see page 1105)**	**Advances in Characterizing Seismic Hazard and Forecasting Risk in Hydrocarbon Systems (see page 1116)**
4:30 PM	The Devastating 2022 M6.2 Afghanistan Earthquake: Challenges, Processes and Implications. Kufner, S., Bie, L., Gao, Y., Lindner, M., Waizy, H., **Rietbrock, A.**, *et al.*	INVITED: Technical Subsurface Workflows for Geological Carbon Sequestration. **Imhof, M. G.**	USGS 2025 Puerto Rico and the U.S. Virgin Islands NSHM Update. **Shumway, A. M.**, Field, E. H., Moschetti, M. P., Jaiswal, K.	Bridging the Data Gap and Relocation Errors for Improved Spatiotemporal Evaluation of Induced Seismicity in the Delaware Basin. **Aziz Zanjani, A.**, DeShon, H. R., Binetti, L.
4:45 PM	INVITED: 2021 and 2022 North Coast California Earthquake Sequences and Fault Complexity in the Vicinity of the Mendocino Triple Junction. **Hellweg, M.**, Dreger, D. S., Dengler, L., Lomax, A., McPherson, R.	Machine-learning Fault Detection on 3D Seismic Migration Images of the San Juan Basin CarbonSAFE Project Site. **Huang, L.**, Li, D., Gao, K., Pawar, R., El-kaseeh, G., *et al.*	Earthquake Geology Inputs for the 2025 Update of the Puerto Rico-U.S. Virgin Islands Portion of the National Seismic Hazard Model. **Jobe, J. A. T.**, Briggs, R. W., ten Brink, U. S., Pratt, T. L., Hughes, K., *et al.*	Are Higher Hf Injection Rates More Prone to Triggering Seismicity? Data From Four North American Basins Say No. **Grigoratos, I.**, Savvaidis, A., Rodriguez, G., Verdon, J., Wiemer, S.
5:00 PM	Bayesian Source Mechanism Inversion and Uncertainty Quantification With Dense Array Strong Motion Data for 2022 Luding Earthquake in China's Sichuan. **Gu, C.**, Prieto, G. A., *et al.*	Adaptive Model Selection for the Maximum Magnitude Event During Injection. **McCormack, K.**, Dvory, N. Z.	A Seismic Source and Ground Motion Characterization Model Developed for a Site in Northeast Puerto Rico. **Beutel, J.**, Gregor, N., Hoeft, J., Hunt, D., LaForge, R.	Frictional and Poromechanical Properties of the Delaware Mountain Group: Implications for Seismic and Aseismic Faulting Associated With Induced Earthquakes. **Bolton, C.**, Affinito, R., Smye, K., *et al.*
5:15 PM	Insights Into Volcanic Rift-Tectonic Fault Interactions From Moment Tensor Analysis of the Seismicity Prior to the 2021 and 2022 Fagradalsfjall Eruptions in Iceland. **Rodríguez Cardozo, F.**, *et al.*	Fracture Network Geometry as Revealed by Seismicity and Distributed Temperature Sensing During Egs Collab Experiment 2. **Hopp, C.**, Rodríguez Tribaldos, V., Ajo-Franklin, J., Huang, L., Wood, T., *et al.*	Evaluating Predictive Performance of Global and Regional Ground Motion Models Using a New Caribbean Strong-Motion Dataset. **Cao, Y.**, Seyhan, E.	Probability of Statistically Unexpected Earthquakes in Different Basins in Texas. **Igonin, N.**, Savvaidis, A.
5:30 PM	Observations of the 2017 Earthquake Swarm in SW Iceland Used for Mapping Stress Prior to the 2021 Fagradalsfjall Eruption. **Hrubcova, P.**, Vavrycuk, V.	INVITED: Seismicity at the Coso Geothermal Field: Past and Present Applications. **Nale, S.**, Zimmerman, J., Blake, K., Sabin, A.	Assessing Site Characterization in Puerto Rico: Towards the 2025 Update of the Puerto Rico and Virgin Islands Portion of the USGS National Seismic Hazard Model. **Ahdi, S. K.**, Kehoe, H. L., Stephenson, W. J., Boyd, O. S., P., *et al.*	STUDENT: How Well Do We Really Know the b-Value? New Estimates of Earthquake Magnitude for the Delaware Basin and the Effect of Magnitude Uncertainty on Induced Seismic Hazard Estimates. **Gable, S.**, Huang, Y., Shelly, D. R.
6–7 PM	Plenary: The Future of Tsunami Hazards and Readiness Research (Panel Discussion)			

Time	208C	209A	209B	209C
	Future Directions in Physics-based Ground-motion Modeling in Preparation for the Fall 2023 Meeting (see page 1202)	**Single-station Passive Exploration Methods: Status and Perspectives (see page 1261)**	**Emerging Developments in Operational Monitoring Systems and Products (see page 1182)**	**Advancing Science With Global Seismological and Geophysical Networks (see page 1128)**
4:30 PM	Updated Broadband Cybershake PSHA Model for Southern California. **Callaghan, S. A.**, Maechling, P. J., Silva, F., Milner, K. R., Su, M., *et al.*	Modeling Noise Hvsr in Media With Lateral Irregularity Using the Diffuse Field Assumption and Ibem for an Irregular Soft Layer. **Sánchez-Sesma, F. J.**, Weaver, R. L., Perton, M., Rodriguez-Zosayas, D. A., *et al.*	Utilizing the Cloud to Modernize Delivery of Earthquake Information and Products. **Hunsinger, H.**, Brown, J., Haynie, K. L., Hearne, M., Hunter, E., *et al.*	Continuing Detection and Location Using Continuous Long Period Data Recorded at Global Seismic Networks. **Poli, P.**
4:45 PM	Virtual Earthquake Analysis of Future Alpine Fault Earthquakes and Ground-Shaking Using the Southern Alps Long Skinny Array (SALSA). **Townend, J.**, Holden, C., Chamberlain, C. J., Warren-Smith, E., Juarez-Garfias, I., *et al.*	Single-Station Microtremor HVSR Curve Inversion and Ambient Noise Tomography of the Three-Component Seismic Data From a Nodal Array in Downtown Reno, Nevada. **Mirzanejad, M.**, Seylabi, E.	Integrated Seismic Program (ISP): A New Python GUI-based Software for Earthquake Seismology and Seismic Signal Processing. **Cabieces, R.**, Olivar-Castaño, A., C. Junqueira, T., Relinque, J., Vackár, J., *et al.*	Global Trends in Microseism Amplitude on a Warming Planet. **Aster, R. C.**
5:00 PM	Prediction of Near-Field Time-Histories Using Machine Learning and a Hybrid Dataset (Calibrated Physics-Based Ground-Motion Simulations and Observations). Esfahani, R., **Cotton, F.**, Scherbaum, F., Ohrnberger, M.	Directional Amplification and Ground Motion Polarization in Casamicciola Area (Ischia Volcanic Island) After the 21 August 2017 Md 4.0 Earthquake. **Pischiutta, M.**, Petrosino, S., nappi, R.	Using the University of Utah Messaging Passing System to Help Realize Real-Time Machine-Learning Modules in Network Operations. **Baker, B.**, Armstrong, A. D., Pankow, K. L., Koper, K. D.	Wireless Collection of Environmental and State-of-Health Data in Seismographic Networks. Steim, J. M., **Franke, M.**, Oncescu, L. C.
5:15 PM	STUDENT: The i-FSC Proxy: A Physics-Based Model for Predicting Near Field Topographic Site Effects and Studying Earthquake-Induced Landslide Distributions. **Bou Nassif, A.**, Maufroy, E., Lacroix, P., Chaljub, E., Causse, M., *et al.*	Estimating VS30 From Horizontal-to-Vertical Spectral Ratio Based on Supervised Machine Learning. **Hayashi, K.**	Using a Consistent Travel-time Framework to Compare Three-dimensional Seismic Velocity Models for Location Accuracy. **Begnaud, M.**, Davenport, K., Conley, A. C., Porritt, R. W., Gammans, C. N. L., *et al.*	The Minimus Digitizer Platform: A User-Friendly Ecosystem for Efficient Network Management and Seismic Station Configuration. **Lindsey, J. C.**, Watkiss, N., Reis, W., Whealing, D.
5:30 PM	INVITED: Evaluation of the Impacts on Risk Assessments for Distributed Infrastructure Systems from Ground Motion Median, Variability, and Spatial Correlation in CyberShake Simulations. **Lee, Y.**, Goulet, C. A., Hu, Z., Callaghan, S. A.	Detecting and Locating Underground Cavities by the Finite-Interval Spectral Power of Seismic Ambient Noise. Kristekova, M., **Kristek, J.**, Moczo, P., Galis, M.	Rapid Delivery of Earthquake Catalog With Azure. **Antolik, L.**, Cooke, A., Lisowski, S., Friberg, P., Branum, D., *et al.*	Reviewing How the Management and Operation of the Global Seismographic Network Has Evolved, With a Look Into the Future: A Partnership Between the Community, NSF, and the USGS. **Frassetto, A. M.**, Dalton, C. A., *et al.*
6–7 PM	Plenary: The Future of Tsunami Hazards and Readiness Research (Panel Discussion)			

Poster Sessions

The 2020-2021 Southwest Puerto Rico Seismic Sequence: Current State of Knowledge and Implications [Poster] (see page 1103)

109. Student: Determining First Motion Focal Mechanisms for Small Magnitude Earthquakes in the Southwestern Puerto Rico Seismic Sequence From January 6th and 7th, 2020. **Rivera Ramos, J.**, Vanacore, E. A.
111. Diffuse Transtensional Deformation in the 2020 Puerto Rico Earthquake Sequence. **Nobile, A.**, Viltres, R., Vasyura-Bathke, H., Trippanera, D., Xu, W., *et al.*
113. Operational Response of the PRSN for the Southwest Puerto Rico Seismic Sequence. **Báez-Sánchez, G.**, Colón-Rodríguez, B.
112. Student: Post-Seismic Relaxation of 2020 Southwestern Puerto Rico Seismic Complex From New Gnss Network. **Justiniano, C.**, López, A., Mattioli, G., Jansma, P.
108. Student: The M6.4 Mainshock in the 2020 Southwestern Puerto Rico Seismic Sequence: New Insights From Joint Inversion. **Solares-Colón, M. M.**, Goldberg, D. E., Yeck, W. L., Melgar, D., Vanacore, E. A., *et al.*
110. The Puerto Rico Strong Motion Program – a State of the Art and Records Obtained During the m6.4 January 7, 2020 Earthquake. **Martinez-Cruzado, J. A.**, Martinez-Pagan, J., Santana-Torres, E. X., Hernandez-Ramirez, F. J., Suarez-Colche, L. E.

2025 Puerto Rico and the U.S. Virgin Islands National Seismic Hazard Model Update [Poster] (see page 1106)

115. Geospatial Scope of the 2025 Puerto Rico-U.S. Virgin Islands National Seismic Hazard Model Update. **Herrick, J. A.**, Shumway, A. M.
114. Student: Reviewing 4 Decades of the Puerto Rico Seismic Network Catalog: From Catalog Correction and Homogenization to Declustering. **Chacon, D. M.**
119. Student: Seismotectonic Context Update and Tsunami Numerical Modeling for the NE Region of the Caribbean Plate, Puerto Rico; Insights From Seismic Reflection and Seismicity. **Porras, H.**
116. Uprm Contributions to the 2025 Update of the Puerto Rico Seismic Hazard Map. **Lopez, A. M.**, Martinez-Cruzado, J. A., Huerfano, V. A., Vanacore, E. A.
118. Vs30 Mapping using MrVBF in Puerto Rico and Hispaniola. **Mitra, D.**, Sethi, S.
117. Student: Vs30 Measurements at Puerto Rico Seismic Sites. **Toro Acosta, C.**, Vanacore, E. A.

Advances in Characterizing Seismic Hazard and Forecasting Risk in Hydrocarbon Systems [Poster] (see page 1118)

79. Student: Ambient Noise Monitoring in a Region of Disposal-induced Seismicity, Central Alberta. **Rojas-Parra, J.**
77. Characteristics of Seismogenic Zones Associated With the m5.2 Range Hill Event Near Midland, Texas. **Huang, D.**, Chen, Y., Breton, C., Dommisse, R., Savvaidis, A.
78. Fault Stability and Pore Pressure Thresholds for Seismogenic Rupture in the Midland Basin. **Hennings, P.**, Ge, J., Horne, E., Nicot, J., Smye, K.
76. Seismic Hazard and Risk Forecasting for the Groningen Gas Field: Case Study for Gas Year 2022/2023. **Osinga, S.**, Kraaijpoel, D. A., Aben, F. M., Pluymaekers, M. P. D., Vogelaar, B. B. S., *et al.*
75. Widespread Anthropogenic Uplift, Subsidence, Co-Seismic Faulting and Earthquakes in the Delaware Basin of Texas and New Mexico. **Hennings, P.**, Staniewicz, S., Smye, K., Chen, J., Horne, E., *et al.*

Advances in Marine Seismoacoustics [Poster] (see page 1120)

1. Student: Impacts of Oceanographic and Geologic Factors on Ocean-Bottom Seismic Noise. **Niklasson, S.**, Rowe, C. A., Bilek, S.
2. Novel Autonomous and Cabled Obs Solutions for Offshore Seismic Research. **Lindsey, J. C.**, Watkiss, N., Reis, W., Whealing, D.
3. Novel Longer-Term Ocean Bottom Station Concepts Enabled by Advancements in Low Power Equipment. **Perlin, M.**

Advancing Science With Global Seismological and Geophysical Networks [Poster] (see page 1129)

49. A Truly Very Broad Band Borehole Seismometer With Flat Response Over 5 Decades of Frequency. Guralp, C. M., **Rademacher, H.**
50. Student: Ambient Seismic Noise Studies of the Alpine Fault, New Zealand. **Juarez Garfias, I. C.**, Townend, J., Chamberlain, C. J., Francois-Holden, C.
48. Current Issues and Difficulties Being Faced by the Ukrainian Seismic Network. **Amashukeli, T.**, Malatesta, L., Farfuliak, L., Gaviev, O., Petrenko, K.

Collective Impact in Earthquake Science [Poster] (see page 1131)

84. Student: A New Approach for Assessing Fragility Curves in Seismic Vulnerability and Risk Studies. an Application

to Costa Rica. Jiménez Martínez, M., Navas Sánchez, L. A., González-Rodrigo, B., Hernández-Rubio, O., Dávila Migoya, L., **Benito Oterino, M.** *et al.*

85. Center for Collective Impact in Earthquake Science (C-CIES). **Velasco, A. A.**, Weidner, J., Karplus, M. S., Bilek, S., Bolton Valencius, C., *et al.*
81. Student: New Seismic Exposure Model for Guatemala City, a New Seismic Risk Approach. Dávila Migoya, L., **Benito Oterino, M.**, Flores, O., Cabrero, J. M.
80. Social Science and Education Research for ShakeAlert, the Earthquake Early Warning System for the West Coast of the United States. **McBride, S. K.**, Sumy, D. F., de Groot, R.
83. The Launch of Seismica: From Early Career Researchers' Perspective. **Karasözen, E.**, Agostinetti, N. P., Convers, J., Hicks, S., Mark, H., *et al.*
82. Visualization of Aftershock Forecasts Driven by User Needs. **Schneider, M.**, Wein, A., van der Elst, N., McBride, S. K., Becker, J., *et al.*

De-risking Deep Geothermal Projects: Geophysical Monitoring and Forecast Modeling Advances [Poster] **(see page 1150)**

72. Student: Applying Waveform Correlation Analysis to Microseismicity at the Forge Sites to Detect and Characterize Fractures. **Asirifi, R.**
73. Bidirectional Displacement Waveforms of Hhz Induced Microearthquakes - Evidence for Volumetric Shear-Slip Distributions in Ambient Crust Hydraulic Stimulation. **Hofstetter, R.**, Leary, P. C., Malin, P. E.
71. Developing a Machine Learning Model to Pick Phase Arrivals on DAS Data at the Forge Site. **Chen, X.**, Ratre, P., Zhu, W., Xiao, C., Asirifi, R., *et al.*
74. Time-Lapse Changes in Velocities at Patua Geothermal Fields Using Seismic Ambient Noise. **Qiu, H.**, Nakata, N., Qin, L.

Earth's Structure From the Crust to the Core [Poster] **(see page 1164)**

99. Crust and Upper Mantle Velocity Structure Beneath the Chhotanagpur Plateau, India Using Waveform Modeling of Shear-Coupled Pl Waves and Other Phases. **Das, M. K.**, Agrawal, M., Patel, A.
107. Deep Crustal Imaging in Binchuan, China Based on a Wavefield Decomposition Analysis Using Wavelets on the Dense Array Datasets. **Zhang, J.**, Yang, H.
100. Student: Lateral Variations of Crustal Lg-Wave Attenuation in the Scandinavia Peninsula and Its Vicinity. **Liu, Z.**, Zhao, L., Xie, X., Yao, Z.
96. Student: Lithospheric Structure of the Sabine Uplift From Joint Modeling of Receiver Functions and P Autocorrelations. **Sadler, B.**, Pulliam, J.
98. Student: Mapping the Mantle Transition Zone Using the Coda Correlation Wavefield. **Liu, M.**, Ritsema, J., Spica, Z.
97. Student: On the Detection of Sharp Upper Mantle Discontinuities across North America: Silencing Echoes in the Crust with Sparse Non-linear Radon Filters. **Carr, S. A. B.**, Olugboji, T., Ziqi, Z.
105. Student: Seismic Autocorrelation to Explore Subglacial Crustal Structure. **Chandra, R.**, DellaGiustina, D. N.
106. Student: Seismic Waves Attenuation in Georgia. **Buzaladze, A.**, Sandvol, E. A.
104. SItomo – a New Matlab Toolbox for SKS Splitting Intensity Tomography and Application to the Dense SWATH-D Seismic Array in the European Alps. **Link, F.**, Mondal, P., Long, M. D.
103. Student: Towards Using Mermaid Waveforms in Seismic Tomography. **Willis, R. M.**, Bozdag, E., Snieder, R.
102. Student: Unraveling the Iceland Plume Track Through Greenland's Mantle Transition Zone. **Hariharan, A.**, Nathan, E. M., Fischer, K. M.
101. Updated SALSA3D Tomographic Velocity Models for Improved Travel-Time Prediction and Uncertainty. **Conley, A. C.**, Porritt, R. W., Davenport, K., Begnaud, M., Rowe, C. A., *et al.*

Earthquake Source Parameters: Theory, Observations and Interpretations [Poster] **(see page 1179)**

16. Student: A Relative Moment Tensor Inversion Scheme for Local Earthquakes: Application to San Juan Cluster. **Drolet, D.**, Bostock, M. G., Plourde, A. P.
17. Adjoint Earthquake Source Inversion Method Using P-Wave Spectra and Focal Mechanism Solutions. **Cheng, Y.**, Allen, R. M.
6. An Improved Estimation of Stress Drop and its Application on Induced Earthquakes in the Weiyuan Shale Gas Field in China. **Zhang, J.**, Yang, H., Zi, J., Su, J.
11. Brune Stress Drop, b-Value, and Modeling Through Finite Element Models (FEM) of Earthquakes that Occurred close to the 30 October 2016, Mw 6.3 Norcia Earthquake. **Calderoni, G.**, Megna, A., Mele, G., Rovelli, A., Lombardi, A.
15. Student: Characterization of the 2020 Mw 5.7 Magna, Utah Seismic Sequence Full Wavefield Decay. **Trahan, K. M.**, Vanacore, E. A., Lecocq, T.
14. Student: Characterization of the Southwestern Puerto Rico Seismic Sequence Full Wavefield Decay. **Friedman-Álvarez, C. D.**, Vanacore, E. A.

18. Estimating Faulting Mechanisms From Single-Station Seismic Data. **van der Lee, S.**, Sita, M., Agaba, V., Braunmiller, J.
21. Estimating Magnitudes of the 1868 and 1877 Earthquakes Using Tsunami Records. **Barrientos, S. E.**, Zelaya, C., Díaz-Naveas, J.
4. Extension of Aseismic Slip Propagation Theory to Slow Earthquake Migration. **Ariyoshi, K.**
20. FocMecDR: A Cross-Correlation-Based Double-Ratio Earthquake Focal Mechanism Inversion Algorithm. **Zhang, M.**
8. Student: Global Evaluation of Large Strike-Slip Ruptures Using a Bayesian Estimation of Stress Glut Second Moments. **Atterholt, J.**, Ross, Z. E.
12. MTUQ: A High-Performance Python Package for Moment Tensor Estimation and Uncertainty Quantification. **Thurin, J.**, Braunmiller, J., Rodriguez Cardozo, F. R., Ding, L., Liu, Q., *et al.*
5. Student: Not So Planar Faults – On the Impact of Faulting Complexity and Type on Earthquake Rupture Dynamics. **Zaccagnino, D.**, Doglioni, C.
9. Student: Regional Alaska Earthquake Moment Tensors Inverted Using 3D Green's Functions. **McPherson, A.**, Tape, C., Thurin, J.
13. Robust Explosion Screening Based on Moment Tensor Angular Distance. **Modrak, R.**, Kintner, J., Thurin, J., Tape, C.
10. Student: Seismic Moment Tensors Evaluation of Earthquakes in Central Zagros (Iran). **Abbasi Hafshejani, Z.**
7. Student: Source Parameter Analysis Indicates Both Hydrous Phase Breakdown and Thermal Shear Runaway Drive Unusual Subduction Seismicity in Central Colombia. **Aravena, P.**, Warren, L. M., Abercrombie, R. E., Bishop, B., Cho, S., *et al.*
19. Source Stress Drop for Continental Collision Zones: Deviation From "Textbook" Earthquake Models. **Salaree, A.**, Saloor, N.

Emerging Developments in Operational Monitoring Systems and Products [Poster] (see page 1184)

62. Developing International Standards and Guidelines for Curating, Disseminating, and Validating Simulated Ground-Motion Data. **Aagaard, B. T.**, Askan, A., Rezaeian, S., Ahdi, S. K., Yong, A. K.
59. Edge Continuous Waveform Buffer Enhanced Station Monitoring Using a Web Interface and Containerized Deployment. Mielke, B. E., **Guy, M. R.**
61. Modern Tools and Approaches to Earthquake Monitoring and Product Generation at the Southern California Seismic Network (SCSN). **Yu, E.**, Bhaskaran, A., Chen, S., Tam, R., Tepp, G., *et al.*
60. Motus: The U.S. Geological Survey National Earthquake Information Center's New Earthquake Monitoring System. **Patton, J.**, Guy, M. R.
58. Near Real-Time Repeating Earthquake Monitoring System. **Dominguez, L. A.**, Taira, T., Cruz-Atienza, V. M., De la Luz, V., Kostoglodov, V.
57. Pysolate: A Python-Based Thresholding Tool to De-Noise or De-Signal Seismic Waveforms Based on the Continuous Wavelet Transform. **Aguiar, A. C.**, Chiang, A., Myers, S. C.

From Sensors and Networks to Site Characterization and Site Response: Coming Full Circle [Poster] (see page 1200)

37. A Rugged, Portable and Intelligent Analogue Seismometer for Future and Pre-Existing Arrays – Güralp Certis. **Lindsey, J. C.**, Watkiss, N., Reis, W., Whealing, D.
35. Student: Application of Parametric and Non-Parametric Git in Low to Moderate Seismic Context: Case of Mainland France Earthquake Ground Motion for 1996-2021 Period. **Buscetti, M.**, Traversa, P., Perron, V., Hollender, F.
39. Framework for Incorporating Site Characteristic Information at Advanced National Seismic System Sites into the Center for Engineering Strong Motion Data. **Schleicher, L. S.**, Huddleston, G. J., Ahdi, S. K., Steidl, J., Hagos, L., *et al.*
33. Invited: On the Study of Amplification in the Cerro Prieto Volcano, Mexicali Valley, Mexico Using Cross- and Auto-Power Spectrum Technique. Huerta-López, C. I., **Vidal-Villegas, J. A.**
38. Site Characterizations and Linear Site Responses at Selected Borehole Strong-Motion Arrays From the United States and Japan. **Wang, Z.**, Carpenter, S.
36. Vs30 at Two Seismic Stations in the Central Valley of California Using S-Wave Refraction Tomography and Masw. **Chan, J. H.**, Catchings, R. D., Taira, T., Goldman, M., Criley, C. J., *et al.*
34. Student: Vs30 Site Characterization in the City of St. Helena, Napa County, California Using Active-Source Refraction Tomography. **Samuel, D. A.**, Catchings, R. D., Goldman, M., Sickler, R. R., Chan, J. H.

Future Directions in Physics-based Ground-motion Modeling in Preparation for the Fall 2023 Meeting [Poster] (see page 1204)

29. Averaged S-Wave Site Amplification Factors for Sites With Vs30 ≥ 760 M/s Derived From Git Analysis of K-Net and KiK-Net Ground Motions and Its Consequence for Ground Motion Modeling. **Kawase, H.**, Nakano, K., Ito, E.
31. Basin Effects From 3D Simulations in Southern California: Basin-Depth Scaling and Nonergodic Site Adjustments.

Moschetti, M. P., Thompson, E. M., Withers, K. B., Shumway, A. M., Powers, P. M.

30. Strong-Motion Simulation of the 1944 Tonankai Earthquake Along the Philippine Sea Plate Based on the Damage Ratios of Wooden Houses With In-Situ Measurements of Microtremors at the Population Centers of Heavily-Damaged Villages and Towns. **Ito, E.**, Nakano, K., Kawase, H.
32. The Impact of the Three-Dimensional Structure of a Subduction Zone on Time-Dependent Crustal Deformation Measured by HR-GNSS. **Fadugba, O. I.**, Sahakian, V. J., Melgar, D., Rodgers, A. J., Shimony, R.

General Seismology (see page 1209)

130. Insight, 2018–2022: Results From the First Mission With a Primary Focus on the Interior of Mars. **Panning, M. P.**, Banerdt, W. B., Smrekar, S., Le Maistre, S., Lognonné, P., *et al.*
132. Pn Wave Attenuation Beneath the Caribbean Plate. **Zhao, L.**, Xie, X., Yang, S., Yao, Z.
129. Variations of the System Properties of a High-Rise Building Over 1 Year Using a Single Station 6c Approach. Rossi, Y., Tatsis, K., Reuland, Y., **Clinton, J.**, Chatzi, E., *et al.*
131. Vertical Component Impulse Response Functions in a High-Rise From Earthquake and Ambient Vibration Data. **Kohler, M.**, Prieto, G. A.

Geophysical Data Analysis in Cloud Computing Environments [Poster] (see page 1210)

51. Invited: A Cloud Ecosystem for Data and Software Developed by SCOPED. Denolle, M. A., Wang, Y., **Tape, C.**, Ni, Y., Waldhauser, F., *et al.*
52. Student: Constructing Cloud Resources for the Individual Researcher From the Ground Up: An Example of Earthquake Detection in the Cloud. **Krauss, Z.**, Ni, Y., Henderson, S., Denolle, M. A., Wang, I.
54. Leveraging Cloud Services for the Earthscope Data Repositories. Trabant, C., **Berglund, H.**, Mencin, D., Carter, J., Casey, R., *et al.*
53. Seismic Networks in the Cloud. **Franke, M.**, Capitani, G., Radman, S. M.

High-frequency Ground Motion Measurements, Assessments and Predictions [Poster] (see page 1214)

22. Combined Effect of Brittle Off-Fault Damage and Fault Roughness on Earthquake Rupture Dynamics. **Thomas, M. Y.**, Bhat, H. S.
23. Estimation of Kappa (κ_0) and Associated Uncertainties in Iran Using Broadband Inversion Method. **Davatgari Tafreshi, M.**, Pezeshk, S.
27. How Well We Are Predicting High-Frequency Response Spectra for the CEUS? **Graizer, V.**
24. Student: Lateral Variations of Attenuation in the Crust of Alaska Using Lg Q Tomography. **Mahanama, A.**, Cramer, C. H.
28. Separating Broad-Band Site Response From Single-Station Seismograms. **Zhu, C.**, Cotton, F., Kawase, H., Bradley, B. A.
25. Stochastic Finite-fault Ground Motion Simulation of the 2021 Mw5.9 Woods Point Earthquake: Facilitating Local Probabilistic Seismic Hazard Assessment. **Tang, Y.**, Mai, P.
26. Student: Understanding the Origin of High-Frequency Ground Motions of Earthquakes in California and Nevada. **Chatterjee, A.**, Trugman, D. T., Lee, J., Hirth, G., Tsai, V. C.

Legacy Seismic Data Collections: The Present State of and Future Outlook for Data from the Past [Poster] (see page 1219)

55. Historical Nuclear Event and Collapse Data From the Livermore Nevada Network Between 1979- 1992. **Price, A.**, Rodd, R. L.
56. Revisiting Earth's Inner Core: Historical Data Using Modern Approaches. **Ringler, A.**, Lee, T. A., Anthony, R. E., Wilson, D. C.

Monitoring Climate Change With Seismology [Poster] (see page 1221)

65. Student: Changing Climate and Microseismic Noise in Alaska. **John, S.**, West, M. E.
63. Estimation of First-Year Sea Ice Thickness With Seafloor Distributed Acoustic Sensing Using Flexural-Gravity Waves From Environmental and Anthropogenic Sources. **Baker, M. G.**, Abbott, R. E.
66. Student: Ross Ice Shelf Micro-Icequakes and Ocean Swell Induced Seismicity. **McGhee, E. A.**, Aster, R. C.
64. Using Distributed Acoustic and Temperature Sensing to Characterize the Rapidly Changing Nearshore Arctic Ocean (PEMDATS). **Stanciu, A.**, Frederick, J. M., Baker, M. G., Abbott, R. E., Conley, E. W., *et al.*

Normal Faults: From Source to Surface [Poster] (see page 1233)

89. Student: A Semi-Automated Algorithm for Fault Displacement Profile Extraction. **Quintana, M.**, Rodriguez, A., Chadly, D., Oskin, M. E.

90. Student: Across-Scales Co-Seismic Deformation and Fault Scarp Morphology From the 1954 Dixie Valley-Fairview Peak Earthquake Sequence. **Andreuttiova, L.**, Hollingsworth, J., Vermeesch, P., Mitchell, T.
88. The Rocks That Did Not Fall: A Multidisciplinary Analysis of Near-Source Ground Motions From an Active Normal Fault. **Trugman, D. T.**, Brune, J., Kent, G., Smith, K., Louie, J., *et al.*

Seismology for the Energy Transition [Poster] (see page 1252)

69. Baseline Seismic Monitoring Survey for UKGEOS Glasgow Geothermal Production Using DAS. **Holmgren, J. M.**, Werner, M. J., Butcher, A., Kendall, J., Chambers, J., *et al.*
70. Seismic Imaging, Full-Waveform Inversion and Inverse-Scattering. **Wu, R.**, Zheng, Y.
68. Simulating Time-Lapse Seismic Monitoring of Geologic Carbon and Hydrogen Storage With a Stress-Dependent Rock Physics Model. **Creasy, N.**, Gao, K., Huang, L., Gross, M., Gasperikova, E., *et al.*
67. Vector Double-Beam Characterization for Discrete Fractures in Geological Carbon Storage Sites. **Zheng, Y.**, Parsons, J., Hu, H., Huang, L.

Seismology's Role in Assessing Volcanic Hazard at Multiple Time Scales [Poster] (see page 1255)

46. 20-Year Seismic Run-Up to the 2015-2016 Eruption of Volcan Momotombo, Nicaragua, and Final Acceleration by Adjacent 2014 m6.1 Tectonic Earthquake. **McCausland, W.**, Tenorio, V., Navarro, M., Strauch, W., White, R. A.
47. Anomaly Detection and Image Spectrometry in Assesing Multitemporal Activity of the Turrialva Volcano, Costa Rica, and La Palma, Spain. **Benito Oterino, M.**, Rejas, J., Marchamalo Sacristán, M., Bonatti, J.
40. Geodetic Measurements Reveal Time-Averaged Surface Deformation in the Valles Caldera. **Maier, N.**, Grapenthin, R., Newman, A., Donahue, C., Lindsey, E., *et al.*
41. Student: Linking Deep Long Period Earthquakes to Magmatic Processes Underlying Mauna Kea. **Scholz, K. J.**, Townsend, M., Thomas, A. M.
43. Repeating Low-Frequency Earthquakes Near Wrangell Volcano, Alaska. **Wech, A.**, Newton, T., Thomas, A. M.
42. The Hawai'i Magmatic System Resolved by High-Resolution Traveltime Tomography. **Biondi, E.**, Zhu, W., Li, J., Ross, Z. E., Zhan, Z.
45. Student: Two Decades of Seismicity at Mount St. Helens. **Hirao, B. W.**, Thomas, A. M., Zhang, H., Schmandt, B., Thelen, W. A.

Single-station Passive Exploration Methods: Status and Perspectives [Poster] (see page 1262)

95. Dynamic Characteristics Assessment and 3D Site Effects Analyses of Earth Dams Based on Ambient Noise Measurements. **Verret, D.**
92. High-Resolution Imaging of the Firn Layer in Antarctic Near the West Antarctic Ice Sheet Divide Camp. **Qin, L.**, Nakata, N., Zhang, Z., Qiu, H., Karplus, M. S., *et al.*
93. Seismic Energy Partition Applied to Dispersion Diagrams of Surface Waves. **Piña-Flores, J.**, Cárdenas-Soto, M., García-Jerez, A.
91. Strong Ground Motion Variation due to Local Complex Geology During the Earthquake of September 19, 2017 (Mw 7.1). **Cárdenas-Soto, M.**, Sánchez-González, J., Martínez-González, J., Cifuentes-Nava, G., Escobedo-Zenil, D., *et al.*
94. The Use of the H/V Ratio for Back-Calculation of Normalized Shear Modulus G/g0. **Karray, M.**, Gul, O., Chiaradonna, A., Sezer, A.

Transforming our Seismological Community through Inclusive Mentorship and Diverse Narratives [Poster] (see page 1283)

87. An Online "Careers Module" to Recruit Undergraduate Students Into the Geoscience Workforce With Universal Design for Learning Approaches. **Sumy, D. F.**, Houlton, H. R., Smith, J. C.
86. Three Years In: Reflections on Successes, Challenges, and Next Steps for an Employee-Led Diversity, Equity, and Inclusion Working Group at a National Lab. **Carr, C. G.**, Crumley, R. L., Creasy, N., Ranasinghe, N., Kintner, J., *et al.*

USGS National Seismic Hazard Models: 2023 and Beyond [Poster] (see page 1303)

122. Analyses and Implications of Deformation Models of the U.S. National Seismic Hazard Model 2023. **Hatem, A. E.**, Briggs, R. W., Pollitz, F. F., Field, E. H., Milner, K. R.
125. Evaluating Spatial Smoothing for the 2023 USGS National Seismic Hazard Model. **Llenos, A. L.**, Michael, A. J., Moschetti, M. P., Savran, W. H.
124. Evaluation and Integration of Seismic Directivity Models for the USGS National Seismic Hazard Model. **Withers, K. B.**, Moschetti, M. P., Powers, P. M., Petersen, M. D., Graves, R. W., *et al.*
120. Student: Ground Motion Model for Small-to-Moderate Potentially Induced Earthquakes using Machine Learning Algorithms. **Alidadi, N.**, Pezeshk, S.

121. Hybrid Empirical Ground-Motion Models with Simulation-based Site Amplification Factors for the Island of Hawaii. **Pezeshk, S.**, Haji-Soltani, A.
127. The 2023 Update of the Alaska National Seismic Hazard Model: Overview and Sensitivities. Powers, P. M., **Altekruse, J. M.**
126. Updating the Crustal Seismic Sources for the 2023 National Seismic Hazard Model for Alaska. **Haeussler, P. J.**, Bender, A., Powers, P. M., Koehler, R., Brothers, D. S.
128. USGS NSHM Hazard Tool. **Girot, D. L.**, Powers, P. M.
123. Student: Using Geodetically-Derived Strain Rates in Future US National Seismic Hazard Models. **Castro-Perdomo, N.**, Johnson, K. M., Maurer, J., Materna, K.

Wednesday, 19 April 2023—Oral Sessions

Presenting author is indicated in bold.

Time	*202B/C*	*203*	*204*	*208A*
	Site-specific Modeling of Seismic Ground Response: Are We Quantitative Enough to Predict? (see page 1263)	**New Methods and Models for More Informative Earthquake Forecasting (see page 1228)**	**Understanding and Managing Induced Seismicity (see page 1284)**	**Advances in Probabilistic Seismic Hazard Analysis and Applications (see page 1121)**
8:00 AM	Spectral Decomposition of Ground Motions in New Zealand using the Generalized Inversion Technique. **Zhu, C.**, Bradley, B. A., Bora, S.	The Roles of Coseismic Slip and Afterslip in Driving On-fault Aftershock Distributions: An Analysis of Behaviourally-varied Continental Case Studies. **Churchill, R. M.**, Wermer, M., Biggs, J., Fagereng, A.	Early Oil Production in Oklahoma and California and Its Possible Relationship to Local Earthquake Activity. **Ebel, J. E.**, Valencius, C. B., Krones, J. S.	STUDENT: 2020 National Seismic Hazard Model of Norway. Ghione, F., **Oye, V.**
8:15 AM	Obtaining Site Effect-Free Hard-Rock Time Series in Japan From Surface Recordings based on the Generalized Inversion Technique. **Pilz, M.**, Cotton, F., Zhu, C., Nakano, K., Kawase, H.	A-Positive: An Improved Estimator of the Earthquake Rate That Is Robust Against Catalog Incompleteness. **van der Elst, N.**	INVITED: Integrating High Resolution Crustal Stress Maps and Seismicity Catalogs to Study Injection-Induced Earthquake Sequences in Oklahoma. **Lundstern (Lund Snee), J.**, Zoback, M. D.	INVITED: The 2022 New Zealand National Seismic Hazard Model. **Gerstenberger, M. C.**, Bora, S., Bradley, B. A., Kaiser, A. E., Nicol, A., *et al.*
8:30 AM	STUDENT: Ground Motion Model for Predicting Significant Duration Constrained by Seismological Simulations. **Pinilla-Ramos, C.**, Abrahamson, N. A., Kayen, R. E., Phung, V., Castellanos-Nash, P.	A Decade of Prospective Evaluations of 1-Day Seismicity Forecasts for California: First Results. **Bayona, J. A.**, Herrmann, M., Savran, W. H., Maechling, P. J., Marzocchi, W., *et al.*	Cooperative Seismic Monitoring & Earthquake Response for Saltwater Injection Operations in Texas. **Pascale, A.**, Reynolds, T.	A Comprehensive Probabilistic Seismic Hazard Assessment for Mexico. **Kraner, M. L.**, Yang, W., Shabestari, K., Mahdyiar, M., Shen-Tu, B., *et al.*
8:45 AM	STUDENT: Searching for Empirical Nonlinear Site Response Applicable to Greater Vancouver, British Columbia. **Gomez Jaramillo, N.**, Molnar, S., Ghofrani, H.	Question-driven Ensembles of Flexible ETAS Models. **Mizrahi, L.**, Nandan, S., Savran, W. H., Wiemer, S., Ben-Zion, Y.	En Echelon Faults Reactivated by Wastewater Disposal Near Musreau Lake, Alberta. **Schultz, R.**, Park, Y., Aguilar Suarez, A., Ellsworth, W. L., Beroza, G. C.	Probabilistic Analysis of Seismic Hazard in the Dominican Republic Considering Hybrid Models of Zones and Faults and Including the Local Effect on the Expected Motion. **Germoso, C.**, Aracena, J., *et al.*
9:00 AM	STUDENT: Characterization of Nonlinear Soil Behavior in a Systematic Manner at Japanese KiK-Net Sites and Correlation With Geological and Geotechnical Parameters. **Loviknes, K.**, Bergamo, P., Fäh, D., Cotton, F.	INVITED: Overcoming the Achilles' Heel of the Foreshock Traffic Light System. **Gulia, L.**, Wiemer, S., Biondini, E., Vannucci, G., Enescu, B.	Causative Fault and Seismogenic Mechanism of the 2010 Suining M5.0 Earthquake in Sichuan Basin (China) from Joint Modeling of Seismic and InSAR Data. **Ni, S.**, Gu, W.	The GEM Global Mosaic of Hazard Models: Improvements Since Its First Release and Challenges Ahead. **Pagani, M.**, Johnson, K., Villani, M., Chandrasekhar, S., Styron, R. H., *et al.*
9:15–10:30 AM	Poster Break			

Time	*208B*	*208C*	*209C*
	Subduction Zone Structure From Trench to Arc (see page 1272)	**Understanding Earth Systems with Fiber-optic Cables (see page 1293)**	**Detecting, Locating, Characterizing and Monitoring Non-earthquake Seismoacoustic Sources (see page 1155)**
8:00 AM	INVITED: Improved Quantification of the Volume and Distribution of Water in Incoming Upper Oceanic Crust of Subduction Zones Using Long Offset Streamer Data. **Becel, A.**, Acquisto, T., Shillington, D. J., Cruz Atienza, V., Hagemeier, A., *et al.*	INVITED: Temperature Sensing With DAS for Fiber-Optic Oceanography. **Williams, E. F.**, Ugalde, A., Martins, H. F., Becerril, C. E., Callies, J., *et al.*	Using Seismic Methods to Monitor Bedload Transport Along a Desert Environment Ephemeral Tributary. **Bilek, S.**, McLaughlin, J., Cadol, D., Laronne, J.
8:15 AM	Structural Variations and Seismogenic Character of the Hikurangi Margin, New Zealand. **Van Avendonk, H. J.**, Gase, A. C., Bangs, N. L.	Potential of Ocean Bottom Distributed Acoustic Sensing for Seismic Ocean Thermometry. **Shen, Z.**, Wu, W.	STUDENT: Generating Green's Functions for Use in Seismic Monitoring of Debris Flows Using the Ambient Seismic Field. **Conner, A. E.**, Thomas, A. M., Allstadt, K., Collins, E., Thelen, W. A.
8:30 AM	INVITED: STUDENT: Fluids Control Along-Strike Variations in the Alaska Seismogenic Zone. **Wang, F.**, Wei, S., Elliott, J., Freymueller, J. T., Drooff, C., *et al.*	STUDENT: High-Resolution Imaging of Submarine Structures and Ocean Microseism Sources With Distributed Acoustic Sensing. **Fang, J.**, Yang, Y., Williams, E. F., Biondi, E., Zhan, Z.	Incorporating Numerical Landslide Models Into Broadband Synthetic Seismogram Simulations of Large, Rapid Landslides. **Allstadt, K.**, Collins, E., Mangeney, A., George, D., Peruzzetto, M., *et al.*
8:45 AM	Imaging the Taltal Segment in Northern Chile: Tectonic Implications Inferred from Seismicity Distribution, Local Earthquake Tomography and Moment Tensor Calculations. **Leon-Rios, S.**, Reyes-Wagner, V., Calle-Gardella, D., Comte, D., Roecker, S., *et al.*	Observing Slow-Slip Fault-Activation Processes Using DAS. **Eaton, D. W.**, Wang, C., Ma, Y., Maji, V.	Classifying Landslide Seismic Signals With Unsupervised Machine Learning From Multiple Locations. **Smith, K.**, Huang, H.
9:00 AM	STUDENT: P-Wave Attenuation Structure and Melting Processes of the Tonga-Lau Mantle Wedge. **Zhang, Y.**, Wei, S., Byrnes, J. S. S., Tian, D., Wang, F., *et al.*	Measuring Instrument Response and Self-Noise Level of Telecommunication-Fiber-Optic DAS Arrays. **Zhai, Q.**, Zhan, Z.	Rapid Seismic Assessment of Potentially Tsunamigenic Landslides. **Karasözen, E.**, West, M. E.
9:15–10:30 AM	Poster Break		

Time	202B/C	203	204	208A
	Site-specific Modeling of Seismic Ground Response: Are We Quantitative Enough to Predict? (see page 1263)	**New Methods and Models for More Informative Earthquake Forecasting (see page 1228)**	**Understanding and Managing Induced Seismicity (see page 1284)**	**Advances in Probabilistic Seismic Hazard Analysis and Applications (see page 1121)**
10:30 AM	STUDENT: Evaluating Alternative Approaches to Model Local Site Effects in Physics-Based Ground-Motion Simulations: Insights From Small-Magnitude Earthquakes Recorded in Canterbury, New Zealand. **Kuncar, F.**, Bradley, B. A., de la Torre, C. A., Lee, R. L.	STUDENT: Earthquake Magnitude Prediction Using a Machine Learning Model. **Berman, N.**, Zlydenko, O., Gilon, O., Bar Sinai, Y.	Seismogenic Fault Characterization of the Quinton Sequence in East Oklahoma. **Ogwari, P. O.**, Walter, J., Xiaowei, C., Woelfel, I., Thiel, A., *et al.*	The 2022 Revision of National Seismic Hazard Model (NSHM) for New Zealand: Candidate Ground-Motion Models (GMMs) and Associated Hazard Sensitivities. **Bora, S.**, Bradley, B. A., Manea, E., Gerstenberger, M. C., Lee, R. L., *et al.*
10:45 AM	Are There Unique Parameters and Proxies for Predicting Site Response? Examples From Selected Borehole Strong Motion Arrays. **Wang, Z.**, Carpenter, S.	INVITED: Are Earthquake Sizes Correlated? Insight From Neural Temporal Point Process Models. **Cousineau, K. D.**, Brodsky, E. E., Shchur, O., Günnemann, S.	How Comparable Are Frequency-Magnitude Variations of Natural and Induced Seismic Sequences? A Comparison for the Tectonic Gyeongju and Induced Pohang Earthquake Sequences. **Muntendam-Bos, A. G.**, Woo, J., Ellsworth, W. L.	Correlation of Non-Ergodic Path Effects for Intensity and Ground- Motion Data. Abrahamson, N. A., **Sung, C.**
11:00 AM	Estimating the Earthquake Site Response From Ambient Noise Using the SSRh Approach: Overview, Application and Comparison With Other Techniques. **Perron, V.**, Rischette, P., Buscetti, M., Hollender, F.	Modelling and Model Performance Assessment of the Spatiotemporal Development of Event Rates and Event Clustering for Induced Seismicity in the Groningen Gas Field. **Kraaijpoel, D. A.**, Weits, R. N., Osinga, S., Aben, F. M., Pluymaekers, M. P. D., *et al.*	Annual Seismic Hazard and Risk Forecasting for the Groningen Gas Field: Public Domain SHRA by the Geological Survey of the Netherlands. **Osinga, S.**, Kraaijpoel, D. A., Aben, F. M., Pluymaekers, M. P. D., Vogelaar, B. B. S., *et al.*	Regionally Adaptable Ground-Motion Models for Subduction Seismicity in New Zealand. **Manea, E.**, Bora, S., Kaiser, A. E., Gerstenberger, M. C., Hutchinson, J.
11:15 AM	Using Microtremor-Based Horizontal-to-Vertical Spectral Ratios to Improve Linear Site Response Predictions in the Sacramento-San Joaquin Delta Region of California. **Buckreis, T. E.**, Wang, P., Brandenberg, S. J., Stewart, J. P.	A Test of the Earthquake Gap Hypothesis in Mexico: The Case of the Guerrero Gap. **Husker, A.**, Werner, M. J., Bayona, J. A., Santoyo, M. A., Corona-Fernandez, R.	Evolution of Short-Term Seismic Hazard in Alberta, Canada, From Induced and Natural Earthquakes: 2011–2022. **Reyes Canales, M.**, Yusifbayov, J., van der Baan, M.	A Nonergodic Ground-Motion Model for Japan. **Zengin, E.**, Abrahamson, N. A.
11:30 AM	Quantifying Site Amplification for Seismic Hazard in a Complex Shallow Basin: Case Study of the Wellington Basin, New Zealand. **Kaiser, A. E.**, Manea, E., de la Torre, C. A., Hill, M., Wotherspoon, L., *et al.*	STUDENT: Using Multi-Resolution Grids and MCC-F1 Curve to Improve Aftershock Forecast Testability. **Khawaja, M.**, Asayesh, B. M., Hainzl, S.	Lessons Learned From Monitoring of Reservoir Triggered Seismicity in Tectonically Stable and Seismically Active Areas of Vietnam. **Lizurek, G.**, Leptokaropoulos, K., Staszek, M., Nowaczyńska, I., Tymińska, A.	Development of Non-ergodic Ground-Motions Model for Induced Seismicity by Considering Field-Specific Source and Site Effects. **Lavrentiadis, G.**, Oral, E., Asimaki, D.
12:30–2:00 PM	Awards Luncheon and Presidential Address			

Time	*208B*	*208C*	*209A*	*209B*	*209C*
	Subduction Zone Structure From Trench to Arc (see page 1272)	**Understanding Earth Systems with Fiber-optic Cables (see page 1293)**	**Tectonics and Seismicity of Stable Continental Interiors (see page 1277)**	**Opportunities and Challenges for Machine Learning Applications in Seismology (see page 1239)**	**Detecting, Locating, Characterizing and Monitoring Non-earthquake Seismoacoustic Sources (see page 1155)**
10:30 AM	Converted-Wave Reverse Time Migration Imaging in Subduction Zone Settings. **Langer, L.**, Pollitz, F. F., McGuire, J. J.	INVITED: Strategies for Passive DAS Data Analysis at the Edge. **Martin, E. R.**, Issah, A., Tourei, A., Paulus, S., Pearl, B., *et al.*	Seismicity Triggering by Stress Transfer of Recent Strong (M>6.0) Earthquakes in Greece. **Papadimitriou, E.**, Karakostas, V.	Pickblue: Seismic Phase Picking for Ocean Bottom Seismometers With Deep Learning. Bornstein, T., Lange, D., Münchmeyer, J., Woollam, J., **Rietbrock, A.**, *et al.*	Landslide Monitoring with a Local Infrasound Array in Barry Arm, Alaska. **Lyons, J. J.**, Collins, B., Haney, M., Staley, D., Toney, L.
10:45 AM	Multi-Resolution Imaging the Downdip Extent of the Subduction Megathrust. **Abers, G. A.**, Daly, K. A., Mann, M. E.	STUDENT: Fiber-Optic Monitoring of the Vadose Zone. **Yang, Y.**, Shen, Z., Fu, X., Adams, K. H., Zhan, Z.	Seismicity and Seismotectonics in the Kefalonia Transform Fault Zone (KTFZ), Greece. **Karakostas, V.**, Papadimitriou, E.	STUDENT: Phasehunter: Seismic Wave Onset Time Determination Through Probabilistic Deep Learning Regression. **Novoselov, A.**, Williams, J., Beroza, G. C., Pace, J.	The Land, Air, and Water Signature of Large Calving Events at Barry Glacier, Alaska. **West, M. E.**, Davy, G., Gridley, J., Haney, M., Johnson, P., *et al.*
11:00 AM	STUDENT: The Comparison of Depth-Dependent Seismic Azimuthal Anisotropy Beneath Alaska-Aleutian and Cascadia Subduction Systems. **Liu, C.**, Wu, M., Zhang, S., Sheehan, A. F., Ritzwoller, M. H.	Lighting Up Down Under: Passive Imaging of Urban Melbourne Shallow Subsurface Using Distributed Acoustic Sensing. **Lai, V.**, Miller, M. S., Jiang, C., McQueen, H.	Did You Feel It 50 Years Ago? the 1969 M7.9 Cape Saint Vincent Earthquake. Marreiros, C., Alves, P., Carrilho, F., Oliveira, C. S., **Custodio, S.**	INVITED: STUDENT: Calibrated Uncertainty Estimates for Deep Learning-Based Phase Arrival Time Estimates. **Armstrong, A. D.**, Baker, B., Koper, K. D.	STUDENT: An Unsupervised Machine-Learning Approach to Understanding Seismicity at an Alpine Glacier. **Sawi, T. M.**, Holtzman, B. K., Walter, F., Paisley, J.
11:15 AM	Imaging the Rivera and Cocos Plates Shape in Western Mexico From Local Seismicity Studies. **Nunez-Cornu, F. J.**, Suarez-Plascencia, C., Nuñez, D.	STUDENT: Near-Surface Characterization Using Distributed Acoustic Sensing and Ambient Seismic Noise in an Urban Area: Granada, Spain. **Li, Y.**, Spica, Z., Perton, M., Gaite, B., Ruiz-Barajas, S.	STUDENT: Revealing Activate Fault Structures in the Slow-Deforming Region of Iberia by Applying Deep Learning Techniques to Dense Seismic Recordings. **Neves, M.**, Peng, Z., Custódio, S., Chai, C., Maceira, M.	Ditingtools and Ditingbox: Seismic Big Data Processing via Edge and Cloud Computing. Zhao, M., Xiao, Z., Chen, S., **Zhang, M.**, Zhang, B.	Using Seismoacoustic Modeling to Infer Source Parameters of the 2020 Beirut Explosion. **Burgos, G.**, Guillot, L., Gainville, O., Vergoz, J.
11:30 AM	Physical Properties of the Mantle Beneath Patagonia From Surface and Body Wave Tomography. **Ben Mansour, W.**, Wiens, D. A.	STUDENT: Love Wave Ambient-Noise Imaging of Urban Subsurface Velocity Structures: Exploiting the Potential of Horizontally Orthogonal DAS Array. **Ji, Q.**, Luo, B., Biondi, B.	The 2022-23 Reno, Northern Alberta Earthquake Sequence. Kao, H., **Bent, A. L.**, Mayeda, K., Roman-Nieves, J. I., Cassidy, J. F.	Neural Mixture Model Association of Seismic Phases. Ross, Z. E., **Zhu, W.**, Azizzadenesheli, K.	Single-Channel Infrasound Detection Using Machine Learning. **Albert, S. A.**, Hale, J., Pankow, K. L.
12:30–2:00 PM	Awards Luncheon and Presidential Address				

Time	202B/C	203	204	208A
	ShakeMap-related Research, Development, Operations, Applications and Uses (see page 1257)	**Exploiting Explosion Sources: Advancements in Seismic Source Physics (see page 1185)**	**Understanding and Managing Induced Seismicity (see page 1284)**	**Advances in Probabilistic Seismic Hazard Analysis and Applications (see page 1121)**
2:00 PM	ShakeMap: An Update. **Worden, C. B.**, Engler, D. T., Thompson, E. M., Wald, D. J.	STUDENT: Joint Regional Waveform, First Motion Polarity, and Surface Displacement Inversion Using a Layered Elastic Model With Topography for North Korean Nuclear Explosions. **Chi-Duran, R.**, Dreger, D. S., Rodgers, A. J.	INVITED: Fluid Injection Induced Seismic and Aseismic Slip From a Coupled Poroelastic Stress Change and Rate-State Fault Model. **Liu, Y.**, Deng, K., Verdecchia, A., Harrington, R.	Why Does PSHA Overpredict Historically Observed Shaking Data? **Salditch, L.**, Gallahue, M., Neely, J. S., Stein, S., Abrahamson, N. A., *et al.*
2:15 PM	Dynamic Generation of Shaking Maps for Post-Event Response in New Zealand. **Kaiser, A. E.**, Horpool, N., Goded, T., Chadwick, M., Charlton, D., *et al.*	An Overview of the Rock Valley Direct Comparison Project. **Walter, W. R.**, Snelson, C. M., Abbott, R. E., Zeiler, C.	Combining 3D Dynamic Rupture Modeling and Thermo-Hydro-Geomechanical Modeling Towards Physics-Based Induced Earthquake Simulations. **Ulrich, T.**, Habibi, R., Gabriel, A., *et al.*	INVITED: The First National Earthquake Risk Model for Switzerland. **Wiemer, S.**, Marti, M., Papadopoulos, A., Danciu, L.
2:30 PM	Shakemap-Eu: A European Seismological Service and a Laboratory for Collaborative Research and Capacity Building. **Faenza, L.**, Cauzzi, C., Michelini, A., Lauciani, V., Clinton, J., *et al.*	Evaluating the Efficacy of Inverting Local-Scale, High Frequency Seismograms for Effective Source Mechanisms Using Various Source Assumptions. **Poppeliers, C.**	STUDENT: Modelling Induced Seismicity in the Hengill Geothermal Field. **Ritz, V. A.**, Rinaldi, A. P., Mizrahi, L., Kristjánsdóttir, S., Castilla, R., *et al.*	Characterizing Seismic Risk Across Canada. **Hobbs, T. E.**, LeSueur, P., Journeay, J. M.
2:45 PM	ShakeMap4-Web: Visualizing the ShakeMap4 Products Using a Web App. **Jozinović, D.**, Lauciani, V., Bruni, S., Faenza, L., Michelini, A.	Implications of Local Wave Propagation Effects on the Performance of P/S Source Discriminants Using High-Frequency Simulations of a Chemical Explosion and Small Earthquake. **Pitarka, A.**, Walter, W. R., Pyle, M. L.	STUDENT: Deep Learning Phase Pickers: How Well Can They Detect Induced Seismicity? **Lim, C.**, Lapins, S., Segou, M., Werner, M. J.	Uses and Misuses of the Frequency-magnitude Distribution of Earthquakes. **Wyss, M.**
3:00 PM	INVITED: Migrating Global ShakeMap to the Cloud. **Haynie, K. L.**, Hunsinger, H., Hearne, M., Worden, B.	Shallow Soil Response to an Explosion With Geophones and Distributed Acoustic Sensing. **Viens, L.**, Delbridge, B. G.	Shake, Squeeze, and Rumble: Geophone, Hydrophone, and Microphone Observations and Physics of Engineered Geothermal System-Induced Hhz Microearthquakes. **Malin, P. E.**, Leary, P. C., Heikkinen, P. J.	Does the Logic Tree Hide the Forest? Quantifying Uncertainties in Predicted Risk for Individual Model Settings in the Induced-Seismicity Hazard and Risk Analysis of the Groningen Gas Field. **Aben, F. M.**, Osinga, S., Kraaijpoel, D. A., Pluymaekers, M. P. D.
3:15 PM–4:30 PM	Poster Break			

Time	208B	209A	209B	209C
	Structure and Properties of Subducting Slabs and Deep Earthquakes (see page 1269)	**Tectonics and Seismicity of Stable Continental Interiors (see page 1277)**	**Opportunities and Challenges for Machine Learning Applications in Seismology (see page 1239)**	**Detecting, Locating, Characterizing and Monitoring Non-earthquake Seismoacoustic Sources (see page 1155)**
2:00 PM	INVITED: From the Lab to the Slab: Transformational Faulting at High Pressure and Temperature in Fe-Rich Olivine and Implications for Deep-Focus Earthquakes. **Officer, T.**, Xu, M., Yu, T., Dillman, A. M., Kohlstedt, D. L., *et al.*	INVITED: Exploring the Relationship Between Subsurface Structure and Seismicity for the Eastern United States. **Chai, C.**, Ammon, C. J., Maceira, M., Herrmann, R. B.	Semiai Seismic Detection and Picking: An Application to Active and Passive Seismic Data for the Tomography of the Stromboli Volcano Island. **Gammaldi, S.**, Zhuowei, X., Barberi, G., Yang, W., Patanè, D.	Infrasonic Noise From Lava Eruptions at Nyiragongo Volcano, D.R. Congo. Barrière, J., **Oth, A.**, Subira, J., Smets, B., d'Oreye, N.
2:15 PM	STUDENT: Numerical Study on Phase Transformation Induced Material Fracture. **Sindhusuta, S.**, Chi, S., Foster, C.	Fault Reactivation Potential in Intraplate North America, From Major Seismic Zones to 3D Gravity Imaging of the Sparta, NC Epicentral Zone. **Levandowski, W.**	STUDENT: Developing a Seismicity Catalog at Mayotte With Deep-Learning-Based Picking and Phase Association. **McBrearty, I. W.**, Retailleau, L., Beroza, G. C.	End-to-End Numerical Simulation of a Bolide's Reentry, Impact, Cratering, Fireball and Cloud Generation: Local and Global Consequences. **Ezzedine, S. M.**, Syal, M., Dearborn, D., Miller, P.
2:30 PM	INVITED: A Weak Subducting Slab at Intermediate Depths Below Northeast Japan. **Delbridge, B. G.**, Houston, H., Burgmann, R., Kita, S., Asano, Y.	INVITED: The 2020 Mw 5.1 Sparta, North Carolina, USA Earthquake: Surface Deformation and Paleoseismicity of the Little River Fault. **Figueiredo, P. M.**, Bohnenstiehl, D. R., Merschat, A. J., *et al.*	Magma Movement Revealed by Unsupervised Spectral Feature Characterization of Seismicity at Axial Seamount. **Wang, K.**, Waldhauser, F., Tolstoy, M., Wilcock, W., Sawi, T. M., *et al.*	The Upcoming Re-Entry of the Osiris-Rex Return Capsule: Plans for a Coordinated Seismo-Acoustic Observational Campaign. Silber, E. A., **Albert, S. A.**, Berg, E. M., Bowman, D. C., Dannemann Dugick, F. K.
2:45 PM	Subduction Zone Events Around Japan and Wavefield Anomalies - Structure Beyond Tomography. **Kennett, B. L. N.**, Furumura, T.	Seismic Quiescence in the Rome Trough: Implications for Earthquake Potential and Crustal Structure. **Carpenter, S.**, Bubeck, A., Hickman, J. B., Schmidt, J. P., Wang, Z., *et al.*	Medium Changes and Source Diversity Revealed by Unsupervised Machine Learning. Steinmann, R., Seydoux, L., Shapiro, N., **Campillo, M.**	STUDENT: Feature Engineering and Clustering for Single-Station Seismic Waveform Classification in an Urban Environment. **Thomas, A.**, Ranadive, O., van der Lee, S.
3:00 PM	STUDENT: Influence of a Dipping Anisotropic Slab on Shear Wave Splitting in Japan. **Appini, S.**, Creasy, N., Thomsen, L., Zheng, Y.	Analyses of Balanced Rocks to Constrain Ground Motions in the Eastern U.S. **Pratt, T. L.**, McPhillips, D., Lindberg, N. S.	Mutual Information Between Seismic and Geodetic Data Revealed with Machine Learning in Mexico. **Seydoux, L.**, Steinmann, R., de Hoop, M. V., Campillo, M.	Development of a Cots-Based Platform for Real-Time Seismic and Acoustic Vehicle Detection and Characterization. **Marcillo, O.**, Chai, C., Maceira, M.
3:15 PM–4:30 PM	Poster Break			

Time	202B/C	203	208A
	ShakeMap-related Research, Development, Operations, Applications and Uses (see page 1257)	**Exploiting Explosion Sources: Advancements in Seismic Source Physics (see page 1185)**	**New Observations and Modeling of Triggered Seismicity (see page 1231)**
4:30 PM	INVITED: STUDENT: Aggregate Behavior Analysis of Ground Motion Distributions and Their Effects on Loss Estimation. **Engler, D. T.**, Jaiswal, K., Ganesh, M.	Seismic Source Characterization and Screening for Three Large Mining Events in Sweden, Northwest Russia, and the Eastern United States. **Alvizuri, C. R.**, Kvaerna, T., Dando, B.	Observations of Triggering of Earthquakes and Tremor in Mexico by Remote Earthquakes. **Gonzalez-Huizar, H.**, Velasco, A. A.
4:45 PM	Developing and Implementing an International Macroseismic Scale (IMS) for Earthquake Engineering, Earthquake Science, and Rapid Damage Assessment. **Wald, D. J.**, Goded, T., Hortacsu, A., Loos, S., Spence, R.	Seismic Characterization of the Explosive Subevents in the 2022 Hunga-Tonga Volcanic Eruption Using Joint Moment Tensor Inversion. **Thurin, J.**, Tape, C.	Earthquake Triggering in the Context of 2019 Ridgecrest Earthquake Sequence. **Ghosh, A.**, Zhou, Y.
5:00 PM	STUDENT: Real-Time Ground Shaking Maps Reconstructions With a Hybrid ShakeMap Implementation. **Fornasari, S.**, Pazzi, V., Costa, G.	Examination of the Debate on the 12 May 2010 Low-Yield Nuclear Test. **Zhang, M.**, Wen, L.	Sea level Changes Affect Seismicity Rates in a Hydrothermal System Near Istanbul. **Martínez-Garzón, P.**, Beroza, G. C., Bocchini, G., Bohnhoff, M.
5:15 PM	Ground Motion Processing Software at the U.S. Geological Survey: New Collaborations and Contributions. **Thompson, E. M.**, Aagaard, B. T., Hearne, M., Ferragut, G., Parker, G. A., *et al.*	Theoretical Investigations of Earth- and Sea-Earth Coupled Very-Long Period Atmospheric Waves. **Okal, E. A.**	STUDENT: New Insights From Two 2022 Large Magnitude Earthquake Events Occurring Closely in Space and Time in Abra, Northern Philippines. Aurelio, M. A., **Catugas, S. A.**, Dianala, J. B., Ramirez, A. G., Lagmay, A. A.
5:30 PM	U.S. Geological Survey's ShakeMap Atlas 4.0 and AtlasCat. **Marano, K. D.**, Hearne, M., Jaiswal, K., Thompson, E. M., Worden, C. B., *et al.*	Influence of Model Perturbation on Regional Ground Motions – a Numerical Experiment. **Saikia, C. K.**, Zhou, R., Whittaker, S., Antolik, M., Modrak, R., *et al.*	Earthquakes in the Shadows: Why Aftershocks Occur in Surprising Locations. **Hardebeck, J. L.**, Harris, R.
6–7 PM	Joyner Lecture		
7–8 PM	Joyner Reception		

Time	*208B*	*208C*	*209A*	*209B*
	The Future of Tsunami Science, Preparedness and Response (see page 1205)	**Above the Seismogenic Zone: Fault Damage and Healing in the Shallow Crust (see page 1107)**	**Tectonics and Seismicity of Stable Continental Interiors (see page 1277)**	**Opportunities and Challenges for Machine Learning Applications in Seismology (see page 1239)**
4:30 PM	The Potential for Sediment Transport During Earthquake-Tsunami Multi-Hazards. **Mason, B.**, Qiu, Y.	INVITED: Modeling the Viscoplastic Deformation of Damaged Rocks Using a Perzyna Viscoplasticity Law. **Sone, H.**, Talukdar, M.	Long-Lived Aftershocks in the New Madrid Seismic Zone and the Rest of the Stable North America. **Liu, M.**, Chen, Y.	STUDENT: Pisgan: Physics-Informed Seismic Waveform Generator Trained With a Large-Scale Seismic Benchmark Dataset of China. **Kang, B.**, Gu, C., Zhong, Y., Wu, P., Lu, X.
4:45 PM	History and Future of Tsunami Warning System: Toward Timely, Accurate and Reliable Systems. **Satake, K.**	STUDENT: Spatiotemporal Variations in Shallow Damage Zone Mechanisms Along the Southern Elsinore Fault. **Fullriede, A.**, Gaston, H., Griffith, A., Rockwell, T.	Machine-Learning Detection and Waveform Correlation to Probe New Madrid Seismogenesis. **DeShon, H. R.**, Walter, J., Nuepane, P., Ng, R.	INVITED: Rapid 3D Seismic Waveform Modeling using U-Shaped Neural Operators (U-NO). **Kong, Q.**, Rodgers, A. J., Yan, Y., Ross, Z. E., Azizzadenesheli, K., *et al.*
5:00 PM	Sensor Monitoring and Reliable Telecommunications (SMART) Cables: Integration of Environmental Sensors Into Submarine Telecommunications Cables for Improved Tsunami Science and Response. **Fouch, M. J.**, Lentz, S., Avenson, B.	INVITED: STUDENT: High-Resolution Fault Zone Imaging With Distributed Acoustic Sensing. **Atterholt, J.**, Zhan, Z., Yang, Y., Zhu, W.	Update on the Seismicity and Tectonics of the 2021-2022 Elgin-Lugoff, South Carolina Earthquake Sequence. **Jaume, S.**, Howard, S., White, S.	Ground Motion Models: Comparison Between Traditional Regression-based Techniques and Machine Learning Approaches. **Luzi, L.**, Felicetta, C., Lanzano, G.
5:15 PM	Caribe Wave: A Decade of Tsunami Exercises for Validating the Tsunami Warning System for the Caribbean and Adjacent Regions. **Soto, S.**, von Hillebrandt-Andrade, C., Vanacore, E. A., *et al.*	STUDENT: Inferring Fault Zone Structure from the Azimuthal Variation in the Stacked P-spectra of Earthquake Clusters. **Neo, J.**, Huang, Y., Yao, D.	High-Resolution Imaging of the Elgin-Lugoff Earthquake Swarm Sequence in South Carolina Using a Dense Seismic Nodal Array. **Peng, Z.**, Chuang, L. Y., Mach, P., Frost, D., *et al.*	Applications of Machine Learning to Earthquake Early Warning and Ground Motion Prediction Equations. **Chan, C.**, Chang, C., Chang, C.
5:30 PM	Analyzing Behavioral Responses Caught on Video to the Hunga Tonga–Hunga Haʻapai Eruption, Atmospheric Shockwaves, and Tsunami. **McBride, S. K.**, Sumy, D. F., Krippner, J., Santos Hernandez, J., Damby, D., *et al.*	Do Faults Localize as They Mature? Insight From 17 Continental Strike-slip Surface Rupturing Events ($M_w > 6.1$) Measured by Optical and Radar Imaging Data. **Milliner, C. W. D.**, Avouac, J., Aati, S., Dolan, J., Hollingsworth, J.	Exploring Rupture Models for the 1 September, 1886, Charleston, South Carolina, Earthquake. Bilham, R., **Hough, S. E.**	Fully Automated DAS Signal Denoising Using Weakly Supervised Machine Learning and Spliced Optical Fibers. Lapins, S., Butcher, A., **Werner, M. J.**, Kendall, J., Hudson, T., *et al.*
6–7 PM	Joyner Lecture			
7–8 PM	Joyner Reception			

Poster Sessions

Above the Seismogenic Zone: Fault Damage and Healing in the Shallow Crust [Poster] (see page 1108)

71. Student: A New 3-D Model of the Newport-Inglewood Fault at Long Beach, California, and Its Implication for Earthquake Rupture Propagation and Hazards. **Toghramadjian, N.**, Shaw, J. H.
70. An Experimental Perspective on the Formation of Pulverized Rocks During Transient Coseismic Dilatancy. **Griffith, A.**, Smith, Z. D.
72. Combining Dark Fiber and Seismic Interferometry to Measure Physical Properties of Faults in the Imperial Valley. **Matzel, E.**, Templeton, D., Morency, C., Ajo-Franklin, J.
74. Investigating the Causative Mechanisms of Widely Distributed Fracturing Around the 2020 m6.5 Monte Cristo Range Earthquake Rupture, Nevada USA. **Elliott, A. J.**, Hatem, A. E., Trexler, C., Koehler, R., Dee, S., *et al.*
73. Seismic Identification and Location of Blind, Near-Vertical Faults in Granitic Rocks With Application to Wide-Ranging Geologic Settings. **Catchings, R. D.**, Goldman, M., Chan, J. H., Sickler, R. R., Samuel, D. A.
68. Student: The Competitive Effects of On-fault Normal Stress and Off-fault Seismic Velocity Change on Seismic Cycles. **Zhai, P.**, Huang, Y.
67. The Healing Process and Healing Time Estimate of the Longmenshan Fault After the Wenchuan Earthquake. **Zhao, J.**, Niu, A.
69. Student: The Palos Verdes Fault Damage Zone From the Seafloor to the Basement: Revealed Using Multi-Resolution Controlled Source Seismic Reflection Datasets. **Alongi, T.**, Brodsky, E. E., Kluesner, J. W., Brothers, D. S.

Detecting, Locating, Characterizing and Monitoring Non-earthquake Seismoacoustic Sources [Poster] (see page 1158)

78. Explosive Energy Release of Gas Emission Craters in the Russian Arctic and Their Associated Seismic Magnitudes: Estimates and Implications. **Carr, C. G.**, Carmichael, J. D.
80. Full Moment Tensor and Source Characteristic of Remote Nuclear Explosions at the Lop Nor Test Site, China. **Kintner, J.**, Modrak, R., Nelson, P., Saikia, C. K.
77. Monitoring Vehicle Traffic With Seismoacoustic Data Using Machine Learning. **Chai, C.**, Marcillo, O., Maceira, M., Park, J., Arrowsmith, S., *et al.*
82. Near-regional to Local Event Location Using Infrasound Arrival Times From Single Sensors. **Koch, C.**, Dannemann, F. K., Berg, E. M.
83. Nonlinear Infrasound Propagation Simulation by Hydrodynamic Models. **Kim, K.**, Vorobiev, O., Vitali, E.
75. Seismic Records of Human Induced Avalanche Signals at Taos Ski Valley. **Ringler, A.**, Schlumpf, M., Anthony, R. E.
79. Seismo-acoustic Observations From the 26 September 2022 Nord Stream Events. **Heyburn, R.**, Selby, N. D., Nippress, A., Green, D. N.
76. Understanding the Relationships Between Seismic Parameters and Landslide Characteristics From the Exotic Seismic Events Catalog. **Collins, E.**, Allstadt, K.
81. Using Dynamic Time Warping to Assist Conventional Waveform Cross-correlation. **Ramos, M. D.**, Tibi, R., Young, C., Emry, E. L., Conley, A. C.

Exploiting Explosion Sources: Advancements in Seismic Source Physics [Poster] (see page 1188)

99. Bayesian Optimal Experimental Design for Seismic and Infrasound Monitoring Networks. **Catanach, T. A.**, Callahan, J. P., Villarreal, R.
87. Comparing Near and Far Field DAS Fiber Response for Monitoring Applications. **Stanciu, A.**, Young, B. A., Poppeliers, C.
88. Developing a Predictive Capability for P-to-S Discriminants. **Alfaro-Diaz, R. A.**
94. Discriminating S-Wave Polarization Angles of Explosive and Earthquake Sources With 2D and 3D Simulations. **Nelson, P.**, Creasy, N.
93. End-to-end Numerical Simulation of Explosion Cavity Creation, Cavity Circulation Processes, Subsurface Gas Transport, and Prompt Atmospheric Releases. **Ezzedine, S. M.**, Velsko, C., Vorobiev, O., Antoun, T., Walter, W. R.
89. Evolution of the Seismic Source From Underground Explosions With Depth-of-burial. **Larmat, C.**, Lei, Z., Euser, B., Rougier, E.
96. Gopher 2022: Close-in Signatures From Shallow Explosions in Unconsolidated Environments. **Euler, G. G.**, Baca, E. V., Beardslee, L. B., Boukhalfa, H., Bourret, M., *et al.*
97. High Resolution Imagery of the Source Physics Experiment at Rock Valley. **Matzel, E.**, Pitarka, A., Walter, W. R.
86. Identifying and Characterizing Local Seismicity With a Dynamic Correlation Processor. **Pyle, M. L.**, Aguiar, A. C.
85. Joint Inversion of Seismic and Acoustic Time Series for Time-Variable Source Parameters of the Buried Chemical Explosion at the Source Physics Experiment Phases II: Dry Alluvium Geology. **Berg, E. M.**, Poppeliers, C.
98. Quantifying the Impact of Modeling Uncertainty on the Performance of Waveform-Based Bayesian Inference for Seismic Monitoring. **Catanach, T. A.**, Villarreal, R.
92. Simulations and Predictions of the Source Physics Experiments Phase III (RVDC): Impact on Explosion

Monitoring & Discrimination. **Ezzedine, S. M.**, Vorobiev, O., Walter, W. R., Wagoner, J., Antoun, T.

95. Thermochemical Modeling of a Series of Cavity-Decoupled Explosions at the Nevada National Security Site. **McClurg, M. S.**, Euler, G. G., Bradley, C. R.
84. Student: Time-Varying Source Processes of the Source Physics Experiment Explosions. **Pippin, J. E.**, Kintner, J., Cleveland, M. K., Ammon, C. J., Modrak, R., *et al.*
91. Transportable Absolute Yields of Underground Nuclear Explosions. **Delbridge, B. G.**, Phillips, S., Kintner, J., Carmichael, J. D.
90. Update on an Automated Method to Improve Seismic Array Observations. **Rowe, C. A.**, Stanbury, C. W., Webster, J. D., Gammans, C. N. L.

The Future of Tsunami Science, Preparedness and Response [Poster] (see page 1206)

1. Empowering Young People in Haiti to Play Key Roles in Disaster Risk Reduction. **Mentor-William, G.**, Previl, W., Pierre, J., Dévilmé, G., Stenner, H., *et al.*
5. Expedited Tsunami Warning Alerts Along the US West Coast Using Earthquake Early Warning Tools. **Williamson, A. L.**, Allen, R. M.
9. Implementing Tsunami Ready: An Overview of the Community Awareness and Preparedness Program in the Caribbean and Adjacent Regions. Bayouth García, D., **von Hillebrandt-Andrade, C.**, Soto, S., Brome, A., Aliaga, B.
7. Integrating Volcanic Sources into the Tsunami Warning System for the Caribbean and Adjacent Regions. **von Hillebrandt-Andrade, C.**, Clouard, V., Sostre-Cortés, J. J., Vanacore, E. A., Angove, M., *et al.*
6. Korea Meteorological Administration's Tsunami Forecast and Early-warning System Improvements for Tsunami Preparedness. **Lee, H.**, Jo, T., You, S., Lee, J., Hwang, E., *et al.*
3. Ongoing Work by a Powell Center Working Group on Tsunami Sources for Hazards Mitigation in the United States. **Ross, S. L.**, Eble, M. C., Kyriakopoulos, C., Lynett, P. J., Nicolsky, D. J., *et al.*
8. Operationalization of Koeri Tsunami Warning System in the Eastern Mediterranean and Its Connected Seas: A Decade of Achievements and Challenges. **Ozener, H.**, Cambaz, M., Turhan, F., Güneş, Y., Deniz Hisarlı, P., *et al.*
2. State of California's Third Generation Tsunami Hazard Maps for Emergency Response Planning. **Graehl, N. A.**, Bott, J., Patton, J. R., Wilson, R. I., LaDuke, Y., *et al.*
10. Transforming Research Into Resiliency: The Intersection of Science and Emergency Management in Tsunami Preparedness, Mitigation, Education, and Response Efforts in Washington State. **Tappero, E.**, DiSabatino, D., Dixon, M.
4. Tsunami Sources in the Caribbean and Eastern US. **Powell Center Working Group on Tsunami Sources**.

New Methods and Models for More Informative Earthquake Forecasting [Poster] (see page 1230)

106. Investigating the Fault Slip Behavior of an Extensional Faults System Through the Use of a Novel 3D Stochastic Declustering Algorithm: The Alto Tiberina Fault Case Study. **Murru, M.**, Console, R., Montuori, C., *et al.*
104. Real Time Gutenberg-Richter b-Value Estimation for an Ongoing Seismic Sequence: An Application to the 2022 Marche Offshore Earthquake Sequence (Ml 5.7 Central Italy). **Spassiani, I.**, Taroni, M., Murru, M., Falcone, G.
105. Time Series Analysis From a High-Definition Italian Catalog: Seismicity Rates and Gutenberg-Richter b-Value Evaluation. **Falcone, G.**, Pastoressa, A., Murru, M., Taroni, M., Console, R., *et al.*

New Observations and Modeling of Triggered Seismicity [Poster] (see page 1232)

101. Instantaneous and Delayed Triggering of Tremor Along the Parkfield-Cholame Section of San Andreas Fault. **Peng, Z.**, Shelly, D. R., Taira, T., Meng, H., Aiken, C., *et al.*
102. Remote Dynamic Triggering of Intermediate-Depth Earthquakes in the Mariana Subduction Zone Following the 2012 Indian Ocean Earthquakes. **Price, A.**, Wiens, D. A.
100. Step-Like Motion Associated With Near-Source ScS Phase From the 2011 Tohoku-Oki Earthquake: Potential Triggering by ScS. **Park, S.**, Kanamori, H., Rivera, L.
103. Strong-Motion Records of the M6.4 Ferndale Earthquake on 20 December 2022 and Its Aftershocks. **Haddadi, H.**, Hagos, L., Schleicher, L. S., Dhar, M., Steidl, J., *et al.*

Opportunities and Challenges for Machine Learning Applications in Seismology [Poster] (see page 1242)

125. A Curated Pacific Northwest Seismic Dataset. Ni, Y., Hutko, A., Skene, F., **Hartog, R.**, Denolle, M. A., *et al.*
133. Student: A Dataset of Regional Earthquake Waveforms. **Aguilar, A. L.**, Beroza, G. C.
126. Automatic Seismic Monitoring Using Regional and Local Temporary Networks in Colombia. Castillo, E., **Prieto, G. A.**
129. Classifying Central and Eastern U.S. Seismic Events in the Earthscope Database Using Machine Learning and Lg-Wave Spectral Ratios. **Schmidt, J. P.**, Carpenter, S., Wang, Z.

119. Comparative Study of the Performance of Seismic Waveform Denoising Methods. **Tibi, R.**, Young, *. J., Porritt, R. W.
128. Earthquake Detection in Subduction Zones: Transfer Learning With Amphibious Data From the Alaska Amphibious Community Seismic Experiment. **Barcheck, G.**, Abers, G. A., Roland, E., Schwartz, S. Y.
124. Effective U.S. Event Classification Through Model Ensembling. **Linville, L.**
130. Employing Machine Learning Pickers for Routine Global Earthquake Monitoring With SeisComP: What are the Benefits and How Can We Quantify the Uncertainty of Picks? Saul, J., **Tilmann, F.**, Bornstein, T., Münchmeyer, J., Beutel, M.
121. Student: Ensemble Learning for Earthquake Detection and Phase Picking: Methodology and Application. **Yuan, C.**, Ni, Y., Lin, Y., Denolle, M. A.
123. Expanding Wavelet-Transform-Based Neural Network Denoiser Performance Using Utah Regional Data. **Quinones, L. A.**, Tibi, R.
127. Student: Exploring Generalized Relationships Between Rockfalls and Seismograms. **Kharita, A.**
132. Student: Implementation and Testing of EQTransformer to Detect Microseismicity Near the Alpine Fault, South Island, New Zealand. **Pita-Sllim, O. D.**, Townend, J., Chamberlain, C. J., Warren-Smith, E.
131. Latent Representations of Seismic Waves With Self-Supervised Learning. **Clements, T.**, Cochran, E. S., Yoon, C. E., Baltay, A. S., Minson, S.
134. Machine Learning Models for Urban Image Analysis: Building Height Estimation. Ureña-Pliego, M., Martínez-Marín, R., González-Rodrigo, B., **Benito Oterino, M.**, Marchamalo-Sacristán, M.
122. Student: Reconstructing Seismograms via Self-Supervised Learning: Methodology and Applications. **Yuan, C.**, Lin, Y., Denolle, M. A., Shaw, J. H.
120. Seismicity Behavior Within Rock Valley Illuminated by a Dense Nodal Deployment and Machine-Learning Methods. **Pennington, C. N.**, Kong, Q., Walter, W. R.

ShakeMap-related Research, Development, Operations, Applications and Uses [Poster] **(see page 1259)**

62. Proposed Updates to the Finite-Fault Model Depiction for Shakemap Computations. **Goldberg, D. E.**, Wald, D. J., Thompson, E. M., Worden, C. B.
64. Re-Computation of the Mw6.4 on January 7, 2020 Shakemap Using Fault Characterization. Huerfano, V. A., **Rivera, J.**, Torres, M.
63. Shakemap Implementation and Daily Operations in the Puerto Rico Seismic Network (PRSN). Huerfano, V. A., **Torres, M.**, Rivera, J.
65. Shakemap's Sensitivity to Origin Parameters in the Presence of Dense Instrumental Data. **Hutko, A.**, Hartog, R.
66. The USGS Shakecast Application: An Update on Shakemap's Sibling. **Lin, K.**, Wald, D. J.
61. Waveform Benchmarking Comparisons for Selected Earthquake Records Processed With Prism, Sara, and Gmprocess. **Schleicher, L. S.**, Thompson, E. M., Hagos, L., Brody, J., Steidl, J., *et al.*

Site-specific Modeling of Seismic Ground Response: Are We Quantitative Enough to Predict? [Poster] **(see page 1265)**

46. A Bayesian Kriging Approach for Site Period Mapping of Santiago Basin, Chile. **Mitra, D.**
45. Student: Classification of Aleatory Variability and Epistemic Uncertainty for Probabilistic Seismic Hazard Analyses. **Liou, I. Y.**, Abrahamson, N. A.
55. Delineating Shallow Sedimentary Structure of Matanuska and Eagle River Areas, Alaska, by Inversion of Horizontal-Vertical Spectral Ratio From Local Earthquakes. **Dutta, U.**, Zhao, Y., Yang, Z., Holland, J.
54. Determining Shear Wave Velocities at a Deep Sediment Site in the Mississippi Embayment Using Rayleigh Wave Dispersion From Active and Passive Sources. **Farajpour, Z.**, Langston, C. A., Islam, S., Opara, C., Kaip, G. M.
56. Examining Differences in Basin Amplification Between Interface and Intraslab Subduction Sources From the Kanto Region in Japan. **Smith, J.**, Moschetti, M. P., Thompson, E. M.
57. Local Eikonal Tomography Using Ambient Noise Records From a Dense Array of Seismic Nodes Deployed in a Sediment-Filled, Deeply Incised Valley With an Extreme Subsurface Topography (Rhône Valley, Southern France). **Olivar-Castaño, A.**, Ohrnberger, M., Pilz, M., Händel, A., Boué, P., *et al.*
52. mHVSR-Based 3D Modeling of a Late Quaternary Paleovalley System From Italy: Influence of Internal Facies Architecture on Resonance Frequencies and Shear Wave Velocities. **Di Martino, A.**, Sgattoni, G., Amorosi, A.
47. Student: Seismic Hazard Potential in Punjab Province of India Through Site Response Analysis and Its Liquefaction Assessment. **Srivastava, A.**, Nath, S., Madan, J.
53. Site Effects and Soil-Structure Resonance Study in Santo Domingo (East) and Santiago De Los Caballeros (Dominican Republic) Using Microtremors and Active Seismic Sources. **Cordoba, D.**, Germoso, C., Sandoval, S., Montoya, T., Gonzalez, O., *et al.*
50. Student: Site Specific Seismic Hazard, Vulnerability, Risk and Damage Potential Modelling of Bangladesh

With Seismic Hazard Microzonation for the Cities of Dhaka and Chittagong. **Biswas, A.**, Nath, S.

51. Student: Site-Specific Seismic Hazard Assessment of Northeast India Including Bhutan With Special Emphasis on Microzonation Studies of Imphal City. **Madan, J.**, Nath, S., Srivastava, A.
58. Statistical Green's Function Method Based on Spectral and Phase Characteristics Estimated by Generalized Inversion Technique for Japanese Data -Case Simulations for the 2011 Ibaraki-Oki Earthquake and Hypothesized Nankai-Trough Megathrust Event. **Nakano, K.**, Kawase, H.
48. Student: Towards a 3D Geotechnical Model of the Greater Beirut Area for Seismic Ground Motion Prediction. **Safa, M.**, Bertrand, E., Brax, M.
49. What Constitutes Knowledge of "Site Response"? the Embayment Seismic Excitation Experiment 2022 (ESEE2022). **Langston, C. A.**, Kaip, G. M., Farajpour, Z., Islam, S., Opara, C.
59. WUS and CEUS Graizer's Ground Motion Models and Anelastic Attenuation of Response Spectral Accelerations. **Graizer, V.**

Structure and Properties of Subducting Slabs and Deep Earthquakes [Poster] **(see page 1270)**

28. A Micro-Mechanism for the Nucleation of High-Pressure Phases During Transformational Faulting in Olivine. **Wang, Y.**, Shi, F., Officer, T., Yu, T., Xu, M., *et al.*
29. Along-Strike Variation in Aftershock Productivity of Intermediate-Depth Earthquakes in Japan. **Chu, S.**, Beroza, G. C.
27. Complex Martinique Intermediate Depth Earthquake Hints at Early Atlantic Break-Up. Lindner, M., **Rietbrock, A.**, Bie, L., Goes, S.
23. Student: Exploring Remote Triggering of Intermediate-depth Earthquakes in Japan following the 2004 M9.1 Sumatra and 2012 M8.6 Indian Ocean Earthquakes. **Mach, P.**, Zhai, Q., Neves, M., Peng, Z., Obara, K., *et al.*
25. Faulting in Deforming Natural Lherzolite at High Pressure and Temperature: Implications for Intermediate-Depth Earthquakes Generation in the Lower Seismic Zone. **Xu, M.**, Officer, T., Yu, T., Wang, Y.
26. Imaging Ore-Forming Fluids in Porphyry Copper Deposits Using Local Earthquake Tomography. **Comte, D.**, Palma, G., Vargas, J., Calle, D., Peña, M., *et al.*
22. Student: The Magnitude Difference Between Mainshocks and Their Largest Aftershock Increases With Depth for Shallow and Intermediate-Depth Earthquakes Within the Japan Subduction Zone. **Macy, K. P.**, Warren, L. M.
24. Volume Collapse Instabilities in a Phase Transformation Under High Pressure Yield a Double Couple Deep Earthquake Driven by the Pressure. **Markenscoff, X.**

Subduction Zone Structure From Trench to Arc [Poster] **(see page 1274)**

13. Student: Along-Strike Variations in Sub-Arc Melting Beneath the Alaska Peninsula. **Zhang, Z.**, Wei, S.
14. Student: Earthquake clustering and statistics at the Alaska Peninsula. **Jie, Y.**, Wei, S., Zhu, W.
18. Imaging the Marine Forearc Structure of the 2014 Iquique Earthquake Rupture Area Using Passive and Active Sources. **Reyes-Wagner, V.**, Leon-Rios, S., Calle-Gardella, D., Comte, D., Roecker, S., *et al.*
12. Student: Investigating Plate Interface Structure and Potential Splay Fault Geometry in the Southern Mw 9.2 1964 Great Alaska Earthquake Rupture Area Using a Dense Node Array. **Osasona, J. O.**, Worthington, L. L., Barcheck, G., Abers, G. A., Daly, K. A.
21. Student: Mantle Deformation in a Young Mountain Belt: Insights From Shear Wave Splitting in the Greater Caucasus. **Singh, A.**, Sandvol, E. A., Mackey, K., Martinetti, L., Nabelek, J., *et al.*
15. Receiver Function Imaging of the Complex Plumbing System Feeding Mount St. Helens, Washington. **Portner, D. E.**, Delph, J., Kiser, E., Abers, G. A., Levander, A.
20. Student: Seismic Attenuation Imaging in the Central Andes Using Local and Teleseismic Earthquake Spectra: Insights Into Fluid Migration in the South Amerian Lithosphere Above the Pampean Flat Slab. **Navarro-Aranguiz, A. P.**, Comte, D., Roecker, S., Maharaj, A.
16. Seismic Images of the Crustal Structure Beneath Cordillera Central and Cordillera Oriental, Dominican Republic. Núñez, D., **Córdoba, D.**
19. Seismological and Geodetic Investigations in the Atacama Region of Chile: Investigations of Links Between Plate Interface and Intermediate Depth Processes. González-Vidal, D., Moreno, M., **Tilmann, F.**, Baez, J., Ortega-Culaciati, F., *et al.*
11. Student: Subduction Segmentation Revealed by Full-Wave Ambient Noise Tomography of the Aacse Data. **Sassard, V.**, Yang, X.
17. The HIPER Project: An International Collaboration on the Ecuadorian Margin. Galve, A., **Rietbrock, A.**, Segovia, M., Ruiz, M., Meltzer, A., *et al.*

Tectonics and Seismicity of Stable Continental Interiors [Poster] **(see page 1280)**

36. Australia's AUS8 Seismotectonic Model – A Product of 30 Years of Continuous Improvements of Earthquake Hazard Data, Concepts and Techniques. **Borleis, E.**, Peck, W., Ninis, D.
33. Student: Detection of Seismic Events Near the Southern Anninghe Fault Using a Local Dense Array. **Song, J.**, Yang, H., Zi, J.

30. Student: Investigating the Seismicity of Yucatan, Mexico, Using Machine Learning Techniques. **Castro, J.**, Ortega, R., Gonzalez-Huizar, H., Carciumaru, D. D.
31. Mapping b-Values Based on Background Seismicity in the Korean Peninsula. **Jung, S.**, Son, M.
34. Southwest Australia Seismic Network (SWAN): Recording Earthquakes in Australia's Most Active Seismic Zone. **Miller, M. S.**, Pickle, R., Yuan, H., Zhang, P., Murdie, R., *et al.*
32. Student: Structural Setting and Seismogenesis Mechanism of the 16th September 2021 Luxian Ms6.0 in the Southern Sichuan Basin, China. **Zhang, W.**, He, D.
35. Student: Understanding the Focal Mechanism Distribution of Microseismicity in the Source Region of the 1886 M 7 South Carolina Earthquake. **Adeboboye, O. E.**, Peng, Z., Neves, M., Zhai, Q., Chen, W., *et al.*

Understanding and Managing Induced Seismicity [Poster] (see page 1287)

107. Student: Adaptive Spectrum Analysis for a Precise Attenuation Parameter Estimation on the Induced Seismicity Recorded at Puerto Gaitán (Colombia). **Guzmán, E.**, Molina, I., Prieto, G. A.
108. Student: Controlled-source Seismic Imaging of McMurdo Ice Shelf Near Williams Airfield. **Seldon, Y.**, Karplus, M. S., May, D., Young, T. J., Summers, P., *et al.*
109. Student: Data Mining Microseismicity Associated to the Blue Mountain Geothermal Site. **Gonzalez, L. F.**
110. High-Resolution Induced Earthquake Catalogs Reveal Non-Planar Faults Near Hydraulic Fracturing Wells in Canada and China. **Wang, R.**, Zhang, F., Chen, Y., Yang, D.
111. Induced Seismicity in Southeastern New Mexico. **Rubinstein, J.**, Woo, J.
112. Student: Investigating Complex Triggering in the Midland Basin, Texas, Using Converted Phases. **Rosenblit, J. M.**, De Shon, H., Savvaidis, A.
113. Student: Investigating the Triggering Mechanism of the 2019 Mw 5.0 Earthquake in the Weiyuan Shale Gas Field, China. **Zi, J.**, Yang, H., Su, J.
114. OhioNET: A Decade of Induced Seismicity Monitoring in Ohio. **Dade, S. L.**
115. Optimising Earthquake Detection Methods in Delaware Basin, Southeastern New Mexico. **Basu, U.**, Bilek, S., Litherland, M.
116. Student: Signatures of Congregated Injected Fluid in Weiyuan Shale Gas Field, Sichuan, China. **Abbas, A.**, Hongfeng, Y., Zi, J.
117. Time-Space Evolution of the Groningen Gas Field in Terms of b-Value: Insights and Implications for Seismic Hazard. **Gulia, L.**
118. Student: Variation of Earthquake Nucleation Length of Injection-induced Seismicity Under the (Aging) Rate and State Friction Law. **Tan, X.**, Lui, S.

Understanding Earth Systems with Fiber-optic Cables [Poster] (see page 1295)

43. Student: Constraining Antarctic Ice Sheet Properties using Distributed Acoustic Sensing Data from the South Pole. **Reid-McLaughlin, A. M.**, Karrenbach, M., Zhan, Z., Atterholt, J., Zhai, Q., *et al.*
39. Student: Earthquake Detection Using a Submarine DAS Array in Monterey Bay, California. **Gou, Y.**, Allen, R. M., Chen, L., Taira, T., Henson, I., *et al.*
40. Focal Mechanism Inversion With Distributed Acoustic Sensing. **Li, J.**, Zhu, W., Biondi, E., Zhan, Z.
41. How Close Are We to Integrating Fiber-Optic Distributed Acoustic Sensing in Earthquake Early Warning Systems? **Farghal, N. S.**, Saunders, J. K., Parker, G. A.
37. Student: Imaging Near-Coast Subsurface With Distributed Acoustic Sensing and Double Beamforming. **Miao, Y.**, Spica, Z.
42. Student: Imaging the Subsurface of Long Valley Caldera Through Converted Phases Recorded on a Distributed Acoustic Sensing Network. **Bird, E.**, Zhan, Z., Biondi, E., Zhu, W.
38. Laboratory Study of Coupling and Sensitivity of Optical Fiber Distributed Acoustic Sensing. **Donahue, C.**, Gao, K., Beardslee, L. B.
44. Synthetics for Stress, Strain and Rotation. **Herrmann, R. B.**

Thursday, 21 April 2022—Oral Sessions

Presenting author is indicated in bold.

Time	*202B/C*	*204*	*208A*	*208B*
	Network Seismology: Recent Developments, Challenges and Lessons Learned (see page 1223)	**Crustal Deformation and Seismic Hazard in Western Canada, Cascadia and Alaska (see page 1141)**	**Opportunities and Challenges in Source Modeling for Seismic Hazard Analysis (see page 1246)**	**Coseismic Ground Failure: Advances in Modeling, Impacts and Communication (see page 1138)**
8:00 AM	An Overview and Update on the Advanced National Seismic System (ANSS). **Barnhart, W.**, Wolfe, C.	STUDENT: Examining Possible Links Between Tectonic Tremor and Crustal Earthquakes on the Leech River Fault System in Northern Cascadia. **Bombardier, M.**, Cassidy, J. F., Dosso, S. E.	A New Earthquake Recurrence Model That Better Reflects the Strain Accumulation and Release Processes That Produce Earthquakes. **Neely, J. S.**, Salditch, L., Spencer, B. D., Stein, S.	Post-Earthquake Response Application: A New and Improved Method for Data Collection Using Arcgis Field Maps. **Thomas, K.**, Blair, J., Young, E., Dawson, T.
8:15 AM	ISC: Collaborating with ~150 Seismic Networks. **Storchak, D. A.**, Harris, H., Di Giacomo, D.	Geologic-Geodetic Block Modeling of Northwestern North America for Seismic Hazard Assessment of Western Canada. **Styron, R. H.**, Hobbs, T. E., Journeay, M., Lifton, Z. M., Bennett, S. E. K., *et al.*	Towards Objective Models of Locking on Partially Creeping Faults and Subduction Zones. **Funning, G. J.**	Insights From a New Global Coseismic Landslide Runout Length Dataset. Culhane, N., **Grant, A.**
8:30 AM	Error Estimates for Seismic Body Wave Delay Times in the International Seismological Centre's Bulletin. Nolet, G., **van der Lee, S.**	Geologic Evolution of the Denali Fault System and Associated Crustal Structure. **Miller, M. S.**, Waldien, T., Roeske, S. M.	INVITED: STUDENT: Augmenting Near-Source Probabilistic Seismic Hazard Analysis (PSHA) With North American Crustal Stress Field Data. **Frantzis, C.**, Lundstern, J., Schleicher, L. S., Bensi, M. T.	Updating Global Geospatial Liquefaction Models With a Focus on Feature Engineering. **Zhan, W.**, Baise, L. G., Moaveni, B.
8:45 AM	A One-Stop Shop for Network Status? Developing an Application for a Diverse Set of Users. **Ulberg, C. W.**, Marczewski, K., Hutko, A., Hartog, R.	STUDENT: Distribution and Focal Mechanisms of Incoming Plate Earthquakes Along the Alaska Subduction Zone. **Matulka, P.**, Wiens, D. A.	Accuracy of Finite Fault Slip Estimates in Subduction Zones with Topographic Green's Functions and Seafloor Geodesy. **Langer, L.**, Ragon, T.	STUDENT: Global Geospatial Modeling of Earthquake-Induced Soil Liquefaction Using a System of Voting Machine Learning Classifiers. **Asadi, A.**, Baise, L. G., Chatterjee, S., Zhan, W., Chansky, A., *et al.*
9:00 AM	The Effects of Seismic Network Modernization on Earthquake Detection and Analysis in Southern California. **Tepp, G.**, Stubailo, I., Yu, E., Alvarez, M. G.	Towards Adjoint Tomography of Northern Alaska. **Chow, B.**, Tape, C.	Dynamic Rupture Simulations on the Alpine Fault: Investigating the Role of Fault Geometry on Rupture Size and Behavior. **Lozos, J.**, Warren-Smith, E., Townend, J.	STUDENT: Integrating Regionalized Geotechnical Information Into the U.S. Geological Survey's Liquefaction Product Within a Bayesian Framework. **Engler, D. T.**, Thompson, E. M., Geyin, M., Maurer, B. W., Burgi, P. M., *et al.*
9:15–10:00 AM	Poster Break			

Time	208C	209B	209C
	Active Faults in the Caribbean and Central America (see page 1110)	**Crustal Imaging of High Seismic Hazard Regions (see page 1143)**	**Earthquake Preparation Across Scales: Reconciling Geophysical Observations With Laboratory and Theory (see page 1172)**
8:00 AM	INVITED: Earthquake Magnitude-Frequency Distributions in the Northern Caribbean Plate Boundary Using Combinatorial Optimization. Geist, E. L., **ten Brink, U. S.**	INVITED: Subduction Zone Interface Structure Within the Southern M9.2 1964 Great Alaska Earthquake Asperity: Constraints From Receiver Functions Across a Spatially Dense Node Array. **Onyango, E. A.**, Worthington, L. L., Schmandt, B., Abers, G. A.	What Controls the Characteristics of Compressive Failure and Accelerated Seismic Release? **Davidsen, J.**, Patton, A., Goebel, T. H. W., Kwiatek, G.
8:15 AM	Strain Partitioning Within the Caribbean-North America Transform Plate Boundary in Southern Haiti, Tectonic and Hazard Implications. **Calais, E.**, Symithe, S. J., de Lépinay, B.	3D Crust and Upper Mantle Velocity Structure of India and Surrounding Regions Using Rayleigh Wave Dispersion Analysis. **Dey, S.**, Ghosh, M., Mitra, S.	Complex Multi-Scale Preparatory Processes of Large Stick-Slip Events in Laboratory Experiments. **Kwiatek, G.**, Goebel, T. H. W., Martinez-Garzon, P., Ben-Zion, Y., Dresen, G.
8:30 AM	Earthquake Ruptures on Complex Fault Systems: Insights From Recent and Historical Earthquakes in Haiti. **Hough, S. E.**, Martin, S. S., Symithe, S. J., Briggs, R. W.	Ambient Seismic Noise for Imaging and Monitoring Volcán De Colima. **De Plaen, R. S. M.**, Márquez-Ramírez, V., Arámbula-Mendoza, R., Vargas-Bracamontes, D.	Towards Identifying Fault Heterogeneity Based on Nucleation of Large and Small Events: Insight From Simulations of Earthquake Sequences on Rate-and-State Faults. **Lapusta, N.**, Sudhir, K., Agajanian, M.
8:45 AM	INVITED: Rupture Segmentation of the August 14, 2021 Mw7.2 Nippes, Haiti, Earthquake Using Aftershock Relocation From a Local Seismic Deployment. **Douilly, R.**, Paul, S., Monfret, T., Deschamps, A., Ambrois, D., *et al.*	In Situ Vp/Vs Ratios During the 2019 Ridgecrest Earthquake Sequence. **Lin, G.**, Fan, W.	INVITED: Precursory Deformation in the Lab – Effects of Roughness, Loading Rate and Effective Pressure. **Dresen, G.**, Kwiatek, G., Wang, L., Guerin-Marthe, S., Ji, Y., *et al.*
9:00 AM	Postseismic Response to the 2021 Haiti Earthquake: Advanced Insar Analysis and Implications for the Triggered Fault Creep. **Vajedian, S.**, Maurer, J.	STUDENT: Site Amplification Variability in Yangon, Myanmar Tracked by Regional and Local Seismic Phases From a Dense Nodal Array. **Islam, M.**, Persaud, P., Thant, M., Win, K., Sandvol, E. A.	INVITED: The Seismological Signature of Earthquake Nucleation. **Cattania, C.**
9:15–10:00 AM	Poster Break		

Time	*202B/C*	*204*	*208A*	*208B*
	Network Seismology: Recent Developments, Challenges and Lessons Learned (see page 1223)	**Understanding and Modeling the Uncertainties in Earthquake Ground Motions (see page 1290)**	**Opportunities and Challenges in Source Modeling for Seismic Hazard Analysis (see page 1246)**	**Coseismic Ground Failure: Advances in Modeling, Impacts and Communication (see page 1141)**
10:00 AM	STUDENT: Evaluation of Machine Learning Assisted Earthquake Phase Detection Performance in Different Tectonic Regions and Environmental Noise on the Alaska Seismic Network. **Noel, S.**, West, M. E.	Between and Within-Site Variabilities: How Large Are They? How Far Can We Reduce Them? **Cotton, F.**, Zhu, C., Pilz, M., Haendel, A.	INVITED: Frequency-size Parameters as a Function of Dynamic Range - The Gutenberg-Richter b-Value for Earthquakes. **Geffers, G.**, Main, I. G., Naylor, M.	Determining Coseismic Landslide Hazard Using Regional-Scale Physics-Based Ground-Motion Simulation. **Castro-Cruz, D.**, Dahal, A., Lombardo, L., Tanyas, H., Mai, P.
10:15 AM	Deep Learning-based Detection of Explosions and Earthquakes in South Korea. **Woo, J.**, Park, Y., Ellsworth, W. L.	The Influence of Impedance-Ratio Distributions on 1D Linear Site Response Proxies. **Carpenter, S.**, Wang, Z.	Investigation of Spatiotemporal Variations in the Magnitude Distribution of Induced Seismicity Due to Natural Gas Production in the Groningen Field. **Kraaijpoel, D. A.**, Esteves Martíns, J. C., Osinga, S., *et al.*	STUDENT: Macro-Level Study of Seismically Induced Slope Stability in Kashmir Himalaya. **Sengupta, A.**, Nath, S.
10:30 AM	Routine $M_{w, coda}$ Calculation for Small Earthquakes in Utah. **Whidden, K. M.**, Cordova, A. G., Baker, B., Pankow, K. L., Mayeda, K., *et al.*	Constraining Between-Event Variability of Kinematic Rupture Scenarios: A Case Study of an Mw6.2 Earthquake in Central Italy. **Pacor, F.**, Cejka, F., Sgobba, S., Chiara, F., Valentova, L., *et al.*	Virtual Faults for PSHA. **LaForge, R.**	The Application of a Liquefaction Probabilistic Models to South Italy: A Case Study. **Faenza, L.**, Amoroso, S., Cianflone, G., Cinti, F. R., Dominici, R., *et al.*
10:45 AM	STUDENT: Improving the Detection of Microearthquakes Without Prior Events: Application to Large-N Arrays. **Singha Roy, K.**, Arrowsmith, S.	Physics-Based Broadband Ground Motion Simulations of M6.5 Scenario Earthquakes in Central and Eastern US, Including Surface Topography: Ground Motion Variability Related to Earthquake Rupture Characteristics. **Pitarka, A.**, Rodgers, A. J., *et al.*	STUDENT: PSHA for Lebanon Relying on an Interconnected Fault System. **El Kadri, S.**, Beauval, C., Brax, M., Klinger, Y.	How Do Creeping Landslides Respond to Earthquake Shaking? **Xu, Y.**, Lindsay, D., Burgmann, R., Fielding, E. J.
11:00 AM	The Marsquake Service: Facing Off-World Challenges for Seismic Networks. **Horleston, A. C.**, Clinton, J., Stähler, S. C., Ceylan, S., Giardini, D., *et al.*	STUDENT: Epistemic Uncertainty in Ground-Motion Prediction in the Indian Context: Evaluation of Ground-Motion Models (GMMs) for the Himalayan Region. **Sharma, S.**, Mannu, U., Bora, S.	Revisiting Seismic Hazard in Iran: Role of Stress Drop in Peak Ground Acceleration in a Zone of Immature Faulting. Kamalpour, M., **Salaree, A.**	The Great Alaska Inventory: A Digital Compilation of Ground Failures Triggered by the 1964 Great Alaska Earthquake. **Ellison, S. M.**, Allstadt, K., Thompson, E. M., Martinez, S., Baxstrom, K.
11:30 AM–12:30 PM	Plenary: Machine Learning for Real-time Monitoring (Panel Discussion)			
12:30–2:00 PM	Lunch Break			

Time	208C	209A	209B	209C
	Active Faults in the Caribbean and Central America (see page 1110)	**From Earthquakes to Plate Boundaries: Insights Into Fault Behavior Spanning Seconds to Millennia (see page 1191)**	**Crustal Imaging of High Seismic Hazard Regions (see page 1143)**	**Earthquake Preparation Across Scales: Reconciling Geophysical Observations With Laboratory and Theory (see page 1172)**
	The Societal Cost of Fault Uncertainties in the Caribbean Island of Hispaniola. **Farghal, N. S.**, Velasquez, J.	Strain rates in the Anatolia-Caucasus Region from Sentinel-I InSAR and GNSS, and Integration with Earthquake Catalogues. **Rollins, C.**, Wright, T. J., Maghsoudi, Y., Ou, Q., Lazecky, M., *et al.*	Invited: Seismic Imaging of the Solfatara Volcano (Southern Italy) and Characterization of the Very Shallow Fluids Accumulation Zone. **Gammaldi, S.**, Ismail, A., Amoroso, O., D'Auria, L., Chiuso, T., *et al.*	The Complexity of Earthquake Generation in Nature: Beyond Cascade and Pre-Slip. **Martínez-Garzón, P.**, Poli, P.
10:15 am	Towards an Updated Quaternary Fault Map of Puerto Rico. **Jobe, J. A. T.**, Briggs, R. W., Hughes, K., Joyce, J., Gold, R.	Student: The Coseismic and Long-Term Roles of Earthquake Gates in Strike-Slip Faults. **Rodriguez Padilla, A. M.**, Herrera, V. F., Oskin, M. E., White, S.	3D Mapping of Scattering Attenuation for the Central Italy 2016–2017 Seismic Sequence. **Gabrielli, S.**, Akinci, A., De Siena, L., Del Pezzo, E., Buttinelli, M., *et al.*	Waveform Similarity and Differential Travel Times Illuminate a Spatial Coalescence of Foreshock Activity Prior to Fast Laboratory Earthquakes. **Bolton, C.**, Marone, C., Saffer, D., Trugman, D. T.
10:30 am	Searching for Holocene Slip on the Cerro Goden Fault, Western Puerto Rico. **Turner, J.**, Levandowski, W.	Student: Predicting Off-Fault Deformation Using Convolutional Neural Networks Trained on Experimental Strike-Slip Faults. **Ramos Sanchez, C. F.**, Cooke, M., Chaipornkaew, L., Visage, S., Elston, H., *et al.*	Tomography of Crustal Seismic Attenuation in Switzerland and Surrounding Regions: A New Input for the Next Generation of Seismic Hazard Models. **Lanza, F.**, Diehl, T. C., Eberhart-Phillips, D., Herwegh, M., *et al.*	Spatio-Temporal Localization of Seismicity in Relation to Large Earthquakes. **Zaliapin, I.**, Ben-Zion, Y.
10:45 am	Newly Discovered Tsunami Deposit in Northwest Puerto Rico Supports a Pre-Columbian Megathrust Earthquake on the Puerto Rico Trench That Generated an Atlantic-Wide Tsunami. **Jaffe, B.**, Buckley, M., Watt, S., La Selle, S., Nasr, B. M., *et al.*	Invited: Fault Coupling Controls Fine-Scale Fault Structure and Kinematics Along the San Andreas Fault. **Cheng, Y.**, Bürgmann, R., Allen, R. M.	3D Seismic Attenuation Model: Scattering and Absorption Imaging Beneath the Los Angeles Metropolitan Area. **Nardoni, C.**, Persaud, P.	The Evolving Tidal Sensitivity of the Seismicity Rate in the Decade Before the M7.1 Ridgecrest, California 2019 Earthquake. **Beauce, E.**, Poli, P., Waldhauser, F., Holtzman, B. K., Scholz, C.
11:00 am	A Pre-Colombian Tsunami in Lesser Antilles ? Identification of the Source Using Sediment Deposits and Tsunami Modeling. **Cordrie, L.**, Feuillet, N., Gailler, A., Biguenet, M., *et al.*	Interplay of Seismic and Aseismic Slip on the San Andreas Fault Near San Juan Bautista, Central California. **Shaddox, H. R.**, Bürgmann, R., Bilham, R.	Attenuation of the South American Lithosphere. **Pasyanos, M. E.**, Assumpção, M.	Testing Earthquake Nucleation Length Scale in North-Central Oklahoma With Pawnee Aftershocks. **McLaskey, G.**, Wu, B. S.
11:30 am–12:30 pm	Plenary: Machine Learning for Real-time Monitoring (Panel Discussion)			
12:30–2:00 pm	Lunch Break			

Time	*202B/C*	*204*	*208A*	*208B*
	Earthquake Early Warning Optimization and Efficacy (see page 1166)	**Understanding the Variability in Earthquake Stress Drop Measurements (see page 1297)**	**Constraining Seismic Hazard in the Cascadia Subduction Zone (see page 1133)**	**Deciphering Earthquake Clustering for the Better Understanding of Crustal Deformation Mechanisms (see page 1151)**
2:00 PM	STUDENT: False and Missed Alerts: A Performance Analysis of a Community-Engaged Earthquake Early Warning System. **Chandrakumar, C.**, Prasanna, R., Stephens, M., Tan, M., Holden, C.	Introduction and Update on the International SCEC/USGS Community Stress Drop Validation Study. **Abercrombie, R. E.**, Baltay, A. S., Chu, S., Taira, T.	A Comparison of Foraminiferal and Diatom-Based Transfer Function Estimates of Coseismic Subsidence During the 1700 Ce Earthquake Along the Oregon and California Coast. **Dura, T.**, Hemphill-Haley, E., Cahill, N., Kelsey, H. M., *et al.*	Aftershock Triggering and Spatial Aftershock Zones in Fluid-Driven Settings. **Davidsen, J.**, Karimi, K.
2:15 PM	The Use of Early Earthquake Warning in Hopsitals in Mexico: Safeguarding Vulnerable People. **Vaiciulyte, S.**, Novelo-Casanova, D., Husker, A.	Spectral Scaling Comparison and Validation Between Coda, GIT and Finite Fault Spectra for Ridgecrest, CA (3.3<Mw<6.9). Roman-Nieves, J. I., **Mayeda, K.**, Bindi, D., Morasca, P., Dreger, D. S., *et al.*	STUDENT: Investigating the Earthquake Rupture History of the Northern Cascadia Subduction Zone Using Lacustrine Diatoms, Lake Ozette, Washington, USA. **DePaolis, J.**, Dura, T., Brothers, D. S., Singleton, D., Sherrod, B.	Spatio-Temporal Dynamics of Earthquake Swarms in the Yellowstone Caldera. Angulo, M. V., **Florez, M. A.**, Sanabria-Gomez, J. D.
2:30 PM	Characterizing Earthquake Early Warning's Efficacy. **Wald, D. J.**, McBride, S. K., Reddy, E., Saunders, J. K., Vaiciulyte, S., *et al.*	Multi-scale Analyses of Ridgecrest Earthquake Stress Drop. **Chen, X.**, Yin, J., Pennington, C. N., Wu, Q., Zhan, Z.	Evaluating Turbidite Correlations for Paleoseismology. **Gomberg, J.**	INVITED: STUDENT: Ubiquitous Earthquake Dynamic Triggering in Southern California. **DeSalvio, N. D.**, Fan, W., Barbour, A. J.
2:45 PM	INVITED: Addressing Misconceptions Around Magnitude and Intensity to Inform Earthquake Early Warning Alerting Strategies. **Dolphin, G.**, de Jong, S., Droboth, J., Muturi, E.	INVITED: Assessing the Accuracy of Earthquake Stress Drop Estimation Methods for Complex Ruptures Using Synthetic Earthquakes. **Neely, J. S.**, Park, S., Baltay, A. S.	Searching for Empirical Links Between Shaking and Turbidity Current Generation in the Cascadia Subduction Zone. **Sahakian, V. J.**, Kilb, D., Chaknova, M., Cabrera De Leo, F., Ogston, A., *et al.*	STUDENT: Quantifying Space-time Earthquake Clustering on a Given Fault Network. **Bladis, N.**, Zaliapin, I.
3:00 PM	INVITED: STUDENT: Uses of the Myshake App in Earthquake Early Warning and Rapid Response. **Patel, S. C.**, Marcou, S., Allen, R. M.	Apparent Stress of Moderate Sized Earthquakes in Southern California. **Archuleta, R. J.**, Ji, C., Peyton, A.	Compilation and Assessment of Data Quality for Onshore and Offshore Paleoseismic Proxies of Great Cascadia Megathrust Rupture. **Staisch, L. M.**, Witter, R. C., Watt, J., Grant, A., Walton, M., *et al.*	Anatomy of a Fault Zone: Space-Time-Magnitude Patterns of Microseismicity in the San Jacinto Fault Zone, Southern California. **White, M. C. A.**, Ben-Zion, Y., Vernon, F. L.
3:15 PM–4:30 PM	Poster Break			

Time	208C	209A	209B	209C
	Active Faults in the Caribbean and Central America (see page 1110)	**From Earthquakes to Plate Boundaries: Insights Into Fault Behavior Spanning Seconds to Millennia (see page 1191)**	**Multi-scale Models for Seismic Hazard Analysis (see page 1222)**	**Numerical Modeling in Seismology: Developments and Applications (see page 1234)**
2:00 PM	Late Quaternary Paleoseismological Record of Large Earthquakes in the Lesser Antilles: Implications for Arc Segmentation and Long-Term Seismic Cycle of the Megathrust. **Seibert, C.**, Feuillet, N., Ratzov, G., Beck, C., Morena, P., *et al.*	Untangling Slab Geometry's Influences on the Megathrust Earthquake Cycle. **Biemiller, J.**, Staisch, L. M., Gabriel, A., May, D.	Multi-Scale Imaging of the Ridgecrest Area With Full-Wave Inversion of Regional and Dense Seismic Datasets. **Li, G.**	STUDENT: Modeling Intermittent Rupture in Fault Gouge Using Velocity-Strengthening Rate-and-State Friction with Flash Heating. **Liu, S.**, Lapusta, N., Rubino, V., Rosakis, A.
2:15 PM	20th-Century Interseismic Deformation in the Lesser Antilles Subduction Zone From Coral Microatolls. **Philibosian, B.**, Weil-Accardo, J., Feuillet, N.	Fast Crustal Slip Rates (Vertical and Horizontal) Revealed by Lidar Derived Topography Above the Subducted Chile Ridge, Patagonia. **De Pascale, G. P.**, Perroud, S.	STUDENT: Fusion of Multi-Resolution Seismic Tomography Maps Using Physics-Informed Probability Graphical Models. **Zhou, Z.**, Gerstoft, P., Olsen, K. B.	A Fundamental View on Implementation of the Material Interface in the Finite-Difference Modeling. **Moczo, P.**, Kristek, J., Kristekova, M., Valovcan, J., Galis, M., *et al.*
2:30 PM	General Subsidence of the Lesser Antilles Over a Decoupled Subduction Megathrust. Van Rijsingen, E. M., **Jolivet, R.**, Calais, E., de Chabalier, J., Robertson, R., *et al.*	Piecemeal Rupture of the Central Andes Subduction Zone Megathrust. **Carvajal, M.**, Gubler, A., Cisternas, M., Stewart, D., González, J., *et al.*	Fault Damage Zone Effects on Ground Motions During the 2019 Mw7.1 Ridgecrest, CA, Earthquake. **Olsen, K. B.**, Yeh, T.	Interactions Between Shallow Slow Slip Events and Megathrust Earthquakes Based on 3D Dynamic Earthquake-Cycle Modeling. **Meng, Q.**, Duan, B.
2:45 PM	Analysis and Proposal of Empirical Magnitude Scaling Relationships for Faults Seismic Potential in Central America. **Arroyo Solórzano, M.**, Benito Oterino, M., Alvarado, G. E., Climent, Á.	Coupling and Seismic Cycle Along the Hikurangi Subduction Zone. **Maubant, L.**, Frank, W. B., Wallace, L., Williams, C., Hamling, I., *et al.*	STUDENT: 3-D Broadband Modeling of Near-Field Ground Motions and Deformation in Dynamic Rupture Simulations of the 2019 Ridgecrest Earthquake Including Fault Zone and Fault Roughness Effects. **Schliwa, N.**, Gabriel, A., Ben-Zion, Y.	Three-Dimensional Distributional Finite-Difference Modelling of Elastic Wave Propagation in a Heterogeneous Earth. Masson, Y., **Lyu, C.**, Romanowicz, B. A.
3:00 PM	Potential Shallow Slip and Energy-Deficient Radiation During the 2022 m7.6 Coalcomán, Mexico Earthquake. **Melgar, D.**, Pérez-Campos, X., Ruiz-Angulo, A., Crowell, B. W., Bato, M. G., *et al.*	Deep Transient Deformation and Long-Distance Along-Slab Stress Interactions: The 2013 Seismic Activity and Slow Deformation Beneath Kamchatka and Okhotsk Sea. Rousset, B., Walpersdorf, A., Shapiro, N., **Campillo, M.**	3D Seismic Velocity Model for the Eel River Basin Region and Ground-Motion Simulations for the 2022 Mw6.4 Ferndale, California Earthquake. **Hirakawa, E.**, Graves, R. W., Parker, G. A., Aagaard, B. T.	Effect of Asymmetric Topography on Rupture Propagation Along Fault Stepovers. **Douilly, R.**
3:15 PM–4:30 PM	Poster Break			

Time	*202B/C*	*208A*	*208B*
	Earthquake Early Warning Optimization and Efficacy (see page 1166)	**Constraining Seismic Hazard in the Cascadia Subduction Zone (see page 1133)**	**Deciphering Earthquake Clustering for the Better Understanding of Crustal Deformation Mechanisms (see page 1151)**
4:30 PM	Building out the Earthquake Early Warning sites in the Pacific Northwest Seismic Network - If you build it, you can improve it. **Reusch, M.**	The Role of Transient Deformation in Interseismic Coupling in Cascadia. **Crowell, B. W.**	From Foreshock Outset to Aftershock Decay: High-resolution Analysis of a Recent Earthquake Sequence in the Ecuadorian Subduction Margin. Agurto-Detzel, H., **Rietbrock, A.**, Galve, A., Meltzer, A., Beck, S., *et al.*
4:45 PM	Optimizing Real-Time Gnss-Based Magnitude Estimation for Shakealert. **Murray, J. R.**, Ulberg, C. W., Santillan, M., Crowell, B. W., Melbourne, T. I.	USGS Tsunami Sources Powell Center Working Group on Tsunami Sources: Probabilistic Tsunami Hazard Assessment for the Cascadia Subduction Zone. **Patton, J. R.**, Eble, M. C., Kyriakopoulos, C., Lynett, P. J., Nicolsky, D. J., *et al.*	Linking Fault Roughness at Seismogenic Depths to Earthquake Behavior. **Page, M.**, Cochran, E. S., van der Elst, N., Ross, Z. E., Trugman, D. T.
5:00 PM	Real-Time Gnss Point Positioning for Shakealert. Melbourne, T. I., **Szeliga, W. M.**, Santillan, M., Scrivner, C.	STUDENT: Analyzing Recent Splay Fault Activity in the Cascadia Accretionary Wedge Using High-Resolution Seismic Reflection Data. **Ledeczi, A.**, Tobin, H., Watt, J., Lucas, M.	INVITED: Micro-Seismicity Clustering, Aftershock Decay and b-Values During Laboratory Fracture and Stick-Slip Experiments. **Goebel, T. H. W.**, Kwiatek, G., Davidsen, J., Thapa, N., Dresen, G.
5:15 PM	STUDENT: An Earthquake Early Warning System Validation Framework for Western Canada. **Nye, T.**, Sahakian, V. J., Schlesinger, A., Melgar, D., Babaeimahani, A., *et al.*	Designing or Upgrading a Seismic Network to Meet Specific Performance Criteria Using Array Modeling, a Case Study for Puget Sound Washington State. **Laporte, M.**, Perlin, M.	STUDENT: Why Do We Need New Models of Earthquake Occurrence? **Zaccagnino, D.**, Telesca, L., Doglioni, C.
5:30 PM	Combining Earthquake Early Warning Solutions From Different Algorithms: Application to Switzerland. **Jozinović, D.**, Massin, F., Böse, M., Clinton, J.	Challenges in Assessing Site-Specific Seismic Hazards in Cascadia. **Wong, I. G.**, Gray, B., Wu, Q., Zandieh, A., Bubeck, A., *et al.*	STUDENT: Seismic Magnitude Clustering Is Prevalent in Field and Laboratory Catalogs but Absent in Synthetic Catalogs. **Gossett, D. J.**, Brudzinski, M. R., Xiong, Q., Lin, Q., Hampton, J. C.

Time	*208C*	*209A*	*209B*	*209C*
	It's All About Relocation, Relocation, Relocation (see page 1215)	**From Earthquakes to Plate Boundaries: Insights Into Fault Behavior Spanning Seconds to Millennia (see page 1191)**	**Ground Truthing Multidimensional Site Response Analyses at Borehole Array Sites (see page 1211)**	**Numerical Modeling in Seismology: Developments and Applications (see page 1234)**
4:30 PM	Considerations for Optimally Combining Local, Regional, and Teleseismic Data in Single Event Locations. **Yeck, W. L.**, Shelly, D. R., Patton, J., Earle, P. S., Benz, H. M., *et al.*	INVITED: STUDENT: Assessing Distribution and Pattern of the Earthquake-Related Deformation Caused by Large Continental Normal Earthquakes Using Optical Image Correlation. **Andreuttiova, L.**, Hollingsworth, J., Vermeesch, P., Mitchell, T.	Benchmarking Multidimensional Ground Response Analyses at the Treasure Island Borehole Array Site Using Different Commercial and Open-Source Software. **Hallal, M. M.**, Cox, B., Mohammadi, K., de la Torre, C. A., Stanton, K., *et al.*	Seismic Wave Propagation Finite Difference Simulation Based on Adaptive Mesh Refinement (AMR) Grid. **Zhanng, W.**, Zhang, C., Zang, N.
4:45 PM	How Good Is Your Location? Comparing and Understanding the Uncertainties in Locations of a Sequence of Events in Nevada. **Pyle, M. L.**, Chen, T., Preston, L., Scalise, M. E., Zeiler, C.	Late Pleistocene and Holocene Paleoseismology and Deformation Rates of the Pleasant Valley Fault (Nevada, USA). **Figueiredo, P. M.**, Wesnousky, S. G., Owen, L. A.	Inherent Limitations of One-Dimensional Ground Response Analyses. **Mohammadi, K.**	Seismic Response of Nenana Basin, Central Alaska, From 3D Seismic Wavefield Simulations of Local and Regional Earthquakes. **Tian, Y.**, Tape, C., Chow, B., Smith, K.
5:00 PM	Computation of High-Precision, Deep Magnitude Earthquake Catalogs on a Massive Scale. **Waldhauser, F.**, Wang, K., Beauce, E., Sawi, T. M., Schaff, D. P., *et al.*	STUDENT: Quantifying Seismic Hazards in the Walker Lane Through Assimilation of Spaceborne InSAR Observations. **Rosas, V. G.**, Trugman, D. T., Chen, J.	Ground Truthing Multidimensional Site Response Analyses Using Ls-Dyna. **Stanton, K.**, Rong, W.	STUDENT: Modeling and Simulation of Response Spectra at Regional Distances for the September 19, 2022 (Mw 7.7) and September 22, 2022 (Mw 6.9) Michoacan, Mexico Earthquakes and Comparison With Observed Data. Quirós, L., Santoyo, M. A., **Benito Oterino, M.**, Gamboa Canté, C.
5:15 PM	Manual Correlation of Seismic Arrivals to Improve Hypocenter Locations for the 1993 Rock Valley Sequence in Nevada. **Zeiler, C.**, Scalise, M. E., Smith, K., Chen, T., Phillips, S., *et al.*	Using Dynamic Rupture Simulations to Explore Fault Segmentation and Rupture Length on the Sierra Madre Fault Zone. **Lozos, J.**, Velador Santos, D., Tepal, J.	Quantifying the Influence of Multi-Dimensional Effects in Site Response Analyses Using 2D and 3D Simulations in Sedimentary Basins of Wellington, New Zealand. **de la Torre, C. A.**, Bradley, B. A., Lee, R. L., Kuncar, F., Hill, M., *et al.*	Towards "Box Tomography" of Ultra-Low Velocity Zones at the Earth's Core-Mantle Boundary. **Lyu, C.**, Masson, Y., Zhao, L., Romanowicz, B. A.
5:30 PM	Using Dense Nodal Geophone Data to Refine Rock Valley Fault Zone Earthquake Locations. **Scalise, M. E.**	Towards Decadal Scale Global Geodynamic Models. **Moresi, L.**, Yang, H.	Seismo-Vlab: An Open-Source Finite Element Platform for Site Response Analyses of Km-Scale Features With Random Properties. **Asimaki, D.**, Kusanovic, D., Esmaeilzadeh Seylabi, E.	Crossfade Markov Chain Monte Carlo Simulation for Fault Slip Modeling. **Minson, S.**, Brooks, B., Nevitt, J.

Poster Sessions

Active Faults in the Caribbean and Central America [Poster] (see page 1114)

3. Age Dating and Sedimentology of a Pre-Colombian Tsunami Deposit, Northwest Puerto Rico. **Nasr, B. M.**
5. Student: Imaging of Tectonic Tremor Activity Along the NW Caribbean Coast and its Implication with Subduction Processes: A Study Case with Colombia-Venezuela CARMA Seismological Network. **Cubillos, S.**, Prieto, G. A.
4. Is the Source of the 1918 Puerto Rico Tsunami a Landslide or a Fault Rupture? a View From the Sea Floor. **ten Brink, U. S.**, Chaytor, J. D., Flores, C. H., Wei, Y., Detmer, S., *et al.*
2. New Airborne Magnetic and Radiometric Survey Over Puerto Rico and Surrounding Offshore Areas. **Shah, A. K.**, Pratt, T. L., ten Brink, U. S.
1. Surface Structure of the Punta Montalva Fault in Southwestern Puerto Rico Using High-Resolution Digital Elevation Models. Weilert, L. J., **Laó-Dávila, D. A.**
6. Toward a Multi-Stakeholder Socio-Seismological Observation Network for Seismic Risk Reduction in Haiti. **Calais, E.**

Advances in Probabilistic Seismic Hazard Analysis and Applications [Poster] (see page 1125)

11. A Probabilistic Seismic Hazard Model for Greenland. **Rong, Y.**, Klein, E.
15. Student: Applicability Evaluation of Ground Motion Models (GMMs) for Korean Peninsula. **Lee, H.**, Kim, B.
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9. Effects of the M6.1 Düzce (Türkiye) Earthquake of November 23, 2022 and Seismic Hazard Implications. **Celebi, M.**, Cakir, R., Sozbilir, H.
16. Evaluation of Regional High-Frequency Path Attenuation in Central Mexico Subjected to Subduction Earthquakes and the Potential Impacts on Hazard. Shabestari, K., Mahdyiar, M., **Ruhl, C. J.**, Kraner, M. L., Shen-Tu, B.
20. Geotechnical Field Observations From the 18 September 2022 Mw6.9 Chihshang, Taiwan Earthquake. Asimaki, D., **Mason, B.**, Athanasopoulos-Zekkos, A., Carey, T. J., Garcia, F. E., *et al.*
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32. Student: Imaging the Deformation Belt of Western Hispaniola Using Multi-Component Ambient Noise Cross-Correlations. **Lee, H.**, Rabade, S., Lin, F., Douilly, R.
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71. Three-Dimensional Visualization and Implications for Reconstruction of the Chalk Hill Paleoseismic Site on the Rodgers Creek Fault Near Windsor, California. **Trexler, C.**, Vermeer, J., Hecker, S., Elliott, A. J., Hammer, M.

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91. Student: Absolute Relocations of a Machine Learning Catalog of the Utah Magna Earthquake Sequence Using Nonlinloc-Ssst-Coherence. **Wells, D.**, Lomax, A., Baker, B., Pankow, K. L., Petersen, G.

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117. Seismic Background Noise of Italian Strong Motion Network. **Ertuncay, D.**, Fornasari, S., Costa, G.
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129. Nonlinear Pseudostatic Analysis of Seismic Responses to Differentially Interconnected Structures in Aggregate Masonry Structures in a High-Seismic-Risk. Torres Olivares, S., Gonzalez-Rodrigo, B., Saavedra-Flores, E., Mosquera Feijoo, J., **Benito Oterino, M.**
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61. Estimation of Seismic Hazard in Northern Argentina, Combining Faults and Zones Hazard Estimations (PSHA). Validation of Proximity Factors to Active Faults of the Argentine Seismic Code Inpres-Cirsoc 103. **Benito Oterino, M.**, Fernández Campos, L. M.
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59. Proposal of a New Method for Combining Seismological and Geological Information Aimed at Seimsic Hazard Analysis: Fams Method- Fault and Area Zone Moment Shearing. **Benito Oterino, M.**, Lindholm, C., Gamboa Canté, C., Ornales Agrela, A., Arroyo Solórzano, M.
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60. Student: Review of Hybrid Methods for the Characterization of Seismic Hazard in Central America. Gamboa Canté, C., Ornelas Agrela, A., **Benito Oterino, M.**, Arroyo Solórzano, M., Lindholm, C.
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Abstracts of the Annual Meeting

The 2020-2021 Southwest Puerto Rico Seismic Sequence: Current State of Knowledge and Implications

Oral Session • Tuesday 18 April • 08:00 AM Pacific

Conveners: Gisela Baéz-Sánchez, Puerto Rico Seismic Network, University of Puerto Rico, Mayagüez (gisela.baez1@upr.edu); Victor Húerfano, Puerto Rico Seismic Network (victor@prsnmail.uprm.edu); Stephen K. Hughes, University of Puerto Rico, Mayagüez (kenneth.hughes@upr.edu); James Joyce, University of Puerto Rico, Mayagüez (james.joyce@upr.edu); Daniel A. Laó-Dávila, Oklahoma State University (daniel.lao_davila@okstate.edu); Alberto M. Lopez, University of Puerto Rico, Mayagüez (alberto.lopez3@upr.edu); Margarita Solares-Colón, University of Oregon (msolares@uoregon.edu); Elizabeth A. Vanacore, Puerto Rico Seismic Network, University of Puerto Rico, Mayagüez (elizabeth.vanacore@upr.edu); Christa von Hillebrandt, International Tsunami Information Center, National Oceanic and Atmospheric Administration (christa.vonh@noaa.gov)

A Detailed View of the 2020-2021 Southwestern Puerto Rico Seismic Sequence With Deep Learning

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The still-ongoing 2020-2021 southwestern Puerto Rico seismic sequence is remarkable for its multiple-fault rupture complexity and unusually high aftershock productivity. We applied an automatic workflow to continuous data from 42 seismic stations to build an enhanced earthquake catalog with ~140,000 events for the 2+ year sequence, from 2019-12-28 to 2022-01-01. This workflow included the EQTransformer deep learning model for event detection and phase picking, the EikoNet-HypoSVI probabilistic earthquake location approach with a neural network trained to solve the eikonal wave equation, and relocation with event-pair waveform cross-correlation. EQTransformer increased the number of catalog events in the sequence by ~7 times; EikoNet-HypoSVI event location improved depth estimates. The enhanced catalog revealed how the sequence evolved on a complex system of many small normal and strike-slip faults. This sequence started on 2019-12-28 with a M4.7 strike-slip earthquake, followed by shallow strike-slip M5+ foreshocks in a compact region. The oblique normal-fault M6.4 mainshock then happened on 2020-01-07. Early aftershocks in January 2020, including several M5+ earthquakes, quickly expanded into two intersecting wide fault zones with diffuse seismicity: one extending ~35-km on a northward-dipping normal fault, the other ~60-km-long and oriented WNW-ESE on strike-slip faults. Later aftershocks moved westward, deeper, and to outer reaches of the active fault zones; abrupt rapid seismicity migration followed larger M4.7+ aftershocks in May, July, and December 2020. The observed seismicity space-time evolution indicates cascading failure of stress transfer on multiple critically stressed faults. The high aftershock productivity results from the complex multiple-fault network hosting the sequence, which is characteristic of an immature fault system in the diffuse deformation zone around Puerto Rico at the North American-Caribbean plate boundary region.

Ground Failure Triggered by the 2020 M6.4 Puerto Rico Earthquake

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The mainshock of the Puerto Rico earthquake sequence that started in late 2019, an M6.4 on January 7, 2020, triggered over 300 rock falls and slides that obstructed roads and damaged structures, primarily concentrated where shaking accelerations exceeded 30%g. Shaking from the mainshock also caused liquefaction, cracking, and other ground deformation that damaged homes, a power plant, buildings, and bridges. These impacts occurred primarily in coastal areas where shaking exceeded 50%g but some of the worst liquefaction damage occurred where shaking was as low as 20%g. We present a summary of the ground failure that occurred and its effects on humans and the built environment based on our field campaign and remote sensing observations. We compare ground failure triggered by this earthquake with that from past events in Puerto Rico and other similar environments, and discuss the performance of existing ground failure models for this event and how they can be improved. Detailed inventorying of ground failure from this relatively moderate ground failure event is essential because no geospatial datasets of earthquake-triggered ground failure previously existed for Puerto Rico.

Finding Fault With Earthquakes

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The 2019-2020 seismic sequence brought into to focus the disjunction between geophysical and geological investigations and detailing and recognizing local seismic hazards. Geophysical data and events are real time gathered over 10s of years, geomorphic-tectonic features are near term formed over a few million years or less, whereas geologic structures may have formed even over 10s millions of years. Detailing the seismic hazard requires data on the slip rates of active faults which proved elusive for the Punta Montalva Fault because of climate and low slip rates. Larger scale geomorphic features while useful for recognizing neotectonic activity require time to develop especially where displacement rates are low. The ongoing Guanica-Guayanilla seismic sequence of 2019-20 has provided us with a great opportunity to recognize active fault zones by tracking earthquakes and relating them to faults exposed at the surface. In some cases these seismic fault zones are only recognizable at the surface by faults with orientations that differ significantly with earthquake mechanisms but are still consistent with the overall stress orientations. Not only is the association of earthquakes with surface faults important for scientific investigation it is essential for public communication about earthquake activity. Faults are something real and even visible that the public can relate to and allow us to explain why the earthquakes are occurring. They give us context within a regional tectonic framework about how pieces of our island are moving and why. The Punta Montalva Fault provided that context and something the press and public could relate to.

Insar Measurement of the Coseismic and Postseismic Displacements From the 2020 Southwest Puerto Rico Seismic Sequence

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We analyzed synthetic aperture radar (SAR) images from the Advanced Land Observation Satellite-2 (ALOS-2) satellite operated by Japan Aerospace Exploration Agency and the Copernicus Sentinel-1A and -1B satellites operated by the European Space Agency for the earthquakes near the southwest coast of Puerto Rico from January through July 2020. We use SAR interferometry (InSAR) measurements of displacements in the radar line-of-sight direc-

tions and time-series analysis of the InSAR to improve extraction of coseismic signals. We combine data from different radar look directions to estimate two components of the surface displacement, and we concentrate on the east and vertical components. The large-scale deformation due to slip at depth is dominated by vertical downward motion in and around the Guayanilla Bay with an amplitude of about 20 cm, accompanied by westward motion on the east side and eastward motion on the west side, all consistent with normal fault slip on a generally north-dipping fault plane. InSAR on land does not constrain the strike of the main fault, but the north-west dipping nodal plane of the USGS moment tensor for the main magnitude 6.4 is consistent with the InSAR and is also consistent with relocated hypocenters (HypoDD) of early aftershocks. In addition to the larger displacements likely caused by the magnitude 6.4 mainshock, the ALOS-2 InSAR pair, which spans the time from September 2019 to 20 January 2020, shows that there was fault slip of part of the Punta Montalva Fault between Punta Montalva and Punta Brea. If we assume purely horizontal deformation, the InSAR line-of-sight signal is consistent with 8 cm of left-lateral slip at the surface, during one of the large foreshocks or aftershocks. The longer radar wavelength of ALOS-2 (24 cm) enables InSAR measurements in the more vegetated Punta Montalva-Punta Brea area that is low coherence with Sentinel-1 radar (6 cm wavelength). Additional analysis of Sentinel-1 images acquired between January and June show that the Punta Montalva Fault likely had additional slip at the surface after mid-January that may be related to large aftershocks.

Mature Diffuse Tectonic Block Boundary Revealed by the 2020 Southwestern Puerto Rico Seismic Sequence

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Distributed faulting typically tends to coalesce into one or a few faults with repeated deformation. The progression of clustered medium-sized (≥Mw4.5) earthquakes during the 2020 seismic sequence in southwestern Puerto Rico (SWPR), modeling shoreline subsidence from InSAR, and sub-seafloor mapping by high-resolution seismic reflection profiles, suggest that the 2020 SWPR seismic sequence was distributed across several short intersecting strike-slip and normal faults beneath the insular shelf and upper slope of Guayanilla submarine canyon. Multibeam bathymetry map of the seafloor shows significant erosion and retreat of the shelf edge in the area of seismic activity as well as slope-parallel lineaments and submarine canyon meanders that typically develop over geological time. The T-axis of the moderate earthquakes further matches the extension direction previously measured on post early Pliocene (~>3 Ma) faults. We conclude that although similar deformation has likely taken place in this area during recent geologic time, it does not appear to have coalesced during this time. The deformation may represent the southernmost part of a diffuse boundary, the Western Puerto Rico Deformation Boundary, which accommodates differential movement between the Puerto Rico and Hispaniola arc blocks. This differential movement is possibly driven by the differential seismic coupling along the Puerto Rico – Hispaniola subduction zone. We propose that the compositional heterogeneity across the island arc retards the process of focusing the deformation into a single fault. Given the evidence presented here, we should not expect a single large event in this area but similar diffuse sequences in the future.

New Insights Into the 2019 Puerto Rico Sequence - a Combined Study Based on Correlation Fractal Dimension and Static Stress Changes

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Puerto Rico, situated in a complex geotectonic setting, has undergone destructive earthquakes and tsunamigenic events in the recent past. The seismicity trend witnessed a surge in recent years, and the seismicity was denser towards the South-west of the island of Puerto Rico. We used the fractal correlation dimension (D_c), seismicity trend, and coulomb static stress pattern analysis during this study to get more insights on the sequence of earthquakes that started towards the end of 2019 with more reference to the M_w 6.4 event on 7th January 2020. There was significant clustering of events and a noticeable drop in the value of D_c before the M_w 6.4 event hinting at a numerical precursor. Also, the coulomb static stress analysis changed notably after the onset of the sequence of earthquakes that started towards the end of 2019. A positive stress pattern was observed in the study region till 2019 due to the historical earthquakes over 30 years. The stress pattern changed after the 2019 sequence, with higher stress levels observed in the south–southwest region of the island of Puerto Rico. It is evident that the area is undergoing tectonic readjustments following the increased stress observed across the South Lajas Fault, Punta Montalva fault, Salinas fault, and so on. Assessing the D_c and the static stress patterns, we recognized low D_c windows before the events with increased stress close to the shock's epicenter from the coulomb stress analysis.

A Three-Year Update on the Performance of the USGS Aftershock Forecasts for the 2020 SW Puerto Rico Sequence

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The 7 January 2020 magnitude 6.4 Southwestern Puerto Rico earthquake caused significant damage and triggered a robust sequence of aftershocks. The U.S. Geological Survey has since issued regular forecasts for the number and probability of aftershocks in the following days, weeks, and years. These forecasts are released publicly on the USGS website, allowing for a truly prospective evaluation. The aftershock sequence has been unusually productive for an earthquake of this magnitude, with aftershocks still being experienced monthly. Here we provide an update and evaluation of the first three years of the forecasts.

Aftershock forecasts were generated using the USGS AftershockForecaster software, based on an Epidemic-Type Aftershock Sequence (ETAS) model. The initial forecast is trained on historical activity in similar tectonic environments, and ongoing forecasts use Bayesian updating to adjust to the sequence. Forecasts include both the expected number range and the probability of seeing at least one aftershock of a given magnitude within a given timeframe. Comprehensive tests of the number forecasts show the forecast model performing as expected, with close to 95% of the observations falling within the 95% confidence range of the forecasts. Tests of the probability forecasts, treating each forecast as a Bernoulli trial, also show success. The number and probability tests complement each other, with the number tests having high statistical power when probabilities and expected numbers are high, and the probability tests having power when the expected number may be small or zero. The analysis shows evidence for evolution of the magnitude-frequency distribution throughout the sequence, with fewer large events later in the sequence. This evolution is only partially captured by the existing forecast model, and longer-term forecasts could be improved by considering non-stationarity in the model parameters.

Insights Into the 2019-2022 Southwest Puerto Rico Seismic Swarm and Broader Caribbean Seismo-tectonics With an Automatic Workflow Aided by Machine-learning Pickers

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In December 2019, the southwestern portion of Puerto Rico began experiencing several large, widely felt earthquakes, including a Mw 6.4, which has thus far been the largest of the sequence, on January 7, 2020. The sequence has produced 15 M5.0 or greater and 121 M4.0 or greater earthquakes from late 2019 through mid-2021. Some of the largest mainshocks have caused damage to structures in southwest Puerto Rico (Lopez et al., 2010) and, as of early 2022, the seismicity rate in southwestern Puerto Rico remains elevated above background levels. Seeking to better understand the evolution of this complex sequence, we applied machine-learning (ML) detection, as implemented through the easyQuake (https://github.com/jakewalter/easyQuake). The easyQuake Python package consists of a flexible set of tools for detecting and locating earthquakes from FDSN-collected or field-collected seismograms. We will present a comparison of several different deep learning pickers (GPD, EQTransformer, and PhaseNet) that are user-selected within easyQuake and show relative tradeoffs between different detection capabilities, relative to the routine network catalog generated by the Puerto Rico Seismic Network (PRSN). We show that systematic bias is evident in the timing of phase pick arrivals relative to human-picked phase arrivals and highlight how these biases could lead to cascading errors in ML automatic earthquake catalogs. Aside from the very active portion of southwest Puerto Rico, the results suggest interesting new discoveries of seismicity along the Enriquillo

Fault in southern Hispaniola near the Dominican Republic extent of that fault zone. There is ample seismicity during the study time period near the Puerto Rico trench, adjacent to the proposed location (Doser et al., 2005) of the 1943 Mona Passage earthquake, a finding qualitatively similar to routine results from PRSN. We plan to extend the catalog into the end of 2022 and identify the degree of dynamic triggering across Hispaniola and Puerto Rico, if any, that might be occurring due to the large amount of seismic energy release from the Southwest Puerto Rico Seismic Sequence.

Lessons Learned as a Geoscience Communicator During the 2020-2021 Southwest Puerto Rico Seismic Sequence

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The 2020-2021 Southwest Puerto Rico Seismic Sequence is the first major seismic activity in the Puerto Rico Archipelago since 1918. Local and federal government delivered emergency management and provided expert knowledge. Among these, is the Puerto Rico Seismic Network (PRSN). This presentation will describe the experience of a professor from the University of Puerto Rico, Río Piedras as a geoscience communicator, serving as the liaison between the Puerto Rico Seismic Network, the US Geological Survey, and the local government. In addition, other experiences in geoscience communication before and after the 2020-2021 Southwest Puerto Rico Seismic Sequence are included as examples of communicating science to non-science and non-geologists, emphasizing promising experiences, challenges, and transdisciplinary work. These examples and experiences highlight the importance of geoscience communication when addressing citizens' risk and the capacity of individuals to take action. It will also emphasize lessons learned from each communication delivery and the long-term learning process. More importantly, it highlights the challenge of delivering the message in a way that inspires security and avoids misconceptions.

Behavioral Responses to the 2020-2021 Southwest Puerto Rico Earthquake Sequence: Information-Seeking, Rumors, and Protective Action Decision-Making

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While there are more than six decades of research on how people respond to risk information, less is known about information seeking in the context of competing official and non-official sources of risk information available through social media (National Academies of Sciences, Engineering and Medicine, 2018). There is also a dearth of social science research on disasters in Puerto Rico, more so on risk communication. Moreover, Puerto Ricans have been coping with consecutive extreme events in the last five years, including hurricanes, landslides, an earthquake sequence, and the COVID-19 pandemic, challenging more traditional event-based definitions and studies of disasters. For the last two years, our team has been conducting research to understand how in the context of navigating multiple disaster cycles simultaneously, emergency management-related personnel, as well as residents, make decisions about what actions they should take to protect themselves and others against the possibility of a significant earthquake in the future. Using data collected through in-depth interviews with key informants (n=51), a semi-structured survey (n=428), and focus groups (8 facilitated) in three communities in the municipalities of Guayanilla, Guánica, and San Juan, we explore how emergency responders and residents access, interpret and use official and non-official earthquake risk information available through social media and other sources to inform immediate and long-term protective-action decisions. This research is vital for disaster reduction as it may assist in effectively planning, and in promoting situational awareness, hazard adjustments, and preparedness for future earthquakes.

The 2020-2021 Southwest Puerto Rico Seismic Sequence: Current State of Knowledge and Implications [Poster]

Poster Session • Tuesday 18 April

Conveners: Gisela Baéz-Sánchez, Puerto Rico Seismic Network, University of Puerto Rico, Mayagüez (gisela.baez1@upr.edu); Victor Húerfano, Puerto Rico Seismic Network (victor@prsnmail.uprm.edu); Stephen K. Hughes, University of Puerto Rico, Mayagüez (kenneth.hughes@upr.edu); James Joyce, University of Puerto Rico, Mayagüez (james.joyce@upr.edu); Daniel A. Laó-Dávila, Oklahoma State University (daniel.lao_davila@okstate.edu); Alberto M. Lopez, University of Puerto Rico, Mayagüez (alberto.lopez3@upr.edu); Margarita Solares-Colón, University of Oregon (msolares@uoregon.edu); Elizabeth A. Vanacore, Puerto Rico Seismic Network, University of Puerto Rico, Mayagüez (elizabeth.vanacore@upr.edu); Christa von Hillebrandt, International Tsunami Information Center, National Oceanic and Atmospheric Administration (christa.vonh@noaa.gov)

Determining First Motion Focal Mechanisms for Small Magnitude Earthquakes in the Southwestern Puerto Rico Seismic Sequence From January 6th and 7th, 2020

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The 2020 Southwestern Puerto Rico Seismic Sequence is a complex multiple fault sequence occurring a across a fault zone of relatively small strike-slip and normal faults. Prior to the M6.4 normal fault event the activity centered upon a strike-slip fault off-shore of the Punta Montalva Fault. Here the aim is to examine small magnitude events to pinpoint the initial focal mechanisms (FM) of movement that occurred between January 6 and 7, 2020, before and after the M6.4. Here a total of 35 earthquakes with M3-4 occurring on January 6-7 2020 in southwestern Puerto Rico were studied. The Bayesian Inversion method MTFit was applied to first motion data from the Puerto Rico Seismic Network (PRSN). Before analysis the PRSN data was manually examined and verified. Additionally, the P, SV, and SH amplitudes were manually picked to find determine the S/P amplitude ratios. The amplitude ratios were not included in the initial FM analysis as to avoid the influence of possible site or path effects, but will be included in future analyses. Of the 35 earthquakes analyzed, 26 produced distinguishable FMs. Of these, events prior to the M6.4 event predominantly consisted of strike-slip FMs suggesting that the conversion to a multiple fault sequence is likely due to stress transfer from the off-shore strike-slip fault to the normal fault associated with the M6.4.

Diffuse Transtensional Deformation in the 2020 Puerto Rico Earthquake Sequence

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On January 7th, 2020, a damaging M6.4 earthquake occurred in the northeastern Caribbean, a few tens of kilometers to the southwest of Ponce in Puerto Rico. It was the mainshock of a complex seismic sequence characterized by energetic and shallow-depth seismicity distributed along an east-west elongated area just offshore of the island's south coast. Furthermore, the ground shaking generated by the main events of the sequence produced significant damage to buildings and cost at least one casualty. Here we estimate the fault parameters of the main event of the sequence by combining Interferometric Synthetic Aperture Radar (InSAR), Global Navigation Satellite System (GNSS), and teleseismic waveforms using Bayesian inference. The geodetic data provide only on-land displacements showing that the coseismic deformation was limited to southwestern Puerto Rico and mainly in the area near Guayanilla bay. Furthermore, the geodetic observations suggest that an inland segment of the recently mapped North Boqueron Bay-Punta Montalva fault (NBBPM) may have been reactivated. The Bayesian results, on the other hand, support an east-west oriented fault, dipping northward and accommodating 1.4 m of transtensional motion, with location and orientation parameters rather suggesting an offshore continuation of the NBBPM fault was activated. Together, the results indicate transtensional faulting in response to active diffuse deformation affecting southwestern Puerto Rico and highlight unmapped faults with moderate to large earthquake potential in the Puerto Rico region.

Operational Response of the PRSN for the Southwest Puerto Rico Seismic Sequence

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During 2020 Puerto Rico experienced the greater seismic sequence in recent times. The main event occurred on January 7, 2020, with magnitude of 6.4 Mww located at the southern coast of Puerto Rico main island. This seismic sequence continues active with more than 1,748 significant events, with magnitudes greater than 3.45 Md, and more than 55 events with magnitudes greater than magnitude 4.5, that continued to damage structures. The sequence is characterized also by the occurrence of thousands of events that were felt widely through Puerto Rico and some of them causing damage in the South of the main island. Operationally this sequence implied the activation of personnel of the Geophysical Data Analysis Division at PRSN, shift reorganization and evaluation of current communication protocols at PRSN AOR. This discussion will go over the response of PRSN during the Southwest Puerto Rico Seismic Sequence, the organization and situations faced during operations, and the response due to multiple felt events that affected the Puerto Rican population through 3 years of continuous activity. The challenges in communications with the emergency management agencies of Puerto Rico and the Virgin Islands Region, information disseminated to the general public, and lessons learned during the response of the seismic sequence will also be discussed.

Post-Seismic Relaxation of 2020 Southwestern Puerto Rico Seismic Complex From New Gnss Network

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The Southwest Puerto Rico M_w 6.4 earthquake that occurred on January 7th, 2020 is the most significant event affecting the island of Puerto Rico since the M_w 7.2 earthquake that occurred on October 11th, 1918. Three years monitoring seismicity in the epicentral region has culminated with the conclusion that a complex fault system and processes associated to the interaction of separate crustal blocks within the Puerto Rico–Virgin Islands microplate were primarily responsible for this event. In this study, we present a qualitative analysis of the post-seismic relaxation behavior of southwestern Puerto Rico (SWPR) fault complex with post-seismic deformation using GNSS stations from a new continuously operated GNSS network funded by the NSF RAPID program and installed by the Puerto Rico Seismic Network (PRSN) in late 2020 and early 2021. Our methodology included data acquisition and data processing of GNSS data from UNAVCO GAGE Facility and the use of GIPSY-OASIS II (v6.4) software along with final orbit, clock, and earth orientation parameters from JPL to calculate daily, absolute point position estimates in ITRF14, and then we removed Caribbean plate motion. Observations of velocity vectors from processed GNSS data were made in order to quantify tectonic displacement since site installation and infer the amount of post-seismic relaxation. Our preliminary data indicated parts of the SWPR block are returning to its inter-seismic motion towards the northwest, while other sites, particularly those near the Punta Montalva Fault, reflected that some after-slip or relaxation is still ongoing. Future data analysis using the newly installed GNSS network will be improved with an increased time of data acquisition resulting in more precise constraints on the motion of the SWPR block relative to the larger Puerto Rico-Virgin Islands block to the north and the Caribbean plate to the south.

The M6.4 Mainshock in the 2020 Southwestern Puerto Rico Seismic Sequence: New Insights From Joint Inversion

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The U.S. Geological Survey National Earthquake Information Center (NEIC) now routinely incorporates regional strong motion, high-rate and static Global Navigation Satellite System (GNSS), and Interferometric Synthetic Aperture (InSAR) observations into finite-fault model (FFM) products when such observations are available. The inclusion of these data sets allows for modeling of smaller earthquakes than was typical of NEIC FFMs (often M7 or larger). Considering this advancement, we revisited the January 7, 2020, M6.4 earthquake in Puerto Rico. This earthquake was part of the 2020-2021 Southwestern Puerto Rico (SWPR) seismic sequence, an active sequence with seismicity distributed across a complex set of structures within the Puerto Rico and Virgin Islands block that illuminates new faults previously not recognized. We refined the FFM for this event considering data from broadband teleseismic waveforms, regional strong-motion accelerometers, high-rate GNSS stations, GNNS static offsets, and InSAR pairs. Modeling this event presents some challenges due to the likelihood that multiple causative faults were involved, with a combination of normal and strike-slip motion, and its offshore location. However, the inclusion of regional data allowed us to improve the resolution of our model and investigate the plausibility of a more complex, geologically realistic, fault geometry that includes two fault segments with different rake directions. Our refined model prefers slower rupture velocity and longer rise time than average for an event of this magnitude, suggesting a slowly evolving source rupture process. These results will lead to a better understanding of the seismotectonic characteristics of the region.

The Puerto Rico Strong Motion Program – a State of the Art and Records Obtained During the m6.4 January 7, 2020 Earthquake

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The Puerto Rico Strong Motion Program (PRSMP), under the Department of Civil Engineering and Surveying of the University of Puerto Rico at Mayaguez (UPRM) has as primary objectives to minimize the loss of life and economic losses caused by high-intensity earthquakes in the Puerto Rico region. The PRSMP is made up of two main components. First, a network of 129 strong motion stations in Puerto Rico (100), the Dominican Republic (17), the British Virgin Islands (10), US Virgin Islands (USVI) (1), and Anguilla (1) and second, a network of Instrumented Structures that includes dams, buildings, bridges and a control tower.

The strong motion stations (sms) within Puerto Rico and the USVI consists of 70 (69%) Obsidian data loggers and 31 Etna2 (31%) for a total of 101 stations. Each sms has its own global positioning system (GPS). 68% is energized by means of a photovoltaic system; 23% have backup electric generators, and the remaining 9% depend on the Electric Power Authority and their own backup battery. In relation to communications, 51% of the stations are transmitted through Modem Cellular, 12% through microwaves, 12% through private Internet, 17% transmit data through combinations of microwaves and modems cellular or private internet and the remaining 8% are just stand alone stations. The data is transmitted both to the Primary Data Center in the Civil Engineering building on the UPRM Campus and to the Secondary Data Center located inside a bunker at Finca Montana in the town of Aguadilla that was part of the former Ramey Military Base. The data is sent to both the United States Geological Survey (USGS) and the Puerto Rico Seismic Network (PRSN), under the Department of Geology of UPRM who are in charge of sending the data to IRIS. It should be noted that 23% of sms have a Vs30 study performed. Over 40 records of the M6.4 January 7, 2020 EQ can be obtained at https://prsmp.uprm.edu/M6-4/.

2025 Puerto Rico and the U.S. Virgin Islands National Seismic Hazard Model Update

Oral Session • Tuesday 18 April • 04:30 PM Pacific

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USGS 2025 Puerto Rico and the U.S. Virgin Islands NSHM Update

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The U.S. Geological Survey's National Seismic Hazard Model Project plans to begin the next update of the National Seismic Hazard Model (NSHM) for Puerto Rico and the U.S. Virgin Islands (PRVI) in 2023, with a planned release of the updated NSHM by the end of 2025. The last update to the PRVI NSHM was in 2003. Therefore, the new update will include over 20-years of new science and engineering data, models, and methods. Some of the updates being considered are (1) an updated seismicity catalog based on improved Puerto Rico Seismic Network data, (2) new declustering (space and time and nearest neighbor), smoothing (fixed and adaptive), and seismicity rate models, (3) new magnitude scaling relationships, (4) updated geologic and geodetic deformation models, (5) improved modeling of subduction zone geometries using Slab2.0, (6) evaluation and implementation of ground motion models for both crustal (NGA-West2 and other available Puerto Rico-specific models) and subduction (NGA-Subduction) sources, and (7) comparison of NGA site amplifications to observed amplifications in Puerto Rico. These updates parallel efforts made in other recent NSHMs (e.g., 2021 Hawaii NSHM and 2023 conterminous U.S. and Alaska NSHMs). Uncertainty and engineering impact studies will also be performed for this update. Development and finalization of input models will occur in 2023, followed by implementation of the draft model in early 2024. NSHMs are community- and consensus-based models, with the goal to incorporate the latest data, models, and methods currently available. At least two public workshops, one in 2023 and another in 2024, will allow the scientific community to evaluate the input models and draft model, providing valuable input as the model is developed and finalized.

Earthquake Geology Inputs for the 2025 Update of the Puerto Rico-U.S. Virgin Islands Portion of the National Seismic Hazard Model

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Two decades have passed since the 2003 United States Geological Survey National Seismic Hazard Model (NSHM) for Puerto Rico and the U.S. Virgin Islands (PRVI). In advance of the 2025 PRVI NSHM update, we developed 3 databases to summarize and characterize new onshore and offshore fault source information, excluding the subduction zone, in the region between 62° to 70° W and 16° to 21° N. These include (1) fault section, (2) fault-zone polygon, and (3) earthquake geology (fault slip rate, earthquake recurrence interval) databases, which represent updates to fault parameters used in prior seismic hazard models. We revised and added fault sources from studies published since 2003 that document improvements to fault locations, geometries, or activities. New fault sources meet the criteria of a length ≥7 km, evidence of recurrent tectonic Quaternary activity, and documentation in a peer-reviewed source. While the 2003 NSHM included only 3 fault sections and 2 fault-zone polygons (areal sources), the 2025 draft databases, which will soon be subject to community input, include 24 new faults and up to 5 fault-zone polygons, including revisions to the Mona and Anegada extensional zone areal sources. To characterize activity rates on faults without published slip rates, we assigned slip rate bins to faults based on landscape expression and published paleoseismic trench observations. At least 12 fault sources were evaluated but not included in the revised databases due to a lack of published information or equivocal information about fault location, geometry, or recurrent Quaternary activity. The new databases will serve as inputs to the deformation models during upcoming model implementation.

A Seismic Source and Ground Motion Characterization Model Developed for a Site in Northeast Puerto Rico

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The island of Puerto Rico is located on the approximately 275-kilometer-wide tectonically active Puerto Rico-Virgin Island microplate, within the plate boundary between the North American and Caribbean Plates. The boundary is complex, and involves opposing subduction zones, accretion, a collision zone, as well as smaller compressional, extensional, and transform fault elements. An updated seismic source characterization (SSC) was developed in 2021 in support of a project in northeast Puerto Rico. Shallow crustal fault sources located both on land and offshore were characterized. A background seismicity source incorporating an earthquake catalog with events through November 2020, and including the January 2020 Indos sequence, was characterized by weighting of uniform areal source and gridded seismicity source zones. Subduction interface events from the Puerto Rico Subduction Zone and Muertos Subduction Zone were modeled as finite faults dipping toward the island from the north and south, respectively. A source extending from a 40- to 130-kilometer depth was also incorporated in the SSC to model subduction intraslab events beneath the island.

An updated ground motion characterization (GMC) model included state-of-practice NGA-West2 Ground Motion Models (GMM) for crustal events and recently released NGA-Subduction GMMs for subduction interface and intraslab event. The crustal GMMs were reviewed against shallow crustal earthquake records from the Indios event for applicability along with a Puerto Rico-specific GMM developed by Motazedian and Atkinson (2005), which was also included in the GMC model. NGA-Subduction GMMs were compared against the established Abrahamson et al. (2016) subduction GMM for the subduction interface and intraslab sources. The significant SCC and GMC model features, comparisons to the USGS (2003) seismic hazard maps, and overall results from this study will be presented.

Evaluating Predictive Performance of Global and Regional Ground Motion Models Using a New Caribbean Strong-Motion Dataset

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Most of the existing probabilistic seismic hazard analysis (PSHA) studies for the Caribbean region adopted global and regional ground motion models (GMMs). However, there is a lack of systematic attempts to assess the predictive performance of these GMMs using local strong-motion recordings. We present such a study by first compiling a local strong-motion dataset consisting of 1639 recordings retrieved from the Center for Engineering Strong Motion Data (CESMD) and the Engineering Strong-Motion (ESM) Database. Among them, 729 CESMD recordings are from the 2019-2020 Southwest Puerto Rico earthquake sequence with moment magnitudes $4.5 \leq M_W \leq 6.4$, whereas 910 ESM recordings are from 197 events in Lesser Antilles with moment magnitudes $3.4 \leq M_W \leq 7.4$. We also pre-select global and regional GMMs applicable to the Caribbean region's various tectonic regime characteristics, including the 2014 Next Generation Attenuation-West2 (NGA-West2) and the 2020 Next Generation Attenuation-Subduction (NGA-Sub) models. To facilitate the model comparison, multi-dimensional ground motion trends (e.g., with respect to spectral period, moment magnitude, rupture distance, VS30) are investigated using trellis plots. The performance and ranking of selected global and regional GMMs using the Caribbean dataset are assessed through residual analysis and probabilistic scoring methods such as the log-likelihood (LLH) by Scherbaum et al. (2004). The results show that global models such as the NGA-

West2 and Cauzzi et al. (2015) outperform other crustal models, whereas NGA-Sub models perform reasonably well using the subduction dataset. The outcome of this study is used to construct data-driven and objective logic trees of GMMs for seismic hazard and risk assessment in the Caribbean region.

Assessing Site Characterization in Puerto Rico: Towards the 2025 Update of the Puerto Rico and Virgin Islands Portion of the USGS National Seismic Hazard Model

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The U.S. Geological Survey (USGS) will update the Puerto Rico and Virgin Islands portion of the National Seismic Hazard Model (NSHM) in 2025, following on the 2023 50-State NSHM update. Part of the update will include evaluation of empirical ground-motion models (GMMs) used for both shallow crustal and subduction-zone sources using an updated ground-motion data set. As an early step towards understanding regional ground motion effects, we compile the time-averaged shear-wave velocities in the upper 30 meters (V_{S30}) from measurements at sites where they are available, and assign proxy-based values elsewhere. Two spatially varying V_{S30} maps are used in the latter case: one based on a topographic slope proxy, and one based on a proxy that combines a database of V_{S30} measurements in the U.S. with a suite of remotely sensed geospatial parameters using machine learning. These proxies are compared with recently measured V_{S30} values at 20 stations in PR to assess their efficacy. We also investigate horizontal-to-vertical spectral ratios (HVSRs) from ambient noise recorded at seismic stations across the island, towards the development and improvement of existing site response models in GMMs. An automated HVSR peak-picking algorithm identifies the dominant frequencies (f_d) and amplitudes of peaks and fits a Gaussian pulse function when peaks are present. These new site characterization data will: (1) help determine how the ergodic GMMs developed using global databases, and their respective site-amplification models conditioned on V_{S30}, perform in Puerto Rico; and (2) allow us to look towards developing new site response models using f_d, and compare these models with those in existing GMMs.

2025 Puerto Rico and the U.S. Virgin Islands National Seismic Hazard Model Update [Poster]

Poster Session • Tuesday 18 April

Conveners: Allison M. Shumway, U.S. Geological Survey (ashumway@usgs.gov); Jessica A. Thompson Jobe, U.S. Geological Survey (jjobe@usgs.gov); Thomas L. Pratt, U.S. Geological Survey (tpratt@usgs.gov); Alberto M. López-Venegas, University of Puerto Rico Mayagüez (alberto.lopez3@upr.edu); Victor Huérfano, University of Puerto Rico Mayagüez (victor.huerfano@upr.edu)

Geospatial Scope of the 2025 Puerto Rico-U.S. Virgin Islands National Seismic Hazard Model Update

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The National Seismic Hazard Model Project of the U.S. Geological Survey is tasked with modeling the seismic hazards from potentially damaging earthquakes for the 50 U.S. states and territories. The last comprehensive assessment for Puerto Rico and the U.S. Virgin Islands (PRVI) was completed in 2003 and significant updates are currently being planned for a 2025 update to the model. The 2025 update will include new fault sources from ~24 new faults and up to 5 zones, an updated earthquake catalog, new geodetic deformation models, improved modeling of subduction zone geometries using SLAB2 (Hayes, 2018), new ground motion models (NGA-West2 and NGA-Subduction), site response models, and uncertainty estimates. To support the update, we have developed a geodatabase that organizes the PRVI input datasets including the geologic layers, geodesy, subduction zonation, and modeled seismicity. The Puerto Rico-northern Virgin Islands microplate is relatively rigid with major seismogenic structures located offshore. This setting requires a large footprint for analysis: a 330x260 km zone to encompass the crustal earthquake sources and a 1,340x1,050 km zone for the seismic catalog. Data at these varying scales are preserved in their respective layers and the database serves as a flexible hub for future updates.

Reviewing 4 Decades of the Puerto Rico Seismic Network Catalog: From Catalog Correction and Homogenization to Declustering.

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The PRSN earthquake catalog consists of more than 70,000 events collected since 1986. In preparation for further research and planned update to the seismic hazard map, a review of the entire catalog was conducted to clean up duplicates, remove events outside the area of responsibility, recompute the magnitude of some events due to incorrect parameters and/or the misuse of station channels, among other data preparation activities. This process involved the use of the single solution files to understand the causes of some issues found, and then to correct them (e.g. none or not calibrated factors in particular station channels). Data products developed as a result of this research include a new corrected catalog, a proposal of new station calibration factors for some particular stations and channels, and correlation equations between seismic magnitude scales (Md, Ml, Mw).

Additionally, the obtained catalog was homogenized to the moment magnitude scale Mw, and processed, using the python library OpenQuake, to perform a Catalog Declustering using the methods of Gardner and Knopoff, Musson, Reasenberg, and Zaliapin. 8,437 events were defined as mainshocks by the Zaliapin method, and Reasenberg and Gardner and Knopoff showed a similar behavior with 49,667 and 52,138 total mainshocks identified respectively. Of these events, 4,788 events were consistently identified across all methods as mainshocks. Furthermore, 6 geographic clusters were identified which match the Mona Canyon, 19° N, Sombrero, South Lajas, and Great Southern Puerto Rico fault zones, and provide additional information to the Guanica area due to the seismic activity in late 2019 and early 2020.

Seismotectonic Context Update and Tsunami Numerical Modeling for the NE Region of the Caribbean Plate, Puerto Rico; Insights From Seismic Reflection and Seismicity.

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According to the NGDC/WDS Global Tsunami Database, the Caribbean Sea has experienced more than 100 historical tsunamis in the last 200 years. The most recent tsunamis observed in the Caribbean Basin were caused by the 2019 Puerto Rico- Guanica earthquake with 6.7 Mw and 2020 Haiti earthquake with a 7.0 Mw. In addition, Puerto Rico has been shaken by large earthquakes that have generated several tsunamis that directly affected the coasts of the island in historical times, the 1867-EQ and 1918-EQ. Therefore, there is a high probability that a future event of this type could affect the coasts of Puerto Rico. Due to this potential threat, different tsunami hazard studies have been carried out, based mainly on instrumental and historical seismicity. The pioneering works in the area describe the parameters of the main structures based on historical records, without considering subsurface structures or long periods of recurrence. The incomplete knowledge about seismic sources in the region has direct repercussions within tsunami modeling due to: (i) the strike and dip of a fault are directly related to the run-up and the inundation area and (ii) the active faults with long recurrence periods are not included in these studies. Integrating seismicity with the structural data is key to address tsunamigenic scenarios in the area. This integration involves seismotectonic zoning, which characterizes features along the strike of structures. These features are usually associated with fault plane geometry variations or rheological controls and are responsible for variations in local stress fields that control deformation styles. The aim of this work is to propose a structural model to study tsunamigenic scenarios in the island of Puerto Rico, based on a seismotectonic zonification which includes both long periods rupture and geometric parameters of the different fault segments developed in marine settings around the island.

Uprm Contributions to the 2025 Update of the Puerto Rico Seismic Hazard Map

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A collaborative work between the Geology and Civil Engineering Departments at the University of Puerto Rico - Mayaguez (UPRM) have formed a workgroup to deliver products to be included in the upcoming realization of the Puerto Rico and Virgin Islands Seismic Hazard Map. The latest revision of a Seismic Hazard Map for the island of Puerto Rico dates back to 2003 when the US Geological Survey (USGS) used available gridded seismic hazard curve data, gridded ground motion data, and mapped gridded ground motion values to produce the Puerto Rico and U.S. Virgin Island (PRVI) Seismic Hazard Model (Mueller et al., 2010). This year marks twenty years since that model was published and new datasets can be included in a new realization of an updated Seismic Hazard Model for PRVI. Funding from the USGS have been granted to the UPRM workgroup for two years, however, products delivered during the first year are expected to be included in the new version. These include updates to the seismicity catalog, and an updated velocity vector field obtained from continuous and permanent GPS sites in PRVI that span more than twenty years, and a detailed topography analysis to identify the location of possible active seismic experiments and paleoseismic trenches. The products from the second year include opening two paleoseismic trenches in southwestern Puerto Rico to explore possible active faults in association to the 2020 Southwestern Puerto Rico seismic sequence.

Vs30 Mapping using MrVBF in Puerto Rico and Hispaniola

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The time-averaged shear-wave velocity to a depth of 30m (VS30) is one of the most used parameters for representing seismic site effects. Based on the analysis of Vs30 data of ~75 sites in Puerto Rico and Hispaniola as well as Vs30 data of ~600 sites globally in the active tectonic region in Tropical climate zone, improvements to the spatial prediction of Vs30 map are proposed using a new trend. The new Vs30 map uses *M*ulti-*r*esolution *V*alley *B*ottom *F*latness (MrVBF) instead of slope as the terrain constraint. MrVBF combines multiple resolutions to generate a single index to identify the transition of the valley bottom from steep areas. The updated trend model can distinguish areas where a thin surficial unit may overly another geologic unit from areas where the surficial unit may comprise a significant portion of the upper 30 meters. The new VS30 map uses surficial geology and MrVBF for unconsolidated and lithified units and surface geology for lacustrine, marsh, and artificial fill deposits. The results show an improvement in residual characteristics when compared to the existing VS30 maps available in the public domain in the same region.

Vs30 Measurements at Puerto Rico Seismic Sites

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Average shear wave measurements in a depth of 30 meters subsoil (Vs30), were made with the purpose of identifying the type of subsoil in different seismological station sites of Puerto Rico to better understand the seismic wave amplification at the sites during earthquakes, and provide the data collected to help generate updated Motion Predictions, Building Parameters, Hazard Maps, Shake Maps, and provide site data to Emergency Management entities.

Active source surveys were performed in Spring of 2022 at 22 individual sites using both shear wave and primary wave data. Most collected lines were ~106m in length however at select sites the length was shortened due to logistical limitations. Field data has been collected for 22 individual sites. Here a MASW analysis of the field data for nine broadband stations and one accelerometer on the west side of Puerto Rico are presented. The MASW analysis for stations mainly on the west side of Puerto Rico yielded Vs30's ranging from 200 to 699 m/s, with exception of AGPR and GBPR. The majority of these stations are classified as soil types C and D, which consist of very dense soil, soft rock, and stiff soil. On the contrary, AGPR and GBPR are located on or close to bedrock, with Vs30's of 784.6 and 1693.7 m/s respectively. MASW analysis currently in process for 12 stations located on the eastern side of the Island; the results of which will also be presented here.

Above the Seismogenic Zone: Fault Damage and Healing in the Shallow Crust

Oral Session • Wednesday 19 April • 04:30 PM Pacific

Conveners: Travis Alongi, University of California, Santa Cruz (talongi@ucsc.edu); Alba M. Rodríguez Padilla, University of California, Davis (arodriguezpadilla@ucdavis.edu); Ashley W. Griffith, Ohio State University (griffith.233@osu.edu); Ahmed Elbanna, University of Illinois Urbana-Champaign (elbanna2@illinois.edu); Prithvi Thakur, University of Michigan (prith@umich.edu)

Modeling the Viscoplastic Deformation of Damaged Rocks Using a Perzyna Viscoplasticity Law

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Fault damage zones host abundant fractures, from microscopic to macroscopic scale, created by stress concentrations associated with the fault slip. Sliding and closing of these fractures could promote the overall viscous behavior of damage zone rocks, which cause evolution of fault strength and stress in the interseismic period. We observed the viscous behavior of damage zone analogues created by impacting samples.

Siltstone samples were impacted using a Split Hopkinson Pressure bar at strain rates comparable to those during earthquake ruptures. Samples were then deformed in a conventional triaxial apparatus by applying several steps of differential stresses, followed by a constant stress hold period, to measure the instantaneous and time-dependent responses of the rocks. The volumetric strain response of the specimens were modeled using a Perzyna viscoplasticity law that uses the Modified Cam Clay (MCC) model as the yield criterion (Haghighat et al. 2020). We also alter the relation between plastic strain rate and overstress by raising overstress to the power of 'n' to better fit the experimental data. Given the stress history from the experiments as the boundary conditions, the volumetric strain is modeled and fit to the experimental data to recover constitutive parameters that describe the elastic/inelastic compliances, yield strength, overstress exponent, and parameters used to describe how the apparent viscosity changes with plastic strain.

We find that the Perzyna-MCC formulation fits the experimental data well but observed tradeoffs between parameters such as the overstress exponent and the apparent viscosity. This implies that a unique set of parameters are not constrained in some cases although minimal parameters are defined to describe basic features of the viscoplastic behavior. The correspondence of these constitutive parameters to physical attributes of the rock samples is required to constrain the appropriate magnitudes of these parameters and to eliminate the tradeoffs.

Spatiotemporal Variations in Shallow Damage Zone Mechanisms Along the Southern Elsinore Fault

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Evidence from laboratory earthquake experiments, observational seismology, and theoretical fracture mechanics suggest that inelastic off-fault deformation should be more extensive for large earthquakes than small events. This begs the question of whether or not we can determine the seismic potential of active fault zones by examining properties of their damage zones. Faults accrue off-fault damage throughout their evolution via a number of different mechanisms that can be loosely grouped into quasi-static mechanisms related to slow, long-term processes involved in fault growth and deformation over many seismic cycles, to dynamic mechanisms related to earthquake rupture. We have studied the damage zones in outcrops of similar rocks along three active faults (listed in order of increasing historical or paleoseismic earthquake magnitude) – the Superstition Hills Fault, the Elsinore Fault, and the southern San Andreas Fault – in order to test the hypotheses that (A) we can identify fault damage structures uniquely related to dynamic rupture, and (B) that these structures hold information about the seismic potential of the fault. Here, we focus on results from the Elsinore Fault, where we describe strain partitioning in the damage zone between purely volumetric mechanisms and primarily deviatoric mechanisms that operate at different spatial scales across the damage zone. We argue that the volumetric mechanisms are uniquely dynamic in nature, whereas the deviatoric mechanisms are likely quasi-static. Finally, we compare and contrast these observations with preliminary work along the Superstition Hills fault and the Coachella segment of the southern San Andreas Fault.

High-Resolution Fault Zone Imaging With Distributed Acoustic Sensing

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Multi-scale fault zone structure may largely control the behavior of earthquake ruptures and encode the long-term slip history of the fault. Detailed images of subsurface fault zone structure fill an observational gap between surface mapping and low frequency tomography studies. These images are best illuminated using multiple types of complementary observations recorded by dense instrumentation. Distributed acoustic sensing (DAS), an emergent technology that transforms fiber optic cables into dense arrays of strainmeters, yields high-density and long-duration seismic deployments that can help fill this observational gap at relatively low cost and effort. We illustrate this potential by using a DAS array that extends from Ridgecrest, CA to Barstow, CA to image the Garlock Fault Zone, a major strike-slip fault zone in the Eastern California Shear Zone. The versatility of DAS allows us to employ a multifaceted approach to imaging this fault zone that includes an active source experiment, ambient noise tomography, and travel-time anomalies from earthquakes. These approaches each provide unique constraints that together yield a highly detailed picture of the fault zone's lateral complexity and depth-dependent structure. We observe an asymmetric fault zone with large across-fault differences and a highly heterogeneous shallow structure that simplifies with depth.

Inferring Fault Zone Structure from the Azimuthal Variation in the Stacked P-spectra of Earthquake Clusters

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Fault damage zones can influence various aspects of the earthquake cycle, such as the recurrence intervals and magnitudes of large earthquakes. The properties and structure of fault damage zones are often characterized using dense arrays of seismic stations located directly above the faults. However, such arrays may not always be available. Hence, our research aims to develop a novel method to image fault damage zones using broadband stations at relatively larger distances. Previous kinematic simulations and a case study of the 2003 Big Bear earthquake sequence demonstrated that fault damage zones can act as effective waveguides, amplifying high-frequency waves along directions close to fault strike via multiple reflections within the fault damage zone. The amplified high-frequency energy can be observed by stacking P-wave spectra of earthquake clusters with highly-similar waveforms (Huang et al., 2016), and the frequency band which is amplified may be used to estimate the width and velocity contrast of the fault damage zone.We attempt to identify the high-frequency peak associated with fault zone waves in stacked spectra by conducting a large-scale study of small earthquakes (M1.5–3). We use high quality broadband data from seismic stations at hypocentral distances of 20-80 km in the 2019 Ridgecrest earthquake regions. First, we group the Ridgecrest earthquakes in clusters by their locations and their waveform similarity, and then stack their velocity spectra to average the source effects of individual earthquakes. Our results show that the stations close to the fault strike record more high-frequency energies around the characteristic frequency of fault zone reflections. We find that the increase in the amount of high-frequencies is consistent across clusters with average magnitudes ranging from 1.6-2.4, which suggests that the azimuthal variation in spectra is caused by fault zone amplification rather than rupture directivity. We will apply our method to other fault zones in California, in order to search for fault damage zone structures and estimate their material properties.

Do Faults Localize as They Mature? Insight From 17 Continental Strike-slip Surface Rupturing Events (Mw > 6.1) Measured by Optical and Radar Imaging Data

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As faults accumulate displacement, they are thought to mature from disorganized and distributed fracture networks to more simplified throughgoing fault structures with a more localized zone of inelastic strain. Understanding the degree of inelastic strain localization holds importance for seismic hazard, as smoother faults are thought to host faster rupture velocities and have different seismic shaking intensities from ruptures along rougher, less mature faults. However, quantifying this evolutionary process of strain localization along major fault systems has been difficult due to a lack of near-field coseismic measurements. Here we test if such an evolutionary process exists by measuring the near-field surface deformation pattern of 17 large ($6.0 \leq Mw \leq 7.9$) continental strike-slip surface ruptures. To do this we use a range of geodetic imaging techniques including, a new 3D optical pixel tracking method, and pixel tracking of radar amplitude data acquired by satellite and UAVSAR platforms. With these geodetic imaging data we measure the total coseismic offset across the surface rupture and difference them from the displacements recorded by field surveys, which we assume captures the on-fault, discrete component of deformation. This differencing allows us to obtain an average magnitude of off-fault deformation for each earthquake, which we compare to a number of known source parameters to test the notion of progressive fault localization. Our results show that progressively smaller amounts of off-fault strain occur along fault systems with higher cumulative displacements, supporting the notion that faults systems localize as they mature. We also find strong correlations of off-fault deformation with the long-term fault slip-rate and the geometrical complexity of the mapped surface rupture, and a moderate correlation with rupture velocity. However, we find a weak-no correlation of off-fault deformation with the fault initiation age and the moment-scaled radiated energy. We also present comparisons of off-fault strain with other known seismic source parameters.

Above the Seismogenic Zone: Fault Damage and Healing in the Shallow Crust [Poster]

Poster Session • Wednesday 19 April

Conveners: Travis Alongi, University of California, Santa Cruz (talongi@ucsc.edu); Alba M. Rodríguez Padilla, University of California, Davis (arodriguezpadilla@ucdavis.edu); Ashley W. Griffith, Ohio State University (griffith.233@osu.edu); Ahmed Elbanna, University of Illinois Urbana-Champaign (elbanna2@illinois.edu); Prithvi Thakur, University of Michigan (prith@umich.edu)

A New 3-D Model of the Newport-Inglewood Fault at Long Beach, California, and Its Implication for Earthquake Rupture Propagation and Hazards

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The Newport-Inglewood fault (NIF) is an active, complex strike-slip system that cuts over 60 km through metropolitan Los Angeles and poses one of the greatest deterministic seismic hazards in the US. A portion of the NIF sourced the 1933 Long Beach (M6.4) rupture, southern California's deadliest earthquake. The event is thought to have arrested at Signal Hill, a large restraining bend formed by a left step in the NIF in the Long Beach oil field. The NIF is considered capable of generating much larger (M≈7) and more destructive earthquakes—yet key questions persist about its geometry, segmentation, and slip that are critical in assessing these hazards.

Integrating a diverse range of data, including ~4900 horizon picks and fault penetrations from 350 oil wells, 2D seismic reflection surveys, industry field maps and USGS QFaults surface traces, we present a new 3D model of the NIF at Long Beach, including its connections to the adjacent Seal Beach and Dominguez fault segments.

Current 3D representations of the NIF in the SCEC Community Fault Model describe it as a set of simple, disconnected, vertically-dipping strike-slip faults. Our analysis shows that the fault system is complex, with a series of dip-slip reverse faults of ~60° dip that orthogonally intersect and connect the en echelon, through-going strike-slip fault segments. The strike-slip faults are non-vertical and non-planar, and shallow their dip and merge with one another at depth, extending down through the seismogenic crust.

These diverse hard fault linkages present numerous rupture pathways and arrest points that NIF earthquakes may take as they propagate through Long Beach.

We apply map-based restoration to quantify how much total slip has passed through each of the fault segments at Long Beach. Ultimately, we aim to compare this pattern with dynamic rupture simulations on our fault model, to see if they illuminate preferred rupture pathways and recreate the slip partitioning observed in the geologic record, which represents hundreds of earthquake cycles.

An Experimental Perspective on the Formation of Pulverized Rocks During Transient Coseismic Dilatancy

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Pulverized rocks are enigmatic fault damage zone structures frequently found in large, strike-slip fault zones and characterized by predominantly volumetric deformation due to intense, randomly-oriented mode I fractures. Their genesis has been associated broadly with transient normal stress changes near the propagating tip of earthquake ruptures. Past experiments have shown that brittle rock fabrics with properties similar to natural pulverized rocks can be formed by subjecting rock samples to large uniaxial compressive loads at rapid strain rates (>10^2 s^{-1}), but the differential stresses and strain rates required are much larger than those expected in shallow fault damage zones during dynamic rupture. An alternative hypothesis is that pulverized rocks form during rapid, dilatational strains. Over the past few years, we have utilized a modified experimental configuration for a split Hopkinson Pressure Bar (SHPB) to simulate the fragmentation of rocks under isotropic tensile loads to study this alternative hypothesis. The experimental configuration replaces the uniform cylindrical specimen of traditional SHPB tests with a rock disk bonded between two lead disks. Axial compression of the sample causes radial expansion of the lead, which induces transversely isotropic tension in the rock disk. We use this experimental method to investigate damage accumulation by transient tensile loading in four different rock types, and over multiple earthquake cycles in Westerly granite. We show that the fracture patterns produced have many of the same properties as natural pulverized rocks, and the fracture density (A) varies as a function of lithology and (B) increases during each successive loading cycle. Our work suggests that pulverized rock can be produced under tension at strain rates as low as 10^{-3} s^{-1} or lower, and the fracture density and spatial extent may be controlled by the size of the coseismic tensile stress perturbation and the number of slip events on the fault.

Combining Dark Fiber and Seismic Interferometry to Measure Physical Properties of Faults in the Imperial Valley

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Using interferometry, aftershocks of large events can be treated as a network of virtual seismometers to allow detailed measurements along the fault trace. The Virtual Seismometer Method (VSM) is a technique that provides precise estimates of the Green Function (GF) between earthquakes (Curtis et al., 2009; Hong and Menke, 2006). This isolates the portion of the data that is sensitive to the source region and dramatically increases our ability to see into tectonically active features, such as at depth in active fault zones.By comparison, fiber optic sensors enable dense (meter-scale) sampling of the seismic wavefield over large distances (10's of km). When an earthquake is recorded by such an array, we see detailed ground motion, including highly scattered arrivals that are a record of heterogeneities along the entire path between the source and each channel along the length of the fiber. When used in combination, these two technologies allow us to obtain high quality measurements of physical properties around active faults, even with small magnitude events. Here, we present results from the Imperial Valley Dark Fiber Experiment, which recorded thousands of local earthquakes during its deployment, including a large swarm near the southern end of the Salton Sea and a sequence of events along the Imperial Fault, south of the array. We illustrate the methodology and the sensitivity of the technique with respect to earthquake magnitude, distance and relative geometries, and contrast the application of dense DAS fiber with more traditional seismic arrays. We inverted the resulting GFs to measure the seismic velocity and attenuation of the active region, allowing us to identify large structural heterogeneities and estimate the local faulting and fracture patterns.This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

Investigating the Causative Mechanisms of Widely Distributed Fracturing Around the 2020 m6.5 Monte Cristo Range Earthquake Rupture, Nevada USA

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The 15 May 2020 M6.5 Monte Cristo Range, NV earthquake ruptured 30 km of left-lateral and left-normal faults, yet produced surface rupture only along 9 km of oblique left-normal faults, >10 km west of the epicenter. These surface ruptures are complex and distributed, but can be broadly characterized as two subparallel NE-striking fault zones connected by a narrow west-dipping normal fault. Ground deformation imaged by satellite radar interferometry (InSAR) indicates that the southern (and larger) of these two main surface rupture zones lies along the trace of the source fault. However, the distributed nature of the discrete surface breaks precludes identification of a single main surface trace; instead the faulting at the surface comprises a 500 – 800-meter-wide zone of closely spaced cracks (decimeters to decameters apart and meters to tens of meters long) each exhibiting cm-scale left-extensional offsets. Whether pervasive surface cracking like this represents a hazard to the built environment depends upon the strain it reflects, which is dictated by whether it formed through shaking effects, bulk strain of the volume, or discrete fault ruptures breaching the ground surface.

Using field mapping and remote sensing, we evaluate the spatial distribution of different controls on fracture distribution. We find that almost all of the fractures are located in alluvium that experienced shear strains of >10^{-4} within the continuous deformation field of the rupture. Thus while shaking may play a role in generating some of the fractures, they likely represent the manifestation of tectonic strain in surface materials. We further conclude based on mapping of alluvial landforms that fracture density and distribution is modulated by the age and composition of surface deposits likely reflecting variations in cohesion and yield strength. Excavation could illuminate the depth extent of many of these fractures and help distinguish between generative mechanisms.

Seismic Identification and Location of Blind, Near-Vertical Faults in Granitic Rocks With Application to Wide-Ranging Geologic Settings

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Identifying and locating near-vertical faults using seismic methods can be difficult in granitic rocks, especially for blind faults in sediment-covered areas. We used multiple seismic methods, including two-dimensional Vp tomography, MASW-based Vs, Vp/Vs ratios, Poisson's ratios, and reflection imaging to identify and locate subsurface faults in the western Mojave Desert of southern California. Below the groundwater table within fault zones and relative to non-faulted rocks, Vp is high due to saturation, and Vs is low due to shearing. As a result, Vp/Vs and Poisson's ratios are high (up to 4.0 and 0.45, respectively) in the fault zones. These observations allow us to identify faults based on prominent co-located near-vertical zones of high Vp, low Vs, high Vp/Vs ratios, and high Poisson's ratios, and in unmigrated reflection images, these same faults appear as zones of near-vertically aligned diffractions. Our western Mojave Desert seismic profile traverses a sediment-covered valley and bedrock exposures in local hills. Geologic mapping by others identified surface fault traces in the hills that coincide geographically with the seismically imaged subsurface faults. Furthermore, the seismic images show that there are prominent blind faults beneath the sediment-covered valleys that were not identified from surface mapping. Laterally varying depths of the 1500 m/s velocity contour in the Vp tomographic images coincide with the depths of the groundwater table measured in multiple wells along the seismic profile. Vertical offsets in the groundwater table (1500 m/s) are seen across imaged near-vertical faults, demonstrating that the faults act as barriers to lateral groundwater flow and further confirming their subsurface locations. These combined seismic methods allow effective identification and location

of faulting in both subsurface sediments and granitic or crystalline rocks, and the methods can be applied to image faults in most other terrestrial settings.

The Competitive Effects of On-fault Normal Stress and Off-fault Seismic Velocity Change on Seismic Cycles

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The temporal variation of elastic property of the bulk material surrounding the fault is considered an important contribution to the observed co-seismic velocity reduction and interseismic healing. Paglialunga et al. [2021] found that as fault normal stress increases, co-seismic velocity reduction becomes larger because more cracks reopen with higher stress drops. Larger normal stress can lead to smaller nucleation size and contribute to larger co-seismic slip. By contrast, with larger co-seismic velocity reduction and interseismic healing, more slow slip events can propagate in the seismogenic zone [Thakur and Huang, 2021], because the temporal velocity change related to fault zone damage modulates earthquake nucleation. Hence, fault normal stress and temporal damage zone structure evolution have opposite influences on the spatial distribution and recurrence intervals of earthquakes.

We conducted 2-D anti-plane fully-dynamic seismic cycle simulations and explored the effects of fault normal stress on seismic cycle when there is coseismic damage and interseismic healing in the fault damage zone. The normal stress is in a range of 40-70 MPa and the co-seismic rigidity reduction is in a range of 5-8%. We find larger normal stress results in larger co-seismic slip and fewer slow slip events, while more co-seismic velocity reduction and interseismic healing leads to more partial ruptures as well as slow slip events. With the increase of both normal stress and seismic velocity change, more regular earthquakes occur and slow slip events gradually disappear. For the selected parameter space, the influence of seismic velocity change is not as significant as the effect of normal stress. However, fault zone maturity or the initial rigidity of fault damage zones should also affect the competitive relationship between normal stress and seismic velocity change, and we will characterize earthquakes and slow-slip events in immature and mature fault damage zones when both on-fault normal stress and off-fault seismic velocity vary over earthquake cycles.

The Healing Process and Healing Time Estimate of the Longmenshan Fault After the Wenchuan Earthquake

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The recovery process of fault locking degree is an important reflection of fault healing process, so the fault healing process can be effectively identified according to the evolution characteristics of fault locking degree determined by inversion. According to the inversion results of multi-stage GPS horizontal velocity field data, the time of complete healing can be basically determined for the healed section. For the ruptured sections still in the healing process, the healing time can be estimated by logarithmic fitting (Pei et al., 2019): Firstly, according to the inversion results of multi-stage data, the dynamic locking degree at the same node were extracted, and the value were fitted with a logarithmic function. After the optimal fitting, the required time of complete healing was estimated.

In this paper, we study the evolution process of the locking degree in the middle section of Longmenshan fault after the Wenchuan earthquake. The results show that: along the fault dip direction, multiple columns of nodes show rapid recovery of strong locking from shallow to deep, that is, the fault plane quickly recovers healing state from the surface to deep. Along the strike direction, multiple rows of nodes show rapid recovery of strong locking from southwest to northeast of fault, that is, the fault plane quickly recovers healing state from the rupture termination position to the source direction. At present, the process of fault healing is just the opposite of the coseismic rupture, and the healing area has reached the source, and the healing rate is very fast. Combined with the healing process of the northeast section, it can be inferred that the healing of the whole Longmenshan fault plane will take about 10 years more. After the fault healing, it means that the fault begins to accumulate energy rapidly. The research results of the Wenchuan earthquake show that its recurrence cycle is about 2500-5000 years (Zhang et al., 2008; Zhao et al., 2012), so it will take long time to accumulate enough energy to form an asperity of *M*8 earthquake.

This work was supported by Science for earthquake resilience (XH23047A).

The Palos Verdes Fault Damage Zone From the Seafloor to the Basement: Revealed Using Multi-Resolution Controlled Source Seismic Reflection Datasets

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The distribution and intensity of fault damage zones provide insight into the inelastic response of Earth to strain. Presently, measures of the in-situ distribution of faulting at depth remain limited. Here, we identify and analyze the fault damage zone of the San Pedro Bay segment (~20 km) of the Palos Verdes Fault offshore southern California using: two legacy controlled source (low frequency) 3D seismic reflection volumes, recently collected high resolution sparker (high frequency) multichannel seismic (MCS) lines, and existing multibeam bathymetry surveys. We apply a novel algorithm to identify discontinuities in the seismic data that are attributed to faults and fractures. Using datasets collected with differing source spectra and acquisition parameters allows for the systematic analysis of the damage zone from the shallow subsurface to the basement (0 - 2 km below seafloor). The results show that damage through fracturing is concentrated around mapped faults and decreases with distance from the fault. Analysis of the 3D seismic datasets (depths ~450 - 2 km) reveal that the along-strike averaged (~ 20 km) damage zone decays exponentially with distance and extends to ~ 2 km from the central fault strand. When examining the damage zone at a shorter along-strike (4.5 km) distance in the 3D volumes or in 2D MCS cross-sections, several discrete strands are resolvable. We find that peak 2D MCS fracturing (from the seafloor to 400 meters below) correlates with a fault scarp observable in the bathymetry suggesting that this technique may be useful in determining the dominant or most recently active fault strand.

Active Faults in the Caribbean and Central America

Oral Session • Thursday 20 April • 08:00 AM Pacific

Conveners: Daniel A. Laó-Dávila, Oklahoma State University (daniel.lao_davila@okstate.edu); Lorna G. Jaramillo-Nieves, University of Puerto Rico, Rio Piedras (lorna.jaramillo@upr.edu)

Earthquake Magnitude-Frequency Distributions in the Northern Caribbean Plate Boundary Using Combinatorial Optimization

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On-fault earthquake magnitude-frequency distributions are calculated for northern Caribbean faults using estimates of fault slip and regional seismicity parameters. Integer programming, a combinatorial optimization method, is used to determine the optimal spatial arrangement of earthquakes sampled from a truncated Gutenberg-Richter distribution that minimizes the global misfit in slip rates on a complex fault system. Slip rates and their uncertainty on major faults are derived from a previously published GPS block model for the region, with fault traces determined from offshore geophysical mapping and previously published onshore studies. The optimal spatial arrangement of the sampled earthquakes on these faults is compared with the 500-year history of earthquake observations. Rupture segmentation of the subduction interface along the Hispaniola-Puerto Rico Trench (PRT) fault and the degree of seismic coupling on the PRT fault appear to exert the primary control over this spatial arrangement. Introducing a rupture barrier for the Hispaniola-PRT fault northwest of Mona Passage, based on geophysical and seismicity observations, and assigning a low slip rate of 2 mm/yr on the PRT fault are most consistent with historical earthquakes in the region. The addition of low slip-rate secondary faults as well as segmentation of the Hispaniola and Septentrional strike-slip fault improves the consistency with historical seismicity. The modeling indicates that varying the slip rate on the PRT fault and different segmentation scenarios result in significant changes to the optimal magnitude distribution on faults farther away, such as Enriquillo and Septentrional. Maximum magnitudes on plate boundary faults from the forecasted distributions are less than the physical maximum magnitude calculated from the entire area of the fault, calling into question the feasibility of an M9 on the PRT.

Strain Partitioning Within the Caribbean-North America Transform Plate Boundary in Southern Haiti, Tectonic and Hazard Implications

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GPS measurements and high-resolution offshore seismic data within the transform Caribbean – North American plate boundary in southern Haiti, Greater Antilles, show 6-7 mm/yr of plate boundary-normal shortening within a crustal sliver bounded to the south by the Enriquillo left-lateral strike-slip fault and to the north by a south-dipping reverse fault system offshore the northern coast of the Southern Peninsula of Haiti. This overlooked fault system, which we name "Jérémie-Malpasse", marks the overthrusting of the Cretaceous oceanic crust of the Caribbean basin of the Southern Peninsula over accreted terranes of island arc crust to the north. Geological and geodetic data are consistent with a tectonic model that reconciles recent observations of plate boundary-perpendicular shortening with ample geological evidence for purely strike-slip motion on the Enriquillo fault. This model also provides a framework to interpret the 2010 M_w7.0 and 2021 M_w7.2 earthquakes in southern Haiti, whose oblique slip mechanisms are indicative of a localized transpressional strain regime. These findings imply that regional seismic hazard maps must be updated to account for both the existence of the ~350 km-long Jérémie-Malpasse fault system and for the possibility that future earthquakes in southern Haiti may occur on non-vertical faults with a significant component of reverse slip.

Earthquake Ruptures on Complex Fault Systems: Insights From Recent and Historical Earthquakes in Haiti

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Haiti has experienced several damaging M 7+ earthquakes in recent and historical times. Recent studies used primary archival sources to characterize the shaking distributions of the 1860 Jour de Pâques sequence and 1770 earthquake, and explored rupture scenarios using modern ground motion models. For the 1860 sequence, French-language newspapers published in Haiti provide more detailed macroseismic data than considered in previous studies, permitting identification and analysis of three damaging events. For the 1770 sequence, contemporaneous French-language reports provide detailed descriptions of the earthquake and its effects. Our results support the interpretation that the 1770 earthquake was the largest documented earthquake on the Enriquillo Plantain Garden Fault zone in the last 300 years, with estimated M 7.6. The preferred rupture scenario extends from east of Port-au-Prince to the west along the peninsula, terminating to the west near the Miragoâne pull-apart basin. This basin is interpreted as a left-stepping releasing bend along the EPGF zone, ~75 km west-southwest of Port-au-Prince. Part of the 1770 rupture may have been associated with overthrusting of the *Massif de la Selle*. *Martin and Hough* (2022) conclude that the 1860 sequence released appreciable strain near the Miragoane pull-apart, in the gap between the 2010 and 2021 earthquakes, providing an explanation for why these two rupture zones were not contiguous. The results further suggest that the 2010 and 2021 earthquakes together released less total moment than the 1770 earthquake. The 2010 earthquake may have occurred on the same fault(s) that ruptured in the 1770 earthquake or on one or more nearby subparallel faults. Results thus support the paradigm that fault zone complexity controls rupture segmentation, but rupture history on a complex fault is controlled by a combination of fault zone structure, dynamic processes, and prior rupture history that control individual earthquake ruptures.

Rupture Segmentation of the August 14, 2021 Mw7.2 Nippes, Haiti, Earthquake Using Aftershock Relocation From a Local Seismic Deployment

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The 14 August 2021 M_w 7.2 Haiti earthquake struck 11 years after the devastating 2010 event within the Enriquillo Plantain Garden Fault Zone in the Southern peninsula of Haiti. Space geodetic results show that the rupture is composed of both left-lateral strike-slip and thrust motion, similar to the 2010 rupture, but aftershock locations from a local short-period network are too diffuse to precisely delineate the segments that participated in this rupture. A few days after the mainshocks, we installed 12 broadband stations in the epicentral area. Here we use data from those stations in combination with 4 local Raspberry Shakes stations that were already in place as part of a citizen seismology experiment to precisely relocate 2528 aftershocks from August to December 2021 and derive one-dimensional P and S crustal velocity models for this region. We show that the aftershocks delineate three north dipping structures with different strikes, located to the north of the Enriquillo Plantain Garden (EPG) fault. Additionally, two smaller aftershock clusters occurred on the EPG fault near the hypocenter area, indicative of triggered seismicity. Focal mechanisms are in agreement with coseismic slip inversion from InSAR data with nodal planes that are consistent with the transpressional structures illustrated by the aftershock zones.

Postseismic Response to the 2021 Haiti Earthquake: Advanced Insar Analysis and Implications for the Triggered Fault Creep

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The recent August 14, 2021 MW7.2 Nippes earthquake occurred 75 km to the west of the Mw7.0 2010 earthquake that happened near Port-au-Prince, Haiti, both on the Enriquillo-Plaintain Garden fault zone (EPFGZ). The 2021 earthquake left a seismic gap between the two events that has not experienced any large aftershocks from either event. Identifying if and where postseismic deformation occurred on the EPGFZ following the earthquake is a critical step to identify whether the seismic gap on the EPGFZ will be the site of a future MW7 earthquake or will release its strain aseismically (Martin & Hough, 2022).

In this study, we collect multi-temporal data acquired by Sentinel-1 A/B and ALOS-2 satellites and use an advanced InSAR processing approach implemented in FRInGE package (Fattahi et al., 2019) to map early postseismic deformation following the 2021 Haiti mainshock. Fringe exploits the interferometric covariance matrix formed for each distributed scatterer (DS) over its neighborhood and the phase history of each permanent scatterer (PS) to estimate surface deformation at high spatial and temporal resolution. The measured surface displacement in our study reveals the spatiotemporal evaluation of shallow creep along EPGFZ to the east of the epicenter. We use the cumulative displacement map and profiles across the EPGFZ to investigate the behavior of the fault in a short period following the 2021 earthquake and construct models of cumulative slip. In the future, we plan to address the following questions: (1) does the afterslip reflect the stress triggered by the mainshock? (2) based on the InSAR observations, can frictional parameters be calculated on the fault?

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The Societal Cost of Fault Uncertainties in the Caribbean Island of Hispaniola

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The Caribbean Island of Hispaniola is comprised of two side-by-side countries: Haiti to the west and the Dominican Republic (DR) to the east. With the Island's 20M+ inhabitants, high population cities, such as Port-au-Prince in Haiti and Santo Domingo in the DR, are centers of substantial risk exposure

tied to a multitude of natural hazards, including hurricanes, earthquakes, and floods. Haiti's vulnerability to natural disasters is generally much higher than that of the DR, which has a greater Gross Domestic Product, economic growth rate, and readiness for disaster. The Island hosts many seismically active faults that pose significant seismic risk to both countries. Two recent highly damaging earthquakes in Haiti are the Mw 7.0 January 2010 earthquake, which killed over 200,000 people and resulted in $8B worth of damage, and the August 2021 Mw 7.2 earthquake, which killed more than 2,000 people and caused over $1.5B in losses. The Septentrional and the Enriquillo-Plantain-Garden (EPG) left lateral strike-slip fault zones faults have high slip rates, are spatially extensive, and seismically active. It is estimated that the Septentrional fault can cause a Mw 7.5 or larger earthquake, and the EPG fault can cause a Mw 7.2 earthquake. An accurate estimate of risk metrics, such as average annual loss (AAL) or the probability of a loss exceeding some threshold, affects a country's earthquake preparedness and its speed of recovery, through mitigation, (re) insurance, and catastrophe bond issuance and buy-in. Understanding individual contributions of major faults to these metrics can help governments differentiate risk in particular locations so they can set priorities. In this work, we explore the risk sensitivity to variations in fault segmentation, preferred slip rates, rupture behavior (single vs. multi-segment), and maximum magnitude on both the Septentrional and the EPG fault systems.

Towards an Updated Quaternary Fault Map of Puerto Rico

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Puerto Rico is the largest landmass of the Puerto Rico-Virgin Islands microplate, along the Caribbean–North American plate boundary between the Puerto Rico trench oblique subduction zone and the Muertos Trough incipient subduction zone. Despite recent seismicity and geodetic deformation that record ~3 mm/yr of left-lateral slip across the island, the locations of Quaternary faults accommodating deformation throughout the island are still mostly uncertain. The preservation of recent faulting in the landscape is masked by moderate-to-slow fault slip rates (<1 mm/yr) and distributed faulting, humid tropical weathering, steep topography resulting in frequent landsliding over large parts of the island, and extensive agricultural activity and urbanization near the coastlines and in river valleys. Many of the previously identified potentially active faults are in the arid southwestern region of the island. We present new remote neotectonic mapping of historical imagery from the 1950s-60s and recent 1-m lidar data, integrated with field observations, to create an updated active fault map of Puerto Rico. We focus on faults that offset younger geomorphic surfaces, with age estimates constrained by previous geologic mapping and our landscape interpretations. We also map fault-related features that may represent active deformation in regions where younger geomorphic surfaces are not present. Scarps along the South Lajas, Salinas, Cerro Goden, Great Southern Puerto Rico, and San Marcos faults record vertical and sometimes lateral motion. More subtle fault-related features, such as sag ponds, linear ridges and valleys, and laterally offset channels are present along the Punta Montalva, San Marcos, and Cerro Goden faults. Together, these new observations, integrated with recent fault studies, provide the foundation for an updated Quaternary fault map of Puerto Rico. Future studies will focus on constraining fault slip rates and earthquake recurrence intervals.

Searching for Holocene Slip on the Cerro Goden Fault, Western Puerto Rico

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Identification of Holocene-active onshore faults in Puerto Rico (PR) is key to seismic preparedness on the island and to appraisal of long-term seismic hazard. Human development, vegetation, relatively low sedimentation and high denudation rates, and destructive storms can obscure paleoseismic targets. Here, we develop a crustal stress map of PR that is used to winnow candidate traces identified from aerial and satellite imagery for paleoseismic investigations. The Cerro Goden fault zone (CGFZ) is mapped onshore and offshore in western Puerto Rico. Marine seismic and bathymetric data provide evidence for Holocene rupture and sediment deformation along several 1–3 km long, subparallel strands trending N75E to N88E. Onshore, the CGFZ appears to continue N80E for 4 km along the southern boundary of the La Cadena de San Francisco mountains before rotating to N100E, then to N110E, and splaying into the Great Southern Puerto Rico fault zone. Until recently, however, crustal stress field constraints in Puerto Rico were limited to a single near-shore and five offshore moment tensors with normal mechanisms. With 250 moment tensors now available, albeit none directly along the CGFZ, we create a crustal stress map of the island. Oblique motion dominates with secondary extension rotating from N140E in the northwest to N150E near the Indios sequence. Fault slip potential modeling in the vicinity of the CGFZ shows that steep, ~N20E or N80E strike-slip faults and ~N50E normal faults are optimally oriented for slip, but faults striking between N95E and N185E are unlikely to undergo frictional failure. With these considerations in mind, several potential new trenching sites are identified west near the coastline where the CGF trends N80E.

Newly Discovered Tsunami Deposit in Northwest Puerto Rico Supports a Pre-Columbian Megathrust Earthquake on the Puerto Rico Trench That Generated an Atlantic-Wide Tsunami

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The written record of Caribbean tsunamis extends back over 500 years, but does not include one generated by a great earthquake (> Mw 8.0) on the megathrust at the Puerto Rico Trench. We cored a coastal mangrove pond at East Bajura near Isabela in Northwest (NW) Puerto Rico to search for tsunami deposits from a possible megathrust earthquake. The pond extends inland 150 to 350 meters from a sandy beach, spans about 1 km in the alongshore direction, and is 0.5 meters above present sea level. Pleistocene eolianites 5-10 m high, with gaps, protect the pond from swells. Pond sediments are predominately mud or mangrove peat. More than 30 sediment cores document a thin (1- 7 cm thick) sand sheet at about 60 cm depth throughout the pond. This layer exhibits suspension grading, an erosive basal contact, and an organic cap which suggest deposition from a high energy flow, most likely a tsunami. An event-free Bayesian age-depth model using radiocarbon dates of plant macrofossils above and below the sand sheet constrain the timing of deposition to 1470 to 1530 CE. This age overlaps in age with tsunami deposits emplaced between 1200 and 1500 CE on the coasts of the islands of Saint Thomas, Anegada, Saba, and Anguilla, approximately 200-400 km to the east of East Bajura, that face the Puerto Rico Trench. Modeling by Codrie et al. (2022) of an approximately 200-km long rupture on the Puerto Rico Trench from Saint Thomas to Anguilla indicates a tsunamigenic Mw 8.7 megathrust earthquake is required to account for the pre-Columbian tsunami deposits observed in the Lesser Antilles. Pre-Columbian tsunami deposits from NW Puerto Rico suggests a plausible rupture length of 400 km, which would result in a greater magnitude earthquake and a tsunami that would effect both Caribbean and Atlantic coasts. Future work using the inland extent and elevation of correlated tsunami deposits and tsunami modeling will better constrain the pre-Columbian earthquake and tsunami in the Caribbean.

A Pre-Colombian Tsunami in Lesser Antilles ? Identification of the Source Using Sediment Deposits and Tsunami Modeling

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No earthquake similar to the events of Sumatra in 2004 or in Japan in 2011 was firmly reported in the Lesser Antilles subduction zone. The two largest known tsunamis were generated by a strong intraplate earthquake in the Virgin Islands in 1867, and by the 1755 Lisbon earthquake. In this region, where the convergence rate between the American and Caribbean plates is low, the recurrence time of large earthquakes may be long (several centuries

or millennia) and the historical record of such events is short. It is thus difficult to estimate their impact and it becomes crucial to gain information from longer-term geological records and tsunami modeling. An increasing number of old prehistoric tsunami deposits have been identified in recent years on several islands in the northern segment of the Lesser Antilles arc, between Antigua and Puerto-Rico, in Anegada, St-Thomas (Virgin Islands), Anguilla, and Scrub islands. We reviewed all those studies and evidenced that numerous tsunami deposits are about 500 years old (~1500 cal CE) likely suggesting a large event or a cluster of events during this Pre-Colombian period. We combined information provided by the sedimentological records (distribution and altitude of the sediment deposits) and tsunami models to discuss the origin of this middle age Pre-Colombian event(s). We listed all faults as possible sources of tsunamis in this complex tectonic region and used them to perform multiple run-up models by using high-resolution/topographic grids. By comparing the simulated wave heights and run-up distance to the sediment record, we showed that only magnitude 8-9 mega-thrust or outer-rise scenarios are able to generate tsunami waves that match the characteristic of the observed tsunami deposits. We will present here these results, discuss the realism of the models in light of the recent coupling models of the subduction zone based on short-term geodetic records, and also mention the hypothesis of these deposits being related to major Pre-Colombian hurricane(s).

Late Quaternary Paleoseismological Record of Large Earthquakes in the Lesser Antilles: Implications for Arc Segmentation and Long-Term Seismic Cycle of the Megathrust.

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The seismic potential of the Lesser Antilles subduction zone is poorly known and highly debated. Only two strong damaging and deadly earthquakes have been reported in the historical period in on January 11th 1839 and on February 9th 1843 offshore Martinique and Guadeloupe islands, respectively but their source and magnitude are still uncertain. GNSS and coral data contradict each-others and we cannot conclude on the coupling rate of the plate interface. Given the threat posed by the possible occurrence of a large megathrust earthquake in the future in this region, it was urgent to gain information on the sources, magnitude and recurrence time of past pre-historical events. We present here the results of a submarine paleoseismological study that cover an exceptional ~100 kyr-long time period. We studied the sediments sampled in six up to 26 m-long giant piston cores collected on board of the French R/V Pourquoi-Pas? In deep fore-arc basins in the epicentral region of the 1843 earthquake. Using a multiproxy approach combining geophysical, geochemical, sedimentological analysis, foraminifera species biostratigraphy and radiocarbon dating, we identified, characterized and dated numerous turbidites and homogenites. Some occurred in all basins we sampled over a minimum distance of 160 km. We showed that they were likely triggered by at least 33 earthquakes in the last 120 ka. Peak ground accelerations calculated for various faults indicate that the sources are megathrust events. The spatial extent of the deposits suggests a seismic segmentation of the plate interface. Four of the seismic events, we called major margin events, led to up to 8 m-thick exceptional deposits of turbidites+homogenites. Over the last 60 ka, we inferred at least four 15 and 25 ka-long super seismic cycles in which the recurrence times of earthquakes shorten from ~5 to ~2 ka, what is an unusual behavior.

20th-Century Interseismic Deformation in the Lesser Antilles Subduction Zone From Coral Microatolls

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The earthquake and tsunami potential of the Lesser Antilles megathrust is poorly known, despite the hazard it poses to numerous island populations and its proximity to the Americas. While the fault has not produced large earthquakes in the instrumental era, historical records of great earthquakes in the 19th century and earlier, which were likely megathrust ruptures, suggest that the subduction is not entirely aseismic. We used coral microatoll paleogeodesy to study century-scale vertical deformation in the northern Lesser Antilles. Only one microatoll has been found that is old enough to potentially record 19th-century earthquakes, and no "fossil" microatolls have been found that might record earlier events. However, we found many sites with microatolls recording 20th-century vertical deformation, which demonstrate that the eastern coasts of the forearc islands have been subsiding by up to ~8 mm/y relative to sites closer to the arc. Modeling this deformation as the result of underlying strain accumulation on the megathrust suggests that a portion of the megathrust interface just east of the forearc islands has been locked during the 20th century. If this model is correct, the accumulated strain detected by microatoll studies will likely be released in future megathrust earthquakes, uplifting previously subsiding areas and potentially causing widespread damage from strong ground motion and tsunami waves.

Reconciling our results with decadal-scale instrumental geodesy has proven challenging. Models of instrumental horizontal deformation suggest little or no strain accumulation anywhere along the Lesser Antilles megathrust, and instrumental vertical deformation shows subsidence averaging 1–2 mm/y across the Lesser Antilles, variable between neighboring sites and with varying degrees of agreement with our data. The discrepancy with our results can potentially be explained by the different time scales of measurement, as recent studies elsewhere have indicated that interseismic coupling patterns may vary on decadal time scales and that century-scale or longer records are required to fully assess seismic potential.

General Subsidence of the Lesser Antilles Over a Decoupled Subduction Megathrust

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In the Lesser Antilles, apparently contradictory observations led to different conclusions over the degree of locking of the subduction megathrust, hence on the evaluation of the seismogenic potential of the subduction zone. While two large earthquakes hit the area during the 19th century, existing block models suggested the megathrust is largely uncoupled on average, raising the question of the nature of the earthquakes or of the permanence of kinematic coupling over long periods of time. We re-evaluate in a probabilistic framework the distribution of coupling along the megathrust using velocities derived from GNSS measurements. Our approach allows to consider the formal measurement uncertainties as well as the uncertainties associated with errors in basic assumptions to derive surface predictions. Our model confirms that the megathrust is most likely uncoupled, with a reasonable level of certainty. We compare predictions from this coupling model to vertical displacements averaged over each individual island of the Lesser Antilles arc. While no coupling should result in no net vertical motion over the interseismic period, we observe a general subsidence of the entire arc. We relate such subsidence, ongoing since approximately 125,000 years, to geodynamic processes at the regional scale unrelated to the state of coupling along the megathrust. Our study provides observations of vertical motion over a range of time scales for an end-member, fully uncoupled subduction megathrust, to be put in perspective with equivalent observations over coupling megathrust such as in Chile, Japan or the Himalayas.

Analysis and Proposal of Empirical Magnitude Scaling Relationships for Faults Seismic Potential in Central America

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Central America is a seismically active region where five tectonic plates (North America, Caribbean, Coco, Nazca, and South America) and the Panama Microplate interact, in a subduction zone with transform faults and

near to triple points. This complex tectonic setting makes the estimation of the seismic potential (maximum magnitude: Mmax) a very important task. There are a series of empirical formulas and diagrams by means of which the seismic potential of faults can be estimated from rupture earthquake parameters. In this study, some of these formulas were applied to approximate the magnitude of earthquakes occurred in Central America, and own scaling laws are proposed. This has been accomplished based on the most complete data set of relevant and better characterized earthquakes generated by faults in the region, made up of 64 earthquakes between 1972 and 2021, with magnitudes between 4.1 and 7.7 Mw. The data set consists in a compilation of the seismic events and its relatively well-established rupture parameters (length, width, area, slip, magnitude) and characteristics (location, faults, aftershocks). These analyses allowed to determine which global equations fit best, and to propose new empirical relationships specific for Central America, for the rupture parameters of length, width, and rupture area. These relationships have been validated and logical trees are suggested that combine the proposals for the region and global equations. Based on this, 30 faults of Central America have been selected, for which its Mmax has been estimated considering a total rupture of the fault length mapped. According to that, the countries with more faults with Mmax > 7.0 Mw are Guatemala and Nicaragua. However, most of the faults studied present Mmax between 6.2 and 6.5 Mw, and this magnitudes for shallow earthquakes near to populated centers have already been damaging in the past in countries such as Costa Rica, El Salvador and Nicaragua. The proposed equations contribute as a very relevant step for the adequate characterization of faults aimed at seismic hazard assessment, both probabilistic and deterministic approaches.

Potential Shallow Slip and Energy-Deficient Radiation During the 2022 m7.6 Coalcomán, Mexico Earthquake

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Conventional wisdom for large earthquakes at the subduction interface in Mexico has been that slip stops short of the trench, usually at a depth of ~10km. This has certainly been true for M7+ events in the last ~25 years for which slip models constrained by teleseismic and regional seismic and geodetic data exist. Because shallow slip, or its absence, directly impacts the resulting tsunami, this view has had a strong influence on how tsunami hazards are quantified in the country. However, there is paleoseismic evidence of significant tsunamis which can likely only be explained by near-trench slip. In the northern reaches of the subduction zone, there is also compelling evidence that the 1995 M8 Jalisco earthquake included slip to the trench. Here we present a source analysis of the 2022 M7.6 Coalcoman earthquake in Michoacan using teleseismic, regional strong motion, high-rate GNSS, InSAR, and tsunami data. We will show that the slip pattern abuts the southern terminus of the 1995 rupture, and moreover that there is potentially a modest amount of slip at near-trench-depths. We will show a number of different tests that rely on modeling tide gauges near the event using high-resolution bathymetry and confirm that this shallow slip is a necessary feature of the slip model. Additionally, we will show that the radiated energy of the event is significantly less than what is expected both globally and regionally for an event of this size. This is consistent with shallow near-trench slip which typically radiates poorly at high frequencies. Finally, we will discuss the implications of the source properties both from a hazards and a seismotectonics standpoint.

Active Faults in the Caribbean and Central America [Poster]

Poster Session • Thursday 20 April

Conveners: Daniel A. Laó-Dávila, Oklahoma State University (daniel.lao_davila@okstate.edu); Lorna G. Jaramillo-Nieves, University of Puerto Rico, Rio Piedras (lorna.jaramillo@upr.edu)

Age Dating and Sedimentology of a Pre-Colombian Tsunami Deposit, Northwest Puerto Rico

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Written and geologic evidence show that within the last 500 years most tsunamis impacting Puerto Rico have been generated by local intraplate earthquakes or by earthquakes in the far field across the Atlantic, yet it is unclear whether the Puerto Rico Trench has produced great earthquakes and tsunamis in the Holocene. Multiple prehistoric tsunami deposits have been found along the northern islands within the lesser Antilles arc with ages suggesting a pre-Colombian event 500 to 800 years ago. This study extends evidence of this possible pre-Colombian event farther west along the Puerto Rico Trench, to East Bajura, a coastal mangrove pond in northwest Puerto Rico. At East Bajura pond, we observed a distinct sandy deposit at more than 30 coring locations. We used a Rotating X-Ray Computed Tomography (RXCT) system to scan 19 sediment cores at 130-micron resolution. We utilized the 3D imagery to interpret relative sediment grain size, identify subtle differences between sedimentological units, examine sedimentary structures, and look for sections with minimal bioturbation. Based on the density analysis, we selected a representative core with distinct stratigraphy and abundant organic content for radiocarbon analysis. To constrain the timing of sand deposition, we selected seven samples of semi-translucent mangrove rootlets and wood taken from above and below the deposit for radiocarbon analysis. The deposit age is determined using an event-free Bayesian age-depth model in Oxcal, which indicates deposition of the deposit in East Bajura occurred between 1470 and 1530 CE, which is consistent with ages of tsunami deposits in the lesser Antilles. Further analysis will focus on developing the age-depth model and applying similar age dating and lithostratigraphic analyses on a deeper and thicker sand deposit observed in the East Bajura stratigraphic archive. Ultimately, this work aims to extend the pre-historic record of tsunami events along the northern coast of Puerto Rico.

Imaging of Tectonic Tremor Activity Along the NW Caribbean Coast and its Implication with Subduction Processes: A Study Case with Colombia-Venezuela CARMA Seismological Network

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The discovery of low-frequency earthquakes and especially non-volcanic tremors revealed the complexity and variety of seismic sources associated with active deformations in different tectonic settings. A long-term analysis of episodic tectonic tremor occurrences was inferred from continuous data obtained from seismological broadband stations recorded by The CARibbean Merida Andes Broadband Experiment (CARMA) consisting of 65 broadband stations extending from the Caribbean sea in northern Colombia and Venezuela to the northern South America interior. Through the preliminary detection methodology from a semi-automatic tremor detection algorithm (Chao & Yu, 2018) using seismic data from 2016-2017, we could identify triggered tectonic tremor associated with several M6+ teleseismic earthquakes occurred in this period and its influence along major structural features associated with the Caribbean plate subducting beneath northern South America as well as major crustal faults such as the Bucaramanga-Santa Marta and Boconó faults. This study aims to generate a map of tremor activity locating the identified tremor events using a grid-searching technique exploiting the coherency of multi-scale, frequency-selective characteristics of the non-stationary signals recognized as tremor events in a region in which it has previously been unrecognized and together with geodetic observations can help better understand the tectonic setting in this complex region and whether or not there are slow slip processes.

Is the Source of the 1918 Puerto Rico Tsunami a Landslide or a Fault Rupture? a View From the Sea Floor

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The October 11, 1918, devastating tsunami in northwest Puerto Rico, had been used as an example for earthquake-induced landslide tsunami hazard. Three pieces of evidence pointed to a landslide as the origin of the tsunami: the discovery of a large submarine landslide scar from bathymetry data collected by shipboard high-resolution multibeam sonar, reported breaks of submarine cable within the scar, and the fit of tsunami models to flooding observations. Newly processed seafloor imagery collected by remotely-operated-vehicle (ROV) show, however, pervasive Fe-Mn crust (patina) on the landslide walls and floor, indicating that the landslide scar is at least several hundred years old. ^{14}C dates of sediment covering the landslide floor verify this interpretation. Although we have not searched the region systematically for an alternative tsunami source, we propose a possible source, a two-segment normal fault rupture along the eastern wall of Mona Rift. The proposed fault location matches published normal faults with steep bathymetry and is close to the ISC-GEM catalog locations of the 1918 main shock and aftershocks. ROV observations further show fresh vertical slickensides and rock exposure along the proposed fault trace. Hydrodynamic models from a Mw7.2 earthquake rupture along the eastern wall of the rift faithfully reproduce the reported tsunami amplitudes, polarities, and arrival times. Our analysis emphasizes the value of close-up observations and physical samples to augment remote sensing data in natural hazard studies.

New Airborne Magnetic and Radiometric Survey Over Puerto Rico and Surrounding Offshore Areas

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Puerto Rico and its surrounding shelf lie within a complex deformation zone associated with oblique subduction of the North American plate under the Caribbean plate. The seismicity rate is high, including both Benioff Zone earthquakes (>30 km depth) and shallow earthquakes (< 10 km depth). Damaging events include the 2020-2021 sequence near the southwestern shore, historical 1867 Mw~7.2 and 1918 Mw~7.1 earthquakes near the northwest shore, and in some cases, associated tsunamis. Because of the tectonic complexity of the region, locations of shallow faults that could be active are poorly known. Mapping faults in this region poses challenges because many areas of interest are difficult to access. Most onshore areas are densely vegetated, obscuring the surface expression of faults. Offshore areas are covered by shallow (2-20 m) reef platforms limiting ship access for marine geophysical surveys. Aeromagnetic data can assist the identification and mapping of faults both near the surface and at depths where earthquakes occur. However, existing data are limited to a set of surveys flown in 1957 and 1962 that cover less than 40% of the island of Puerto Rico; these pre-GPS, analog data were digitized from contour maps. There are few shipboard magnetic profiles in the shallow shelf areas. An airborne magnetic and radiometric survey covering the entire island of Puerto Rico and surrounding offshore areas will be flown starting January 2023 as part of a collaborative effort between the USGS Earth Mapping Resources Initiative, Earthquake Hazards Program, and Coastal and Marine Hazards and Resources Program. Data will be collected along north-south flight lines spaced 250 m at heights of ~90-400 m, with greater heights in areas with rugged topography or near population centers. This survey represents the first modern aeromagnetic and first aeroradiometric data to be collected over Puerto Rico. We present preliminary data from this survey and consider potential implications for seismicity in the region.

Surface Structure of the Punta Montalva Fault in Southwestern Puerto Rico Using High-Resolution Digital Elevation Models

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The Punta Montalva Fault is an active fault that slipped during the 2019-2021 Puerto Rico seismic sequence. The fault cuts Miocene limestone and contains surface features that suggest left-lateral displacement. Previous work suggested that the fault connects with the North Boquerón Bay Fault for a length of 33 km and poses a large seismic hazard. However, not much is known about the structure, segmentation, and spatial extent of the fault as it is obscured under thick vegetation. This study used high-resolution topographic and bathymetric lidar data to map the surface structure, segmentation, and spatial extent of the fault. The results would allow us to further comprehend the seismic potential of the fault.

High-resolution mapping revealed that the Punta Montalva Fault comprises three main fault segments on land and three fault scarps on the seafloor to the SE. No surficial evidence suggests the Punta Montalva Fault extends further NW into La Parguera. The DEM revealed that the fault cuts a shallowly dipping sedimentary sequence of the Ponce Limestone that has karst topography in places. On land, the fault is conspicuous where it forms scarps, drags and cuts sedimentary layers, and forms a duplex structure with a predominantly left-lateral offset. A left-lateral offset of an intermittent stream has been refined to 133.6 m. The fault scarps along a marine shelf strike E-W and show a maximum normal offset of 4.8 m. Another fault scarp in the seafloor strikes NW-SE and displays a left-lateral offset of 98.3 m. The total length of the fault segments is ~ 2.67 km long. The surface segmentation suggests that the fault would have a lower seismic hazard than if it were continuous and connected to the North Boquerón Bay Fault. However, subsurface imaging is needed to check whether the surface segmentation and extent are characteristic of the subsurface structure of the fault. Strike-slip and normal offset suggest that the area is being deformed by transtentional deformation, which supports seismic analyses and tectonic models.

Toward a Multi-Stakeholder Socio-Seismological Observation Network for Seismic Risk Reduction in Haiti

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Over the past 50 years, earthquakes cost US$ 800 billions – mostly developed countries – and 1.3 million human lives – mostly in developing countries. While these figures show no sign of inflection, risk awareness continues to apply the classic approach where knowledge owned by scientists is translated “downward” to the public and decision-makers. Could a reverse, “bottom-up” approach where citizens collect and share information on earthquakes, be an alternate model? Here we report on the initial stage of the “OSMOSE” project that aims at testing, through a participatory seismology experiment in Haiti – a country struck by two destructive M7+ earthquakes in 2010 and 2021 – whether disseminating knowledge while placing citizens or communities at the heart of scientific information production and usage can improve earthquake awareness and promote protection initiatives. OSMOSE uses low-cost, plug-and-play, *Raspberry Shake* seismological stations which are hosted by volunteer citizens (15 currently operating in Haiti, https://ayiti.unice.fr/ayiti-seismes/) and relies on a collaborative interdisciplinary effort involving seismologists, geographers, sociologists, anthropologists, and educators. We will report on the first seismological outcomes of the project as well as on preliminary lessons learned on interactions between citizen hosts and scientists and what it may tell us on the very notion of “citizen” in today’s society in Haiti.

OSMOSE is operated by J.P. Ampuero, P. Attie, J. Balestra, J.L. Berenguer, E. Bertrand, Q. Bletery, D. Boisson, R. Bossu, E. Calais, N. Calixte, J. Celestin, J. Cheze, V. Clouard, A. Corbet, M. Corradini, F. Courboulex, B. de Lepinay, B. Delouis, A. Deschamps, G. Etienne, L. Fallou, Y. Font, K. Guerrier, L. Hurbon, R. Momplaisir, T. Monfret, S. Paul, F. Peix, B. Pierre, C. Prepetit, E. Rathon, S. Symithe, J.M. Theodat, S. Ulysse.

Partner institutions (France and Haiti): Geoazur, LAM, PRODIG, EMSC, BME, UEH/FDS, UEH/FASH Catts Pressoir, ESIH.

OSMOSE is funded by the French National Research Agency, CNRS, and IRD.

Advances in Characterizing Seismic Hazard and Forecasting Risk in Hydrocarbon Systems

Oral Session • Tuesday 18 April • 02:00 PM Pacific

Conveners: Asiye Aziz Zanjani, Southern Methodist University (aazizzanjani@smu.edu); Heather R. DeShon, Southern Methodist University (hdeshon@smu.edu); Nadine Igonin, University of Texas at Austin (nadine.igonin@beg.utexas.edu); Alexandros Savvaidis, University of Texas at Austin (alexandros.savvaidis@beg.utexas.edu); Jake Walter, University of Oklahoma, Oklahoma Geological Survey (jwalter@ou.edu)

Detecting an Enormous Number of Small-Magnitude Earthquakes Using EQCCT

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We propose to apply a compact convolutional transformer (CCT) to pick the P- and S-wave arrival times of the earthquakes (EQCCT). The proposed algorithm consists of two branches to pick the arrival time of the P and S phases, respectively. Each branch of the EQCCT is responsible for P- and S-wave arrivals, respectively. We train the proposed EQCCT using an augmented version of the STEAD dataset. The augmentation strategy includes: adding Gaussian noise, randomly shifting the waveforms, adding a second earthquake to the input window, and dropping one or two channels from the seismogram. We split the augmented STEAD data into 85% for training, 5% for validation, and 10% for testing. As a result, our EQCCT model outperforms both EQTransformer and Phasenet, which are the two most popular deep-learning-based phase-picking methods. We consider the picked phases within 0.2s as a true positive (TP). For P and S picks, the EQQCT achieves the lowest mean absolute error (MAE) and standard deviation error (sigma) compared to the EQTransformer and Phasenet methods. Besides, our EQCCT network shows the highest precision, recall, and F1 score. Afterward, we apply the pre-trained model to three independent datasets (not included in the training set), i.e., the Japanese, Texas, and Instance datasets. The proposed method shows promising results in terms of picking accuracy and the missing rate. The real-time application of EQCCT in TexNet demonstrates its production-ready robustness in terms of detection and phase-picking accuracies. Specifically, we applied the EQCCT to one-month continuous data of 23 stations in western Texas. We picked the P- and S-wave phases using EQCCT, and associated and located the picked phases using Seiscomp and NonLinloc, respectively. As a result, we detected and located a total of 11687 events, which is more than 50 times the number of catalog events in the same period (215). Among them, 11105 events have a high location quality. This test indicates that with a much shorter monitoring period, EQCCT can detect far more small-amplitude earthquake events than traditionally based on manual picking.

Discriminating Natural and Injection-Induced Earthquakes in the Presence of Uncertainty: A Case Study in Alberta, Canada

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Ever since Davis and Frohlich proposed criteria for recognizing injection-induced earthquakes, three decades ago, the question of whether a particular earthquake (or earthquake sequence) was natural or induced has continued to present controversies and challenges for seismologists. Factors that are usually considered include spatiotemporal correlation with injection operations, location of known faults, prior levels of seismicity activity, modelled stress changes at the hypocenter, existence of permeable pathways, focal depth and source mechanism. A recent proposed scheme uses a questionnaire to assess both the likelihood that an event was induced as well as the strength of the available evidence. A sequence of seismicity in northern Alberta, Canada on 2022-11-30 produced a M5.3 mainshock, with several significant foreshocks and extensive aftershocks. Determination of whether this sequence was induced or natural highlights many of the challenges in discriminating natural from injection-induced events; although the immediate epicentral region has been historically quiescent, inferred natural and induced seismicity have been observed at distances > 20 km; published fault maps are inconsistent in this area; estimated hypocenter locations exhibit a range of depths, with the shallowest placing the hypocentre near the top of Precambrian basement; and sporadic fluid injections have occurred at various depths within the epicentral region, some of which is ongoing. This presentation reviews and compiles available data for this event, applying several recent schemes to evaluate if the sequence was natural or induced.

Cascading and Multi-Segment Rupture of a Mw 5.3 Injection-Induced Earthquake

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Rupture segmentation and propagating earthquake sequences are observed in major fault systems, however, their scalability to smaller fault systems is unclear. We investigated a 2011 earthquake sequence with a moderate magnitude mainshock (Mw 5.3) in the Trinidad zone, located in the Raton Basin on the Colorado-New Mexico border. The complexity of the 2011 earthquake sequence and broader evolution of seismicity from 2008-2022 was captured using machine-learning for initial earthquake detection with an aftershock array followed by automated template detection. The Mw 5.3 mainshock was likely the culmination of cascading failure with slip across multiple well-separated segments. The majority (92%) of aftershock waveforms clustered into seven distinct groups. The clusters are interpreted as slip asperities along multiple faults. The three southern clusters hosted foreshocks in the days to minutes prior to the mainshock, whereas the four northern clusters were inactive over the same period. The mainshock rupture initiated in the foreshock footprint and moved northeastward across the three southern clusters. Within an hour after the mainshock, seismicity was triggered on the four previously quiescent northern segments. The maximum slip patch from a previous geodetic inversion aligns with the third cluster along the northward rupture path. The ~5.5-6 km rupture length across the three southern clusters is consistent with empirical estimates (5-5.5 km) for a Mw 5.3 earthquake. The northern clusters filled a seismic gap between the two major earthquake sequences of the Trinidad zone, the 2011 Mw 5.3 and the 2001 MbLg 4.5 mainshock earthquake sequences. Seismicity in the Trinidad zone diminished from 2012-2016, and the earthquake rate from 2016-2020 is two orders of magnitude lower than that of the neighboring Tercio and Vermejo Park zones. The complexity of the 2011 Mw 5.3 earthquake sequence presents a challenge for accurate hazard assessment in fluid-injection settings where fault geometry is often unresolved until seismic reactivation and the strength of the crust can be locally modified by fluid-injection.

Characteristics of a Complex Rupture Zone System Associated With the m5.4 Coalson (West Texas) Earthquake

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Seismicity in the Delaware Basin (West Texas) has greatly increased from 46 earthquake of M≥2.5 in 2017 to 692 events in 2022. This area has the highest rate of seismicity in the State of Texas, with 37 M≥4.0 events since 2017, and the highest magnitude earthquake (M5.4, 2022-11-16, Coalson Earthquake) since 1995 in Texas. The Coalson seismicity is 10km South of the M4.9, 2020-03-26, Mentone earthquake sequence and defines a complex rupture zone with 12 M≥4.0 events that occurred from September 18th, 2021 to November 24th, 2022 (all information as reported by the TexNet web catalog last accessed on January 10th, 2023; https://catalog.texnet.beg.utexas.edu/). Based on the USGS "Did You Feel it" (DYFI) reports, the M5.4 event was felt throughout most of the State of Texas and Southeast New Mexico, including the large urban areas of San Antonio, Houston and Dallas.

We have relocated the seismicity in the Coalson area using an initial, local 1D Earth Model and two high-precision relocation methodologies: the extended, arrival-time method NLL-SSST-coherence and the GrowClust double-difference procedure. We also use full waveform Moment Tensor Inversion (MTI) to determine the focal mechanisms of the highest magnitude earthquakes in the area. Combining the MTI results with the spatio-temporal seismicity distribution we identify a complex system of basement rooted faults that extend upwards to the deep salt water injection zone. These active rupture zones follow E-W and SE-NW strike directions, with vertical dip-slip and low-angle normal faults, respectively.

Investigating the Influence of Extraction on Seismicity in Areas of Injection Induced Seismicity

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Over the past decade, there have been a wide variety of cases in the Central and Eastern United States where fluid injection has clearly induced seismicity, both from wastewater disposal wells and from hydraulic fracturing activities. Upon review of detailed operational records, when made available, there have been direct correlations between the timing of injection and the seismicity rate, albeit with a time delay that provides information about forcing mechanisms. However, there have also been some intriguing sequences that provide clues about other aspects of the operational process having influence on seismicity. We will explore several cases in Eastern Ohio where operational activities are less prevalent than other places in the mid-continent (e.g. Oklahoma and Texas), which enables more subtle influences to be diagnosed. In particular, we will highlight cases where it appears that variations in the rate of hydrocarbon extraction also have an influence on the seismicity rate. This relationship appears to occur during both the initial flowback process and in later periods of temporary shut-in. These findings suggest that strategies to mitigate induced seismic events need to consider not only completion and disposal activities, but also operational practices during production.

Bridging the Data Gap and Relocation Errors for Improved Spatiotemporal Evaluation of Induced Seismicity in the Delaware Basin

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The spatiotemporal association between seismicity and oil and gas production remains a challenge due to changes in data availability in time and space, and divergence in methodology applied to different datasets. Improvement in local data availability fostered real-time monitoring of induced seismicity linked to fluid extraction and injection in the Delaware Basin (DB), especially after 2017 deployment of the Texas Seismological Network (TexNet), yet seismic source characterization for pre-TexNet earthquakes remains poor. Here, we apply a multiple event relocation algorithm (MLOC) to improve the 2009-2017 TXAR catalog, which has epicentral uncertainties >15 km and equally poor depth control. Hypocentral decomposition is applied using MLOC to a mixed cluster of post- and pre-2017 earthquakes in Reeves County, Texas. Near-source readings of 39 post-2017 events (the core cluster) are used to define a virtual centroid (hypocentroid). Short paths (< 80 km) in the core cluster ensure the minimization of cumulative errors for hypocentriod (< 0.5 km). Relative epicentral uncertainties for core cluster, relocated with respect to the hypocentroid, are <1 km with depth constraint from near-source readings. The station-phase tabulation for the core cluster is used to estimate the uncertainties for pre-2017 events, which are added successively. For pre-2017 events, additional 86 S-P differential arrival times for single events and 498 differential travel times from cross-correlation are added. Relative epicentral errors for 54 pre-2017 relocated events are <5 km with depth uncertainty in the order of 1-2 km. Our preliminary results indicate a strong spatial correlation between the TexNet GrowClust relocations and relocated pre-2017 earthquakes in Reeves County. The mean value of depth has shifted from 5 km in the initial catalog to 2 km that is more consistent with triggering from shallow production and injection in the DB. Here, we add complementary data, expand the study to basement earthquakes in the basin, explore the effect of window size for clusters, and evaluate seismicity-injection correlation.

Are Higher Hf Injection Rates More Prone to Triggering Seismicity? Data From Four North American Basins Say No.

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Wastewater-disposal wells with higher injection rates have for a long time been associated with a higher seismogenic potential (Weingarten et al. 2015; 10.1126/science.aab1345). In this study, we investigate if this is true also for hydraulic fracturing (HF) wells. Using the methods presented in Grigoratos et al. (2022; 10.1785/0220210320), we identified which HF stimulations induced detectable seismicity at a confidence level above 95% in Texas (Eagle Ford, Delaware Basin), Oklahoma and Canada (West Canadian Sedimentary basin). The framework uses a generalized version of the Seismogenic Index model (Shapiro et al. 2010; 10.1190/1.3353727) to hindcast the time-series of the seismicity rates above the magnitude of completeness on a 5 km grid and compare them against the null hypothesis of solely tectonic loading. In the end, each block is assigned a p-value, indicating the statistical confidence of its causal link with HF operations. For a HF well to be flagged as seismogenic it would have be inside a block with $p < 0.05$ and also within 5 km of an earthquake that occurred during or right after its stimulation period. Notably, across all basins, only 1 to 10% of the HF stimulations are usually responsible for all of the earthquakes linked to HF. We then checked whether their total injected volume or their average daily injection rate is higher than those who did not induce seismicity. The results for all the examined basins showed that the distributions of both seismogenic and non-seismogenic wells were essentially indistinguishable. We discuss possible physical reasons behind this novel finding and the major implications it has for hazard-mitigation strategies.

Frictional and Poromechanical Properties of the Delaware Mountain Group: Implications for Seismic and Aseismic Faulting Associated With Induced Earthquakes

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Tectonic faults can slip through a spectrum of slip modes depending upon their frictional properties and the elastic stiffness surrounding the fault zone. Hence, quantifying the frictional properties of fault zones under in-situ conditions is critical for determining what conditions permit stable (aseismic) or unstable (earthquake rupture) behavior. In the southern Delaware Basin (DB) of west Texas there is a widespread system of steeply-dipping faults that have been made neotectonically active by injection, production and hydraulic fracturing. InSAR and seismic data show that the faults host seismic and aseismic slip, however the frictional properties that permit these different slip modes is not well understood. Here, we measure rate and state frictional properties with velocity stepping and slide-hold-slide experiments conducted on Delaware Mountain Group (DMG) cores that delineate the southern DB. Experiments were conducted inside a true-triaxial pressure vessel in a double direct shearing configuration at the Penn State University Rock and Sediment Mechanics Laboratory. Our data show that the DMG is frictionally weak, with steady-state coefficients of friction of 0.3 – 0.5. Most samples show a systematic progression from velocity strengthening to velocity neutral behavior as function of increasing slip displacement. This is consistent with the idea that fault zone maturity and shear localization play key roles in modulating frictional behavior and fault stability. In addition, we observe a systematic increase in volumetric flow rate at the upstream reservoir due to a step increase in sliding velocity. Presumably, the fault zone dilates during the velocity step, causing a local reduction in pore-fluid pressure, and thus, a local increase in effective normal stress and frictional strength. The poromechanical properties are in agreement with the velocity strengthening behavior of the cores. Broadly speaking, our data are consistent with the lack of seismic activity along the

northern extent of the southern DB and suggest that tectonic faulting within this region should favor aseismic creep.

Probability of Statistically Unexpected Earthquakes in Different Basins in Texas

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The state of Texas has experienced earthquake activity due to fluid injection. An analysis of well-resolved clusters of seismicity from the Dallas-Fort Worth area, Delaware basin, Eagle Ford basin, Haynesville region, Midland basin and the Panhandle was undertaken to determine if there are differences in the statistical attributes of seismicity. A merged, magnitude-corrected catalog including historical seismicity, published catalogs and the public TexNet catalog until December 2022 was used to identify the clusters. The exceedance probability, which is the probability of the largest earthquake in the sequence based on the previous earthquakes, was calculated for each cluster. Statistically significant differences between basins were found. The Midland basin was found to be the most likely to experience larger than statistically expected seismicity, followed by the Delaware, Barnett and Eagle Ford plays. An analysis of the temporal progression of the seismicity in each cluster further shows that the clusters with the lowest exceedance probability have the most episodic time series. This suggests that faults on which strain can accumulate, rather than faults where strain is released through continuous seismicity, are more likely to generate a large earthquake.

How Well Do We Really Know the b-Value? New Estimates of Earthquake Magnitude for the Delaware Basin and the Effect of Magnitude Uncertainty on Induced Seismic Hazard Estimates.

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The Delaware Basin, a subset of the greater Permian Basin located in western Texas and southeastern New Mexico, is currently a hotbed of induced seismic activity where the frequency of relatively large magnitude events ($M > 4$) has been increasing over the last ~5 years including a magnitude 5.4 event in November of 2022. Since large, induced events are quite infrequent, our understanding of seismic hazard, recurrence intervals, and magnitude exceedance for these earthquakes is heavily dependent on a thorough understanding of the magnitude frequency distribution (MFD) and source parameters of numerous small events in the same region. However, magnitude estimates for small earthquakes are often inconsistently measured or simply not available for certain magnitude types. This project aims to both produce updated estimates of earthquake magnitudes for the Delaware Basin region, paying particular attention to how scaling relationships may change for small and large earthquakes, and to understand the effects of magnitude uncertainty on estimates of MFD and seismic hazard for induced earthquakes. We re-estimate magnitude for events in the Delaware Basin using a relative magnitude method calibrated with coda-envelope-based moment magnitudes developed for the Permian Basin. We also investigate the temporal and spatial variations in MFD and b-value using these updated magnitudes. Previously, we have found that for recent events in western Texas, the use of new relative coda magnitudes yields a decrease in b-value during the 1.5 years between January 2021 and June 2022 signaling a greater proportion of large events in the region than what would have been calculated using originally cataloged magnitudes. We extend this analysis to include events prior to 2021 and events located in southeast New Mexico to facilitate a better understanding of induced seismic hazard in this region.

Advances in Characterizing Seismic Hazard and Forecasting Risk in Hydrocarbon Systems [Poster]

Poster Session • Tuesday 18 April

Conveners: Asiye Aziz Zanjani, Southern Methodist University (aazizzanjani@smu.edu); Heather R. DeShon, Southern Methodist University (hdeshon@smu.edu); Nadine Igonin, University of Texas at Austin (nadine.igonin@beg.utexas.edu); Alexandros Savvaidis, University of Texas at Austin (alexandros.savvaidis@beg.utexas.edu); Jake Walter, University of Oklahoma, Oklahoma Geological Survey (jwalter@ou.edu)

Ambient Noise Monitoring in a Region of Disposal-induced Seismicity, Central Alberta

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Ambient seismic noise has been shown to be a useful tool for monitoring subtle changes in the subsurface that are reflected in changes in seismic wave properties. Here, we aim to use ambient noise to characterize reservoir response to sustained fluid injection, and in particular wastewater disposal, over a number of years. Central Alberta has observed an increase in the rate of seismic events since the end of 2019, believed to be associated with water disposal. Using continuous seismic data from January 2019 to August 2021, we calculate the relative change in seismic velocity over time. Our initial results suggest a correlation between velocity changes and seismicity rate; by using an histogram grouping the sum of events for seven days, and compare it to the stacking of the cross-correlation functions over the same number of days. Initial observations go in accordance to the fracture theory where relative wave velocities go down as a reservoir fractures and up as it heals. Nonetheless, these change occur in syncronic way making the observations undesirable for early warning systems. Finally, future plans include utilizing high performance computing and cuda processing to cut down on computational time.

Characteristics of Seismogenic Zones Associated With the m5.2 Range Hill Event Near Midland, Texas

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Seismicity in the Midland Basin has significantly increased in last five years, which can be attributed to wastewater injection in this region. Among the seismicity, a recent M5.2 earthquake (referred to as the Range Hill event) occurring north of the city of Midland, Texas, has been the largest earthquake ever recorded in the Midland Basin. This event is located deep in the crystalline Pre-Cambrian basement-top, suggesting the reactivation of a basement-rooted fault system. However, this basement-rooted fault was missing from the public fault map. To understand the geometry of the reactivated basement-rooted fault, we relocated and delineated the induced seismicity using hypoDD-relocation. Earthquake source mechanisms from full waveform moment tensor inversion allow us to further reveal their rupture pattern. In addition, we leveraged the obtained source mechanisms to invert for the regional 3-D stress field. Within the area, we have identified a broad seismogenic zone containing two groups of seismicity; they share similar seismogenic features and present a seemingly parallel lineation. Seismicity in this zone is trending roughly NE-SW, fairly aligned with the nodal planes. The source mechanisms were determined to be predominantly normal faulting. P-axes have steep plunges (> 60°), while the inverted S1 is nearly vertical. At the same time, T-axes and S3 are running approximately N30°W-S30°E and plunging at shallow angles (<15°). Combining the seismicity geometry, focal depths, and source mechanisms, we infer that this seismic zone contains two basement-rooted normal faults.

Fault Stability and Pore Pressure Thresholds for Seismogenic Rupture in the Midland Basin

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Beginning in late 2020, the rates of seismicity in the Midland Basin (MB) increased significantly to an average of ~5 ML3.0+ events per month and a very notable M_L5.4 earthquake occurred in December of 2022. Like what was experienced in the injection-induced seismicity cycle in the Ft. Worth Basin, the earthquakes in the MB occur in the igneous and metamorphic basement and are organized in localized sequences that exhibit well-defined onset timing and abrupt rate decline behavior. In the Midland Basin it is widely assumed that stressing of strata due to wastewater injection beneath oil- and water-productive Wolfcamp shales is the causal agent. Using a globally-calibrated model of pore pressure evolution (dPp) derived from a comprehensive geologic characterization, we assess the spatial and temporal relationship of dPp to earthquake sequence onset and behavior for 18 sequences. We use dPp as sampled from the deepest model layer in the Ellenburger into which the causative injection has occurred. We find that earthquake sequence onset occurred at dPp ranging from 63 to 513 psi with a mean of 224 psi. Pp gradient at onset ranged from 0.456 to 0.532 psi/ft. Earthquake sequence onset and evolution in the basin occurred in a wide range of stressing (dPp and ddPp) behavior. Some cases, such as Gardendale 1 and 4 and Midway experienced earthquake onset at low dPp, during a steady ramp-up in dPp, and during a period with a low degree of ddPp complexity. Faults reactivated under these conditions must be the most sensitive, natively. At the other extreme, several cases such as Stanton experienced earthquake onset associated with higher dPp, during a rapid increase in dPp, and during a period with a high degree of ddPp complexity. Faults reactivated under these conditions must be inherently more stable. By the end of 2015, ~40 km of fault trace length had dPp from injection of >150 psi above rupture stability which increased to ~320 km as the earthquakes studied developed by the early 2021.

Seismic Hazard and Risk Forecasting for the Groningen Gas Field: Case Study for Gas Year 2022/2023

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The public Seismic Hazard and Risk Analysis (pSHRA) for the Groningen gas field is performed on an annual basis by the Geological Survey of the Netherlands based on the forecasted production strategy for the envisioned end-of-production and beyond. Here, we use pSHRA for the period October 2022 – September 2023 to demonstrate the full workflow, from the gas production forecast and Bayesian calibration of the Seismological Source Model (SSM), to the calculation and disaggregation of hazard and risk on a building level. This includes the forecasting of spatio-temporal-magnitude distributions of seismicity, the propagation through a Ground Motion Model (GMM) with a detailed site-response model, the modelling of building damage and collapse, and finally Local Personal Risk for the 150,000+ buildings in the area. We show how different model choices impact these results, and how hazard and risk can be disaggregated to gain a better understanding of the different aspects driving the hazard and risk. The Groningen gas field, with its suite of models that are developed specifically for this area, offers a unique opportunity to showcase how a full PSHRA workflow can be applied in an induced seismicity setting, and how the results can be used by policy makers and regulators to make informed and science-based decisions.

Widespread Anthropogenic Uplift, Subsidence, Co-Seismic Faulting and Earthquakes in the Delaware Basin of Texas and New Mexico

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The Delaware Basin of west Texas and southeast New Mexico is now the largest producer of oil globally, totaling 4 billion barrels 2010-2021. This production has necessitated disposal by injection of 14 billion barrels of coproduced wastewater. Here we show that the Sentinel-1 Interferometric Synthetic Aperture Radar (InSAR) satellite mission has greatly improved our ability to monitor subsurface deformation that occurred between 2015 and 2021 in response to subsurface fluid movement. The rate of surface deformation has accelerated since 2018 and signals significant geomechanical sensitivity to shale compaction, reservoir pressurization and inflation, faults that deflect the ground surface, and induced earthquakes of multiple causes. The subsidence region extends over ~16,000 km^2 with a maximum subsidence of 17 cm (332 million m^3) whereas the uplifted region extends over 18,000 km^2 with a maximum uplift of 12 cm (155 million m^3). Subsidence correlates linearly with fluid volume produced, while injection causes complex patterns of uplift spreading laterally and complexly. Several earthquake sequence areas that have been active since 2019 have caused co-seismic uplift of several cm and the formation of asymmetrically rotated fault blocks with linear boundaries. Understanding the dynamic change to the shallow injection strata and the sealing units above is a pressing concern for safeguarding the surface environment in the basin and its tens of thousands of old petroleum wellbores.

Advances in Marine Seismoacoustics

Oral Session • Tuesday 18 April • 02:00 PM Pacific

Conveners: Charlotte Rowe, Los Alamos National Laboratory (char@lanl.gov); Ethan Williams, California Institute of Technology (efwillia@caltech.edu); Nishath Rajiv Ranasinghe, Los Alamos National Laboratory (ranasinghe@lanl.gov); Kasey Aderhold, Incorporated Research Institutions for Seismology (kasey@iris.edu)

Acoustic Detection of Volcanic Gas Seeps Using Underwater Distributed Acoustic Sensing.

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Volcanic gases are a main trigger of explosive eruptions. The largest amounts, however, are emitted through passive and non-eruptive degassing during quiescence. The presence of a large body of water near or on a volcano provides an underexploited opportunity to investigate passive volcanic degassing through non-conventional means. For example, naturally occurring underwater bubbles are powerful sound sources as they scatter and refract the underwater sound field. Contrary to subaerial settings, the acoustic detection of bubbles is, therefore, straightforward in aquatic environments, and degassing rates can be tracked at high temporal resolution (~kHz) before mixing and dilution in the atmosphere. Yet, seismo-acoustic approaches using hydrophones have mostly been deployed in non-volcanic areas. In this contribution, we present results gathered using a Distributed Acoustic Sensing (DAS) interrogator at the Laacher See volcanic lake in Germany, where bubbles seep due to volcanic activity. We deployed a 500-m underwater fiber-optic cable connected to the interrogator over 48h. DAS data allowed us to detect and analyze plentiful bubble acoustic signals in various areas of the lake. This work demonstrates the sensitivity of fiber-optic cables to degassing events and its potential for monitoring underwater volcanic emissions or Carbon Capture and Storage (CCS) operations with great accuracy and over wide-spread areas.

Submarine Volcano Seismoacoustics: Why Multi-Modal Data Is Important

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Submarine volcanoes are efficient producers of seismoacoustic energy in the marine environment. Their signals have been recorded for over 80 years, leading to many questions about the signal origins in that time. As marine technology has advanced, our ability to detect and characterize submarine volcanic activity has greatly improved, which has furthered our understanding of these systems. A comprehensive literature search revealed that ~120 emergent and submarine volcanic eruptions were seismoacoustically recorded between 1939 and 2020. These eruptions covered a wide range of tectonic settings, ocean depths, and activity types. However, recordings were often limited with many eruptions only detected as distant T phases, and around 1/3 lacked confirmation of an eruption through non-seismoacoustic data. Since signals from volcanic activity cover a wide range of characteristics, these limited observations complicate interpretations. Fortunately, a growing number of submarine eruptions have been recorded with multiple data types. Comparisons between seismic and acoustic recordings as well as visual, chemical, and geological observations have led to a better understanding of the mechanisms behind specific types of signals and how signals from the same process may vary based on the data type and recording location (on land or underwater). In this presentation, we provide examples of how multi-modal data have helped improve our understanding of submarine eruptions and discuss why they will be essential for making further progress.

Non-Linear Seismoacoustic Responses of Explosions in Different Rock Types and Water: Comparisons With Experimental Data

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We have performed quasi-3D high-resolution numerical simulations of surface and underground explosions using LLNL's massively parallel hydrocode GEODYN to assess the impact of parameters such as yield, height of burst (HOB), depth of burst (DOB) and geological material on the resulting overpressure in air and seismic motions at distance. The material properties span a large spectrum from hard rock, such as granite with low porosity, limestone, sandstone, tuff, salt, and very weak material, such as dry and wet alluvium. Arrival times to surface station are determined by the shock wave propagation and the coupling of ground motion. We show that overpressures and peak velocities due to the same yield at the same scaled HOB/DOB are functionally very similar regardless the geological fabric and therefore the response can be scaled. Moreover, the impulse is calculated by integrating the initial positive pressure time-history. It was found that the functional form of the impulse as a function of scaled HOB/DOB is also consistent for emplacements above ground, at ground level and down to depths where cratering occurs regardless for all geological materials even though the material properties show drastic geomechanical variations. While the current study used numerical simulation from idealized blast and settings, additional factors can complicate observed seismic signals and bias the amplitudes and subsequent yield and HOB/DOB estimates. For example, we show that the emplacement lithology strongly impacts seismic amplitudes for deeply buried explosions. Furthermore, the behavior with HOB/DOB is different for the materials considered. Results are compared with legacy chemical and nuclear experimental data, and the more recent forensic (LSECE) and proof-of-concept (MDE) surface explosions conducted at the Nevada National Security Site.

Exploring the Potential of Low-cost Hydrophones in Constraining Subsea Faults and Seismic Early Warning for the San Francisco Bay Region

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Mapping the buried, offshore extent of faulting has a major challenge in the evaluation of seismic potency and hazard of active faults. The issue is mainly due to the lack of adequate station coverage caused by cost and logistic issues of station deployment. However, following the 2022 Kish Island earthquake cluster in the Persian Gulf, we showed that low-cost hydrophones ("HBox") deployed offshore in shallow water can be provide crucial information regarding the location of small earthquakes, hence offering assistance in constraining offshore fault properties. In this study, we present a site-selection algorithm for efficient deployments of these instruments in the San Francisco Bay area as a means to increase the ability to monitor off-network, offshore micro-seismicity of the San Andreas Fault. Our selection criteria are based on the simulated apparent velocity and frequency of seismo-acoustic waves, bathymetric slope analysis, as well as logistic constraints on predicted station signal-to-noise ratio.

New Constraints on the Factors That Control the Lithosphere-Asthenosphere Transition and the Driving Forces of Plate Motions From the Pi-Lab Experiment

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The transition from the lithosphere to the asthenosphere is an important part of plate tectonics. The exact depth and the factor(s) that control it are widely debated. The PI-LAB (Passive Imaging of the Lithosphere-Asthenosphere Boundary) included 39 ocean bottom seismometers and 39 ocean bottom magntotelluric instruments near the equatorial Mid-Atlantic Ridge. We find seismic attenuation quality factors of 175 ± 16 at lithospheric depths (< 50 km) and 90 ± 15 at asthenospheric depths (> 60 km). These values fall within the range of other global results and do not necessarily require melt pervasively in the asthenosphere (Takeuchi et al., 2017; Saikia et al., 2021). SKS splitting measurements reveal predominantly weak anisotropy (< 1 s) with fast directions that are mostly consistent with strain caused by plate motions, again potentially consistent with a thermal model. However, near the ridge axis SKS splitting is strong (1.7 – 3.7 s) with predominantly ridge parallel fast directions. This is much different than observations from other ridge systems and likely requires the presence of aligned melt beneath the ridge. This melt organisation may be facilitated by the existence of a thick, sub-ridge lithosphere, as predicted by models for slow-spread lithosphere (Parmentier and Morgan, 1990; Holtzman and Kendall, 2010). Our new body wave tomography model includes a 10 – 20 km thick low velocity channel in the southeast and a strong punctuated anomalies in the north. I will discuss a range of causes for these observations. However, the striking agreement between seismic and magnetotelluric imaging and very strong anisotropy near the ridge likely require a small amount of partial melt in discrete regions, given the independent and complementary sensitivities of the methodologies. Therefore, while temperature plays a first-order role in dictating the lithosphere-asthenosphere transition, melt can also affect the location and sharpness of this interface. This melt likely plays an important and dominant role in driving the plates and facilitating their motions.

Advances in Marine Seismoacoustics [Poster]

Poster Session • Tuesday 18 April

Conveners: Charlotte Rowe, Los Alamos National Laboratory (char@lanl.gov); Ethan Williams, California Institute of Technology (efwillia@caltech.edu); Nishath Rajiv Ranasinghe, Los Alamos National Laboratory (ranasinghe@lanl.gov); Kasey Aderhold, Incorporated Research Institutions for Seismology (kasey@iris.edu)

Impacts of Oceanographic and Geologic Factors on Ocean-Bottom Seismic Noise

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Seismic sensors have traditionally been largely restricted to on-land installations, yet the oceans cover roughly 70% of the Earth's surface. Coupled with heterogeneous distribution of seismic sources, limited seismic sensing in the oceans results in many regions being poorly sampled for Earth model development, and poorly monitored for detection of natural and anthropogenic seismic sources. Extending seismic measurements and observations into the oceans is an important future direction in seismology. The ambient noise level recorded by ocean-bottom seismometers (OBS) is in general much higher than the ambient noise levels on land, and details of the seafloor noise regime are not well described. To investigate the broadest regions for potential instrumentation, it is necessary to characterize the global seafloor seismic noise environment to aid in selection of sites for permanent sensors.

We present progress in evaluation of OBS noise characteristics at temporary network deployments distributed throughout the Earth's oceans. Many variables affect noise at the seafloor, including sensor type and instrument design, sensor orientation, instrument installation, ocean depth, geologic setting, and meteorological and oceanographic phenomena. We choose a single type of instrument in order to focus our analysis on noise variations due to oceanographic and geologic factors. Our long-term objective is to characterize source and path effects of seafloor noise across the globe by combining existing noise observations with predictions of noise from known sources, and to use this characterization to guide site selection and optimization of seafloor seismic array geometry.

Novel Autonomous and Cabled Obs Solutions for Offshore Seismic Research

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Seismologists have historically focused on land-based seismic research, due to the logistical and financial challenges presented by offshore installations. Guralp has developed technology which allows the seismology community to monitor offshore seismicity with greater ease, improving global seismic data resolution.

Autonomous free-fall OBS units allow users flexibility in deployment and ability to redeploy in different locations. The Guralp Aquarius functions at any angle without using a gimbal system, and can wirelessly transmit SOH and seismic data to the surface via an integrated acoustic modem. These features allow researchers to monitor and transmit data without offshore cabling, reducing logistical challenges whilst maintaining some degree of real-time data transmission.

Alternatively, cabled solutions give users access to high-resolution data in real-time via a physical link to an onshore data centre. As an example, the Guralp Orcus provides a complete underwater seismic station with observatory grade seismometer and strong-motion accelerometer in a single package. The slimline Guralp Maris also provides a more versatile solution, making use of the same omnidirectional sensor as the Aquarius and can be installed either on the seabed or in a narrow-diameter subsea borehole.

SMART cables show great potential for increasing the number of cabled ocean observatory deployments in the future with substantially reduced deployment costs to the research institute. Combining several applications into a single system, including seismic monitoring and telecommunications, large scale monitoring networks can be created cost effectively by combining efforts from several industries. Guralp is deploying a demonstration SMART Cable system to monitor volcanic and seismic activity offshore in the Ionian Sea in collaboration with Instituto Nazionale Di Geofisica e Vulcanologia (INGV). This will be the first practical demonstration of this technology and there are plans for additional projects in the future.

Novel Longer-Term Ocean Bottom Station Concepts Enabled by Advancements in Low Power Equipment

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With over 70% of the earth's surface covered in ocean, the ability of land-only stations and networks to understand our planet is limited. To increase our global coverage, there is a continued need for higher quality and longer term seismic stations to augment existing networks. Meeting this need has traditionally been limited by the costs and complexities of the stations themselves and the significant operational costs of deploying and recovering systems.

Recent advances in high-performance, low Size Weight and Power (SWaP) instrumentation allows an examination of new approaches to increase the performance, density and duration of ocean bottom seismometer systems. The combination of higher value and lower footprint stations allows for new and previously infeasible approaches to be within reach.

Existing and emerging technologies in instrumentation, power generation, periodic telemetry and station design are examined to develop opportunities for advancement of worldwide coverage of seismic data.

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Advances in Probabilistic Seismic Hazard Analysis and Applications

Oral Session • Wednesday 19 April • 08:00 AM Pacific

Conveners: Yufang Rong, FM Global (yufang.rong@fmglobal.com); Matt C. Gerstenberger, GNS Science (m.gerstenberger@gns.cri.nz); Marco Pagani, GEM Foundation (marco.pagani@globalquakemodel.org); Sanjay Bora, GNS Science (s.bora@gns.cri.nz); Harold Magistrale, FM Global (harold.magistrale@fmglobal.com); Elliot Klein, FM Global (elliot.klein@fmglobal.com); Richard Styron, GEM Foundation (richard.styron@globalquakemodel.org)

2020 National Seismic Hazard Model of Norway

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The purpose of a national seismic hazard model is to provide an estimate of the likelihood and strength of earthquake ground shaking that might occur at any given site in Norway. To provide this information about how different parts of the country might behave in the event of larger magnitude earthquakes, the database and the computational methods applied should be continuously updated. In Norway, this was not the case, where the last national seismic hazard model was developed in 1998, based on limited data and outdated methodology. Other following studies were only conducted on the European-scale level, and the details of Norwegian earthquake catalogues were never integrated sufficiently. Therefore, NORSAR developed in 2020 a new national seismic hazard model based on 20 more years of data, including for the first time the arctic region of Svalbard, and using new state-of-the-art methodology.

The Probabilistic Seismic Hazard Analysis applied the CRISIS software package and combined in a logic-tree approach three different zonation models that are based on seismicity patterns, and extent and presence of active and passive faults. In addition, one zonation-free approach was incorporated, where earthquake activity rates were extracted on a regular grid. Earthquake recurrence parameters for each zone were obtained from direct magnitude-frequency analysis using an earthquake catalogue homogenized to Mw estimates (from 1497 to 2018). Four suitable Ground Motion Prediction Equations (GMPEs) have been used and all results are evaluated at relevant Norwegian bedrock conditions using a reference shear wave velocity equal to 1200 m/s. The results are provided in terms of Peak Ground Acceleration (PGA) and several Spectral Acceleration (SA) periods for 475, 2475 and 10.000 years for Norway mainland and Svalbard. These results are particularly useful to the engineering community and as basis for design constructions in accordance with Eurocode 8 standards.

The 2022 New Zealand National Seismic Hazard Model

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Recently an approximately three year project to revise the New Zealand National Seismic Hazard Model (NSHM) was completed. This was the most significant revision of the NSHM in more than 20 years and included fundamental changes to all components of the model. An underlying philosophy of the model development was that to best represent what we know about earthquake occurrence and, hence, make the best forecast, we need to represent a wide range of datasets, hypotheses and models in all components of the NSHM.

The Seismicity Rate Model (SRM) is the collection of component models that each forecast the magnitude, location and rate of earthquakes for the next 100 years. The Ground Motion Characterisation Model (GMCM) is the collection of models that forecast the range of shaking for each of the ruptures in the SRM and is covered in detail in another presentation. Broadly the SRM is broken into two components: 1) ruptures on known faults, and 2) ruptures on faults that are not yet known about. For the known faults we have implemented the UCERF inversion recipe which allows for jointly fitting multiple datasets and models to provide rates on ruptures. Some key inputs are: the Community Fault Model; Deformation models, which provide slip rates on all faults; Rupture sets, which provide geometric constraints on potential ruptures; Models of timings of past earthquakes on known faults; and, Magnitude-frequency distributions of earthquake occurrence. For unknown faults, we have developed a hybrid model that represents a significant departure from smoothed seismicity models which are typically used in seismic hazard. Similar to the inversion model, the hybrid model also combines, geological and geodetic data with the earthquake catalogue to provide a more complete forecast than smoothed seismicity alone. Models have also been developed for lower-seismicity regions which incorporate geodetic strain and the low-bias seen in the NZ earthquake catalogue in lower rate regions. Finally, the SRM accounts for the much greater variability in rate observed in New Zealand than is modelled by standard Poisson assumptions.

A Comprehensive Probabilistic Seismic Hazard Assessment for Mexico

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Earthquakes larger than M_W7.0 have impacted the country of Mexico over the past century approximately once every 5-6 years, with six events having occurred since 2017. The Cocos and Rivera plates subduct eastward beneath the North America and Caribbean plates, creating a concentration of high hazard along the west coast seen on all existing seismic hazard maps (SHM). Despite frequent significant earthquakes, few peer-reviewed fully probabilistic seismic hazard analyses (PSHA) for the entire country exist. Risk assessment companies (e.g., Verisk Analytics) attempt to develop the most up to date view of risk using the most scientifically advanced, comprehensive, and accurate PSHA. Here, we present a comprehensive seismicity rate model that includes all significant seismic sources in Mexico including subduction zones, mapped active crustal faults, deep intra-slab earthquakes, and background seismicity to account for unknown faults. Our model incorporates a complete historical earthquake catalog homogenized to moment magnitude, an active fault database compiled from all regional and global data sources and publications, coupling information, and strain- and moment-rates from kinematic models of GPS data. We evaluate various ground motion models, including those from the NGA-Sub project, and select a suite of models appropriate for the various types of earthquakes in Mexico. Lastly, we integrate soil effects including a site amplification model for Mexico City based on published work. We present hazard results in terms of peak and spectral acceleration values (PGA & SA), and discuss the similarities and differences between our results and both peer- and non-peer-reviewed studies (e.g., GEM, CENAPRED, and national SHMs).

Probabilistic Analysis of Seismic Hazard in the Dominican Republic Considering Hybrid Models of Zones and Faults and Including the Local Effect on the Expected Motion.

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A recent seismic hazard study has been carried out in the Dominican Republic, modeling the main faults as independent seismic sources and using a hybrid probabilistic methodology that combines zones and faults. In this way, maps of the expected motion in terms of peak ground acceleration and spectral accelerations SA(T) on rock sites have been obtained for a return period of 475 years, resulting in notably higher accelerations in the area of the faults than those obtained by only zoned methods. This result is consistent with the near-fault effect that is observed in the records of many earthquakes and that is also contemplated in some seismic codes. On the other hand, a study of microzonation in urban areas of Santo Domingo and Santiago de los Caballeros cities has been developed, based on data obtained in a campaign of urban noise recording, processed with different techniques in order to extract valuable information about the fundamental frequency and geological shallow structure Vs30. Integrating the results of the two previous studies, the expected motions in the two cities have been estimated, including the local effect, finding the distributions of PGA and SA(T) for the mentioned return period, which represent the accelerations with a probability of exceedance of 10%. in 50 years. The main value of these maps is that they integrate both the fault proximity effect and the site effect, in a probabilistic approach, providing data of interest to check the corresponding Source and Soil factors of the seismic codes. The work has been developed within the framework of three research projects: "KUK ÀHPÁN: Integrated Regional Study of Structure and Evolution 4D of the Lithosphere in Central America". Implications in the Calculation of Seismic Hazard and Risk" ; " MICROSIS-I : seismic microzoning in urban areas of the Dominican Republic, based on active and passive" and "Evaluation of the seismic hazard of Hispaniola island and the seismic risk in populations of the Dominican Republic".

The GEM Global Mosaic of Hazard Models: Improvements Since Its First Release and Challenges Ahead

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The GEM Global Mosaic of seismic hazard models (the mosaic herein) is a publicly accessible collection of models for probabilistic seismic hazard analysis that allows computation of hazard for inland areas globally. The mosaic includes 31 models developed by national institutions, international projects, groups of scientists and the GEM hazard team. They are all represented using the standard OpenQuake-Engine input model (a .xml markup language) and can be executed in this code to calculate different results. Since its first release at the end of 2018, the mosaic has undergone several improvements, mainly by replacing outdated hazard models with more recent versions or substituting obsolete components with more recent ones. For example, within a project executed in collaboration with the USGS, the GEM hazard team recently performed a comprehensive appraisal of the ground-motion models used and, where possible, replaced old models with more up-to-date versions. Extensive work was also put into homogenizing the minimum magnitude for calculation and obtaining more comparable hazard results across models. There are various challenges the GEM hazard team is currently tackling to improve the mosaic. Some of the most important ones are to generate global forecasts for the whole set of models and improve the forecasting skills of individual models. The first goal requires the creation of hazard models covering the oceans, an activity we recently started, the homogenisation of models at their boundaries to avoid double counting and improvements within the OpenQuake Engine. The second objective needs improvements at the methodological level for both the model-building process and the calculation of hazard. For example, this entails the development of earthquake occurrence models with the ability to model the time-dependence and transients of seismicity, ground-motion models better calibrated on the local strong-motion information or more efficient ways to incorporate epistemic uncertainty and compute hazard results.

The 2022 Revision of National Seismic Hazard Model (NSHM) for New Zealand: Candidate Ground-Motion Models (GMMs) and Associated Hazard Sensitivities

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For the 2022 revision of the national seismic hazard model (NSHM-2022), the ground-motion characterization modeling (GMCM) adopts a hybrid approach (to capture epistemic uncertainty) that involves using a multimodel and backbone ground-motion modeling framework. For active shallow crustal sources seven GMMs were considered that include four global, one New Zealand specific GMM and two New Zealand specific backbone GMMs developed within the purview of NSHM-2022. Similarly, the candidate models for subduction (interface/intraslab) sources include three recently developed global GMMs (NGA-Sub) and one New Zealand specific backbone model. The candidate GMMs were assessed primarily by performing comparisons of median ground-motions and aleatory uncertainty owing to the limited data in the magnitude and distance range that dominate hazard in the country. Nevertheless, data driven evaluations were also carried out using the global datasets in addition to the recently compiled strong motion database for New Zealand. Moreover, for subduction GMMs, corrections were also made in the median models for backarc distance scaling and in the aleatory sigma model for soil non-linear effects. We demonstrate the impact of updated GMCM on the hazard calculations: 1) by showing comparisons with respect to 2010-GMCM and 2) relative sensitivity of different GMMs and parameter choices corresponding to different source types. Final weights on different models were decided after an expert elicitation workshop.

Correlation of Non-Ergodic Path Effects for Intensity and Ground- Motion Data

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Modified Mercalli Intensity (MMI) data has much denser spatial sampling than ground-motion data. Therefore, MMI data may provide better constraints on non-ergodic path effects than the available ground-motion data. We evaluate if the path effects for MMI data are consistent with the path effects for ground-motion data to determine if the MMI data will provide useful constraints on the non-ergodic ground-motion models (GMMs). For the MMI data, we selected records with intensity greater than four and rupture/hypocentral distances less than 200 km. The non-ergodic behavior is captured through the approach of Sung et al. (2023) which quantifies the anisotropic path effects due to the 3-D velocity structure using the varying coefficient model in an iterative process. In the first step, the spatially variable path term per site with the spatial correlation based on the separation between earthquakes is estimated. The second step uses the results of step 1 as the input to the new covariance function to calculate the spatial varying path terms and epistemic uncertainty for a specific source location for all site locations. The result shows that the path terms for MMI and short-period spectral accelerations have a high correlation, whereas the MMI and long-period ground motions have a lower correlation. Therefore, for short spectral periods, the non-ergodic path behavior from the MMI data may provide useful constraints on path terms for non-ergodic GMMs. A second issue is the magnitude-dependence of the non-ergodic path terms. The ground-motion data used for non-ergodic path terms is dominated by small-magnitude data. The MMI data from historic large-magnitude events that have few or no ground-motion data can be used to test the extrapolation of non-ergodic path terms to large-magnitude events.

Regionally Adaptable Ground-Motion Models for Subduction Seismicity in New Zealand

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The New Zealand National Seismic Hazard Model has undergone its first significant revision in 10 years, and a newly compiled high - quality ground - shaking motion database was built and comprises all the seismic events with Mw≥4 recorded across NZ since 2000 (Hutchinson et al., 2021). Beside this, significant improvements were also done on the evaluation of the local site parameters for stations within the national seismic network (Wotherspoon et al., 2022).By exploiting this database, a new ground motion model (GMM) for subduction seismicity was developed for various intensity measures such as, peak ground acceleration and 5% - damped pseudo - spectral acceleration up to 10 seconds. Beside common predictors (e.g. magnitude, depth, distances, Vs30), additional parameters were added to quantify the distinct attenuation patterns of the seismic waves observed along and behind the Havre Trough - Taupo Rift for the Hikurangi subduction zone trench. We observed different trends in the residuals in these regions based on the hypocentral-depth location on the slab and three distinct attenuation coefficients were added for each region in accordance with the observed 3D attenuation. This delineation with depth of the ground motion despairs after 1 second while the effect of the attenuation is still being present but reduced at longer periods.To capture the local site amplification along the sedimentary structures, the local site variability was constrained based on multiple site parameters (e.g. fundamental frequency of resonance. Additionally, epistemic uncertainty in regional source, path and site properties was constrained using a partially non-ergodic methodology.

The new GMMs have a robust performance compared to regional observations and their forecast capabilities of the different parameters are consistent with the ones computed using the selected GMMs. The subduction model is recommended for application to interface and inslab earthquakes with Mw ranging from 4 to 7.8, and rupture distance less than 500 km.

A Nonergodic Ground-Motion Model for Japan

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Spatially varying coefficient (SVC) models are prominent tools for developing a nonergodic ground-motion model (NGMM) that can explicitly account for the repeatable source, path and site effects. Such models allow us to extrapolate the coefficients to points in the region where the data are not available and also to track the uncertainties. In this study, we use Gaussian Process Regression to model the systematic source, path, and site effects for the Japan region using the residuals from the Abrahamson and Gulerce (2020) ground-motion model for subduction earthquakes, including both forearc and back-arc stations. For ray paths crossing the volcanic arc with rupture distances greater than 100 km, there is a much steeper attenuation with distance seen for backarc stations than for forearc stations in Japan. This large difference in attenuation across the volcanic arc is not seen in other subduction zones. We investigate the influence of the volcanic arc and the geologic and tectonic structures of Japan on the varying coefficients of the NGMM. We find that the typical non-ergodic linear distance scaling approach used to define the non-ergodic anelastic attenuation can perform poorly in capturing the anisotropy in the distance scaling of the ground motion from the forearc to the backarc in Japan. That is, the rapid attenuation in the distance scaling across the volcanic arc cannot be explained by a proxy for Q only. Additional effects due to the 3-D velocity structure need to be considered. We consider an additional path term capturing the effect of the 3-D velocity structure and discuss its implication for probabilistic seismic hazard analysis.

Development of Non-ergodic Ground-Motions Model for Induced Seismicity by Considering Field-Specific Source and Site Effects

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We present the development and application of a fully non-ergodic ground motion model (GMM) tailored to induced earthquake characteristics and operation needs of O&G fields. Non-ergodic GMMs are a promising development in probabilistic seismic hazard analysis as they offer the potential to reduce the aleatory variability that controls the seismic hazard, especially in larger return periods. This reduction in aleatory variability is accompanied by epistemic uncertainty in regions with sparse recordings or a systematic shift in the median ground motion in regions with dense recordings. The non-ergodic GMMs is developed as a spatially Gaussian Process model in which the systematic source and site effects are modeled with spatially varying coefficients that depend on the coordinates of the source and the site, and the systematic path effects are modeled by cell-specific geometrical spreading and anelastic attenuation.

While some nonergodic ground motion models have been developed for natural earthquakes, they have not been extensively tested at regions in which the seismic hazard is controlled by induced events, such as O&G fields and geothermal energy harvesting sites. These regions are often well characterized and densely instrumented but are dominated by small-magnitude triggered by field operations. Using information already collected at O&G fields, here we specifically: (i) use the dense instrumentation to identify repeatable effects of induced earthquakes and their temporal variability; (ii) combine high-resolution subsurface characterization to identify repeatable path effects better; (iii) use a parametric study of dynamic rupture models to improve the prediction of source effects by accounting for the source complexity of small magnitude induced events and (iv) use the known locations of stress perturbations induced by field operations and the short-term return periods of induced events to develop near-real-time updating of the presented GMMs.

Why Does PSHA Overpredict Historically Observed Shaking Data?

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Probabilistic seismic hazard assessments (PSHA) based on current practice consistently appear to overpredict historically observed shaking data. Comparing the forecasts and datasets, independently prepared by different groups using similar methods, PSHA results (mean PGA converted to MMI or other intensity measures using published conversion equations) from California, Japan, Italy, Nepal, and France display a similar trend, even correcting for the lengths of the observation times. This overprediction is unexpected because recent numerical simulations show that if key PSHA parameters such as recurrence rate, ground motion prediction equations, and associated uncertainties are appropriate, the observed fractional exceedance is equally likely to be above or below that predicted. Furthermore, the standard deviation of fractional exceedances should decrease for larger ratios of observation time to return period length (i.e., observations should be closer to the prediction as observation time increases). However, in most regions studied to date, the observations of historical shaking data are below the predictions of PSHA, and no consistent improvement appears with longer observation times. The consistent overpredictions across a variety of tectonic settings suggest possible systematic biases. Our studies suggest that the discrepancy is possibly due to the ground motion intensity conversion equations. Additionally, the median PGA hazard fractile may be more appropriate than the mean for performance evaluations, as it tends to decrease the overprediction. Understanding the causes of this discrepancy between forecasted PGA and observed ground shaking is important for improving seismic hazard assessments.

The First National Earthquake Risk Model for Switzerland

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The first open-access seismic risk model for Switzerland at a national scale was released in March 2023 and this contribution summarizes the process of model building, key results, model sensitivities, communication aspects and impact. Switzerland is a country with moderate earthquake hazard but a high earthquake risk, because of the high population density, high building costs, vulnerable historical building stock and numerous areas of high site amplification. The 2020 Risk Report published by the Swiss Federal Office for Civil Protection ranked earthquakes as the third most significant risk faced by Switzerland, after electricity shortages and pandemics.

The federal council commissioned the Earthquake Risk Model Switzerland (ERM-CH) in 2017 and the Swiss Seismological Service (SED) was designated as the lead agency to build and operate the model. A total budget of about 5 Mio CHF was invested to enhance all relevant components of the risk modelling chain, with a special focus on enhancing the resolution and accuracy of the local site amplification model. The model uses an extensive logic tree to capture uncertainty in a consisted and harmonized way across all model components. We also payed close attention to ensure consistency with other products of the SED, such as rapid ShakeMaps. Using the new model, the SED will now distribute within one hour of a significant earthquake a rapid impact assessment. The model will serve a wide range of potential stakeholders, including civil protection at national and cantonal levels, the insurance industry, engineering companies as well as the public. The main products such as a risk index map were tested through focus groups and systematic surveys for understandability and clarity. The model results show,as expected, that seismic risk is substantial and focused on areas of high population density and poor soil condition. This key message has a substantial impact on earthquake awareness in Switzerland.

Characterizing Seismic Risk Across Canada

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The Geological Survey of Canada has recently published a national seismic risk model, quantifying seismic risk at the neighbourhood level across Canada. This article presents summary results of this model, including loss exceedance curves at the national and provincial levels, neighborhood level risk indicators, and expected 500-year economic losses. We find that national 500-year economic losses have the potential to exceed capacities of the insurance sector to absorb expected financial consequences. We also present results of the Seismic Risk Index, a compound measure of seismic risk which factors in both physical and social dimensions of vulnerability. The Seismic Risk Index identifies communities most at risk from earthquakes in Canada, many of which are small communities in Western Canada, and large municipalities in British Columbia, Ontario and Quebec. We will also share our newly launched custom web application, RiskProfiler, designed to allow stakeholders to visualize and explore these results in a user-friendly way. This work is relevant not only to those in Canada, but also other researchers engaged in creating or maintaining seismic risk models at a national or regional level.

Uses and Misuses of the Frequency-magnitude Distribution of Earthquakes

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The frequency-magnitude distribution shows that, on average, the numbers of earthquakes (N) increases by a factor of 10 for each step of one unit of decreasing magnitude (M). Thus, b=1 in $log N = a - bM$ (equation 1, with a a regional constant). Co-authors and I have shown that b varies as function of local stress levels, with low b correlating with high stress. Proofs of this are provided by the variation of b as a function of focal mechanisms, and by decrease with hypocentral depth. This enables mapping of asperities along active faults and locations of magma chambers of volcanoes. In contrast to these useful facts, many believe falsely that the return time (Tr) of large earthquakes can be estimated from local a and b-values, and base probabilistic seismic hazard estimates (PSHA) on this erroneous assumption, worldwide. This error is anchored in the guidelines by ICOLD (International Committee on Large Dam) of how to estimate seismic hazard. Several authors have pointed out that a relation between equation 1 and Tr has never been proven to exist, but has been disproven for about 200 active faults. Some of the clearest examples that the PSHA as advocated by ICOLD yields false result, comes from paleoseismology and crustal deformation rates along the San Andreas (SA) fault's two M8 class earthquakes of 1857 and 1906. Along the 300 km segment of the SA that ruptured in 1857, the ICOLD recommendation of using PSHA requires that about 10,000 earthquakes of $M \geq 3.7$ should have occurred, since recording of this size earthquake has been complete, but in fact only 7 have been recorded. Investigations of quality data have shown that the simple PSHA assumption advocated by ICOLD is incorrect in 99% of cases. This wrong assumption of PASHA should be replaced by deterministic seismic hazard estimates, based on the existence of active faults and their likely rupture lengths, which allows an estimate of their Mmax, and hence the regional expected maximum accelerations of probable future ruptures.

Does the Logic Tree Hide the Forest? Quantifying Uncertainties in Predicted Risk for Individual Model Settings in the Induced-Seismicity Hazard and Risk Analysis of the Groningen Gas Field

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The public Seismic Hazard and Risk Analysis (pSHRA) for production-induced seismicity in Groningen comprises a seismic source model (SSM) that provides a (spatio-temporal) seismicity rate and associated magnitude distribution, a ground motion model (GMM) to compute hazard, and a fragility and consequence model (FCM) that calculates Local Personal Risk for each building. Epistemic uncertainties of six key model parameters for the pSHRA are taken into account via a logic tree: 2 SSM (magnitude-frequency model, maximum magnitude), 2 GMM and 2 FCM model parameters. Due to the unique context of production-induced seismicity and its associated models, this logic tree may not cover all relevant epistemic uncertainties. Here, we aim to identify other model settings that may be a significant source of uncertainty. To do so, a sensitivity analysis was performed for 19 model settings, which are a selection of deterministic input data, model parameters, model chain components, and model choices/assumptions. One model setting was varied per sensitivity test with respect to a base case. The metric used to quantify the sensitivity to each particular model setting was the mean risk over the entire building database. One or more variations per setting were tested. The risk sensitivity of a model setting is deemed ‘significant’ if a significance threshold of 1.4x the mean risk of the base case is surpassed. This threshold represents aleatoric variability, based on the effects of alternative choices in the earthquake completeness magnitude. Most sensitivity tests increase risk relative to the base case. The model settings with a significant sensitivity are: The inclusion of period-2-period correlation in the site response of the GMM, alternative magnitude-frequency models, adapted fragility parameters of unreinforced masonry in the FCM, and the use of the Coulomb stress measure in the SSM calibration. These results help focus ongoing research in pSHRA uncertainty reduction, and provide insight into possible candidates for inclusion in a logic tree.

Advances in Probabilistic Seismic Hazard Analysis and Applications [Poster]

Poster Session • Thursday 20 April

Conveners: Yufang Rong, FM Global (yufang.rong@fmglobal.com); Matt C. Gerstenberger, GNS Science (m.gerstenberger@gns.cri.nz); Marco Pagani, GEM Foundation (marco.pagani@globalquakemodel.org); Sanjay Bora, GNS Science (s.bora@gns.cri.nz); Harold Magistrale, FM Global (harold.magistrale@fmglobal.com); Elliot Klein, FM Global (elliot.klein@fmglobal.com); Richard Styron, GEM Foundation (richard.styron@globalquakemodel.org)

A Probabilistic Seismic Hazard Model for Greenland

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Greenland belongs to a stable continental region where seismic activity is low. Due to this factor and low population, only one probabilistic seismic hazard model of Greenland has been published, showing only a peak ground acceleration map. We constructed a probabilistic seismic hazard model for Greenland in order to complete our global earthquake risk map. We used a smoothed seismicity method due to the lack of recognized active faults. An earthquake magnitude-frequency distribution was derived based on the recorded earthquakes from 1933 to 2013. We assumed a maximum earthquake magnitude of 7.0 for the distribution, given that the magnitude of the largest recorded tectonic earthquake in the region is about 6.0. The NGA-East ground motion models were employed for ground shaking calculations. Finally, we presented seismic hazard maps in terms of peak ground acceleration, spectral acceleration at 0.2 s and 1.0 s, and hazard curves for several of the major cities.

Applicability Evaluation of Ground Motion Models (GMMs) for Korean Peninsula

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There are growing opinions that Korea is no longer safe from earthquakes after recent several earthquakes with magnitudes over 5.0 (e.g., moment magnitude 5.4 Gyeongju earthquakes occurred on September 12, 2016). Korean organizations and researchers have been conducting various studies regarding GMMs and selecting GMMs to reduce damage to earthquakes occurring in Korea, but it is necessary to re-evaluate which GMM is most suitable for Korea with recently developed GMMs.

In this study, we evaluate 8 GMMs of the active crustal region, 6 GMMs developed for the stable continental region, and 7 regional developed Korean GMMs. For several GMMs developed without consideration for site effect are applied the site amplification functions (Matsuoka and Midorikawa 1996, and Aaqib et al. 2021), so a total of 31 GMMs are considered. We compute Log-Likelihood differences (LLH; Scherbaum et al. 2009), the multivariate logarithmic score (mvLogS; Mak et al. 2017), the Euclidean distance-based ranking (EDR; Kale and Akkar 2013), the Euclidean metric distance (EMD, Cremen et al. 2020), the deviance information criterion (DIC; Kowsari et al. 2019), and a cumulative-distribution-based area metric (AM; Sunny et al. 2021) values for the response spectra of the 1,009 ground motions (M over 3.5) and GMMs for various periods (0.01, 0.05, 0.1, 0.2, 0.3, 0.5, 1, 2, 5, and 10 s). The un-normalized weight method is selected to consider all six ranking methods. For PGA and *Sa*, several GMMs developed for Korea, or the SCR region results in the top five models, respectively. Also, weighted GMMs are developed and evaluated to be suitable for use. The weighted GMMs and Eea15 rank at the top overwhelmingly.

Coordinated National Seismic Hazard Assessments for Tajikistan, Kyrgyzstan and Kazakhstan

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Probabilistic seismic hazard assessments (PSHA) were undertaken in Tajikistan, Kyrgyzstan and Kazakhstan by local agencies with the coordination and support of the Lawrence Livermore National Laboratory. The study included a regional bulletin unification effort that collected and digitized all paper-based seismic bulletins in the countries’ archives as well as compiling all available digital data in a single database. The earthquake catalogue resulting from this effort was further processed for PSHA purposes including improvements in earthquake magnitudes and locations, removal of 72,000 non-tectonic events, magnitude harmonization and determination of completeness intervals. Two versions of the PSHA-ready catalogue were generated, one with declustering and one without. In addition, an inventory of known active faults was compiled along with their estimated slip rates. Source characterization utilized both these datasets. For the ground motion characterization, all recorded strong motion data from past events in the region was collected from various agencies, some of which also had to be digitized. Contemporary ground motion models (GMMs) from US, Japan, Europe and Middle East were tested against the recorded data, which allowed determination of the GMMs to use along with their logic-tree weights. Each country worked on their national models, and these were harmonized at the borders. In addition to each individual country’s models, a regional model was developed as an alternate model, and used in a logic-tree fashion with 50%-50% weights. The results presented here are currently being considered by the engineering community in these countries for use in the building code modernization that is much needed in the region.

Deterministic Seismic Hazard Scenarios in the City of Managua (Nicaragua) in the Framework of the Kuk Ahpan Project

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During the last years, several shallow crustal seismic sources (h< 15 km) have been proposed in Nicaragua, some of them with high influence in the seismic hazard in the capital, Managua. Here we present several seismic scenarios related with the main crustal faults in the nearby of the city. We have characterized the corresponding hazard scenarios in a deterministic way, giving the peak ground accelerations (PGA) including local site effects. Firstly, the critical ruptura scenarios have been identified with earthquakes in the faults: Estadio, Tiscapa, Aeropuerto and Cofradía, with a range of magnitudes Mw between 6 and 7. On a second step, the corresponding ground motions have been simulated on rock conditions. Then, we have compiled information about soils classes in the city area, from different sources and we elaborated a micro zonation map of the city. In a third phase we estimated the ground motion including local effects by use of the amplification factors defined by "Norma Sismorresistente para la Ciudad de Managua" (MTI, 2022). The obtained results are ground motion maps for the three scenarios, together with response spectra in different soil conditions. These results are compared with those provided by the seismic code for Managua in order to evaluate if the design spectra of the code are (or not) conservative, in the case of these critical scenarios would take place.

Effects of the M6.1 Düzce (Türkiye) Earthquake of November 23, 2022 and Seismic Hazard Implications

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On November 23, 2022, a M6.1 earthquake occurred (23.01:08:15, UTC; 10.0 km depth at 40.8175° N and 30.9868° E) on a right-lateral fault near Düzce, Türkiye (USGS). Local institutions measured the event as M6.0 (AFAD-Government of Türkiye Preliminary Report dated 23 November 2022) and M5.9 (Kandilli Observatory). The event occurred in a small seismic gap between historic ruptures on the well-known North Anatolian Fault (NAF), which is similar to the San Andreas Fault (SAF) in California. Both faults are right-lateral, have similar slip rates (20-25 mm/year) and exhibit "jumping" of fault segments at stepovers during rupture. Because of these similarities, seismologists and geologists in United States have been keenly interested in the active NAF system. In 1999, two major earthquakes occurred on NAF that affected the current area and wider areas of the Marmara Sea region. Numerous structures collapsed or suffered significant damage in the region during the 1999 earthquake. A base-isolated highway viaduct connecting the vital Bolu Mountain highway tunnel immediately south of Düzce suffered significant damage to specific base-isolation units and were later replaced. Liquefaction resulted in catastrophic damage to several mid-rise apartment buildings in the City of Adapazari (west of Düzce). Aspects of the 1999 event are documented in U.S. Geological Survey Circular 1193 (https://pubs.usgs.gov/circ/2000/c1193/). We suggest that the recent event (a) likely increased stress on the western NAF in the area of Marmara Sea, and (b) increased the seismic risk to highly populated areas (e.g. Istanbul and vicinity). Positive aspects of the 2022 earthquake are that none of the government-financed condominium buildings constructed following the 1999 events collapsed, indicating that building codes were sufficient where properly applied, and there were no deaths due to the event.

Evaluation of Regional High-Frequency Path Attenuation in Central Mexico Subjected to Subduction Earthquakes and the Potential Impacts on Hazard

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Attenuation relations play an important role in seismic hazard analysis. In 2020 as part of Next Generation of Attenuation Equation for Subduction Earthquakes (NGA-Sub), global and regional ground motion models have been developed. In this study we evaluated NGA-Sub relation for Central America and Mexico (CAM) in wealth of five decades of Mexican strong-motions database (Instituto de Ingenieria, UNAM). Our initial evaluation of the high frequency ground motions of few of the past subduction-interface earthquakes against the published GMPEs suggested possible systematic bias in the median GMPEs for simulating the expected PGA and Sa0.3 ground motions of subduction zones on stiff sites in Mexico. To further study the issue, we selected strong motion time-history recorded at rock stations for some of damaging historical subduction earthquakes since 1980 to present. Typical misfit analysis was used to compare the recorded ground-motion on sites with reported stiff site conditions with the NGA-Sub for CAM median predicted relations. To avoid the impacts of source effects and possible non-linear high frequency site effects, the study was limited to the stations at large source-to-site distances. The results of the misfit analysis indicate systematic under estimation of PGA and Sa0.3s both across Central Mexico and along coastal stations compared to the recent GMPEs. The results indicate an even larger bias for the Hill Zone stations within the Mexico City region compared to rock/stiff soil stations across inland and coastal areas, corroborating studies suggesting special high frequency GM amplification within Hill zones due to impedance contrast of low-velocity volcanic rocks overlying higher velocity limestones.

We will present the details of the misfit analysis and our findings on the scale of the bias. We also will present the impact of the GMPE bias in high frequency on regional hazard and risk assessment for low-rise structures in the Mexico City.

Geotechnical Field Observations From the 18 September 2022 Mw6.9 Chihshang, Taiwan Earthquake

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We performed post-earthquake reconnaissance in Taiwan following the 18 September 2022 M_W6.9 Chihshang, Taiwan earthquake. The National Science Foundation-funded Geoengineering Extreme Events Reconnaissance (GEER) Association sponsored our work. The earthquake occurred on the Central Range strike-slip fault, with the rupture direction extending north from the epicenter. Near-field seismic stations measured PGAs exceeding 0.5 g along the fault. PGVs increased in the direction of the rupture with average intensities of 8 cm/sec near the epicenter, increasing along the fault to 89 cm/sec at the northern terminus. The ground motion recordings of the east (approximately fault normal) component show strong velocity pulses in the direction of the rupture. Our team investigated earthquake-induced landslides, surface fault rupture, and bridge damage using traditional reconnaissance techniques as well as unmanned aerial vehicles (UAVs) equipped with cameras and lidar. Despite the earthquake ground motion being relatively strong given the small source-to-site distances to important locations throughout the alluvial plain from Chihshang to Ruisui, we did not observe any surface manifestations of liquefaction. We speculate that liquefaction did not occur due to a combination of short earthquake durations as well as a variation of soil types throughout the alluvial plain. The observations are important for geotechnical engineers practicing in seismically active areas with nearby, active faults capable of creating strong velocity pulses. In particular, we have an opportunity to further our understanding of liquefaction (or non-liquefaction) during short, pulse-like earthquake motions.

Implementation of Distance Conversion Equations in Seismic Hazard

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With an increase in settlements near seismically active faults, accurate Probabilistic Seismic Hazard Assessment (PSHA) close to the fault has become of extreme significance. PSHA incorporates different distance metrics to calculate the seismic hazard of an area. These distances have similar values at large distances from the fault. However, closer to the fault, there can be considerable variation between different distance metrics. As an example, an accelerograph used in the 7.3 M_W earthquake in Tabas, Iran was located at an epicentral distance of 57 km but with a rupture distance of only 8 km. These differences can cause large variations in the calculated seismic hazard of the area. Monelli et. al. (2014) discovered a difference of up to 58% in design ground motion while conducting a PSHA sensitivity study using point-based and rupture distances. In this study, we develop empirical equations to convert R_{JB} to other distances and calculate their associated sigma. We use these equations to conduct deterministic and probabilistic studies to present the effect of using consistent distance metrics. The deterministic study is conducted for four sites located at different azimuths from the faults. We have considered a vertical strike-slip fault, a 50 dip-slip fault, an area source of radius 100 km, and a volume source with a depth from 5 km to 10 km. We used Pezeshk et al. (2011), which is based on R_{RUP} distance, as the GMM for all the studies. Our results show a meaningful increase in seismic hazard due to the use of consistent distance metrics. We have also compared our results with other published studies. A method to include the additional variability in PSHA due to distance conversion has also been discussed. The proposed empirical equations are developed based on the geometry of the fault and can be used for any GMMs for seismic hazard calculations.

Improving Lunar Seismic Source Models With L.R.O.C Data for Preliminary Lunar Probabilistic Seismic Hazard Assessments

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The future of lunar exploration is quickly progressing towards the presence of long-term installations, both crewed and uncrewed. Probabilistic seismic hazard analysis (PSHA) is used to inform the development of seismic design criteria for terrestrial structures. We now look to leverage PSHA to inform design criteria for future lunar bases. Apollo-era seismometers, which were active from 1969 to 1977, provide essential information about lunar seismicity, including 28 shallow moonquakes (SMQs) recorded during their operational period. However, the limited dataset, the distribution of the instruments on the lunar surface, and the sensor performances yield highly uncertain input criteria for a PSHA. In particular, localization of seismic sources is difficult to ascertain. Imaging from the Lunar Reconnaissance Orbiter Camera (LROC) has facilitated the detection and characterization of very young, surface-breaking thrust faults expressed by lobate scarps. Activity on these young faults may be the source of SMQs. Global, high resolution (0.5 mpp) coverage and mapping of lobate scarps allow us to extrapolate the Magnitude-Frequency Distribution (MFD) across the entire lunar surface and contextualize the absence of shallow moonquakes detected on the far side of the Moon. In our investigation, we analyzed and incorporated the previously-established spatial correlations between the lobate scarps imaged by LROC and the detected shallow moonquakes. Using the lobate scarps as a prior, we leverage Bayesian updating to fuse data from Apollo-era seismometers and LROC imaging to develop a more robust spatial source model for lunar seismicity. We provide insights into the significance of clusters of lobate scarps on magnitude distributions and outline a method for using fault maps to help extrapolate limited and localized seismometer information across the entire lunar surface for the development of a global MFD.

Methods for Unbiased Ground-Motion Intensity Conversion Equations and Implications for Hazard Map Assessment in California

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Ground-motion intensity conversion equations (GMICE) are used to describe the relationship between ground-motion amplitude and shaking intensity. GMICE are crucial for ShakeMap, ShakeAlert, and comparisons of results of probabilistic seismic hazard analysis (typically given in ground motion) to observations of historical shaking characterized by the intensity. While GMICE are particularly useful when they can be used to convert directly from ground motion to intensity, without the inclusion of the earthquake magnitude or distance to the site, we show that this approach leads to biased intensity estimates for PGM values above or below the median for the scenario.

The current approach to developing GMICE is to conduct an initial regression for intensity as a function of peak ground motion (PGM), commonly acceleration or velocity. Some GMICE include magnitude and distance effects using residuals in subsequent regressions, but these terms are only added into the initial equation that predicts intensity as a function of PGM. With this approach, there is an implicit assumption that the PGM and intensity are causal and fully correlated, which is not the case. We show that the current approach to GMICE development overestimates the variability of predicted intensity because residuals of the intensity from an intensity prediction equation (IPE) and the residuals of the PGM from a ground-motion model (GMM) are only partially correlated. We explore these effects and their causes using simulated data and GMICE from California based on the Worden et al. (2012) GMICE based on PGA. These results can be generalized to other GMICE, as the formulation of the Worden et al. (2012) model is consistent with standard practices used to develop GMICE, and intensity scales have been shown to be approximately interchangeable. This issue appears to be a major factor in explaining why published hazard maps for California and other areas appear to overpredict shaking relative to historical data.

Regional Ground Motion Model Evaluation for the Southern Eastern African Rift System

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Current seismic hazard assessments in the southern East African Rift System (EARS) use ground motion models (GMMs) developed from global datasets. Considering the region's early-stage continental rift setting combined with a deep seismogenic zone, it is unclear whether these models can predict the expected ground motion levels accurately. Both seismically vulnerable communities and faults with the potential to host magnitude (M) 7-8 earthquakes are located within this tectonically active region, resulting in a significant seismic risk. We explore the available ground motion records from earthquakes along the eastern and western branches of EARS to assess the suitability of the global GMMs commonly used, with particular focus on focal depths of the earthquakes and ground motions at close distances, and adapt selected GMMs to obtain a regional GMM. First, we compile a ground-motion database of earthquakes that is critically lacking for the southern EARS. This database includes a regional catalog of 882 earthquakes since 1980 (M 3 to 6.5) with available waveform records within epicentral distances of 300 km. For accurate calculations of earthquake locations (including focal depths), we relocate 250 events down to depths of 35-40 km. Data are scarce for events larger than M 5, especially at distances less than 100 km. Next, we find that ground motions are generally overestimated at close distances (<100 km) by the global GMMs, especially at shorter oscillator periods and peak ground acceleration. Finally, we use the referenced empirical approach and mixed-effects regression to obtain a regional GMM for southern EARS. This work provides valuable input to be used in future seismic hazard assessments for the region, producing a relocated earthquake catalogue and a much-needed regional GMM, to better understand the spatial distribution of earthquakes, examine tectonic EARS processes with depth, and quantify the expected ground motion levels.

Regional-Scale Seismic Fragility Assessment of Buildings in Istanbul Using Simulated Ground Motions

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Manifold studies have demonstrated the validity of simulated ground motions from various perspectives, i.e., via the comparisons of time-series against recorded motions, response spectra versus ground motion prediction equations (GMMs), and engineering demand parameters (EDPs) under different intensity measures (IMs). In particular, simulated ground motions become

more appealing for those seismic-prone regions in which recorded motions are scarce or GMMsare unavailable. In the past, modest computational resources hindered the simulation of high frequency ground motions, which is a crucial factor to perform nonlinear time history analysis of structures. In this study, as continuation of an ongoing earthquake research for the Istanbul city, we utilize measured material properties and geological site conditions from a comprehensive microzonation study, high-resolution topography data, and realistic fault rupture models. A suite of 57 physics-based large-scale earthquake ground motion simulations with highest frequency that can reach up to 12 Hz, are carried out by means of supercomputing facilities. A detailed building inventory that consists of more than 16,000 buildings in the Zeytinburnu district of Istanbul is adopted to build the structural models and conduct massive nonlinear structural analysis. Finally, following a probabilistic seismic demand analysis (PSDA), we investigate the seismic fragility of buildings at regional scale. This study can further enhance the accuracy of seismic fragility assessment of buildings in the Zeytinburnu district.

Seismic Vulnerability and Risk Assessment in Urban Areas in Dominican Republic. An Application to Santo Domingo Este.

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The Dominican Republic has a high seismicity, due to the position of the Hispaniola Island on the northern edge of the Caribbean plate where seismicity is especially intense, causing the entire island to be affected by a high seismic hazard. Seismic risk reduction involves attacking one of the two factors that contribute to it: the hazard and/or the vulnerability. Regarding the first factor, the options are limited, since the hazard cannot be reduced, this implies that the only way to reduce the risk is by reducing the vulnerability of the built environment. As part of the research project "Evaluation of the seismic hazard of Hispaniola island and the seismic risk in populations of the Dominican Republic", seismic hazard maps of the island and a list of the most important populations exposed to the greatest hazard have been obtained. From this, the municipality of Santo Domingo Este, was identified as a zone of priority interest to assess seismic risk. In this study, we start from the seismic vulnerability assessment based on the existing construction typologies in the area, where a field survey and a visual analysis through the Street View Map images were carried out. The information collected was classified into a limited number of typologies that statistically represent the entire housing stock. An exposure database was generated that contains the geometries of the buildings, and attributes that influence their seismic performance, such as occupants, construction materials, height, function and area. Based on these attributes, a vulnerability model is assigned to the buildings, based on the HAZUS scale which indicates how they will behave in the face of seismic shaking. Regarding seismic risk, empirical and analytical methods will be used and the most suitable capacity and fragility curves will be identified for the construction typologies of the Dominican Republic. The results will yield maps of the expected losses for the seismic scenarios identified with different exceedance probabilities in the hazard study.

The Earthquake Fatality Load and Capacity by Country: Measures of Impact

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We propose two new quantitative measures of the impact on a country by fatal earthquakes. (1) The *earthquake load* in a country is the ratio of fatalities to population size, in units of fatalities per person over a given period in recent history. It measures the level of suffering by the population in seismically active countries, that is, it indicates the average annual cost in lives. The list of this new parameter in countries with adequate data for this estimate is lead in severity by Ecuador, Iran, Peru, Turkey and Chile considering the last five centuries. (2) The *earthquake potency* for a country, defined as the sum of recorded fatalities divided by the number of earthquakes that it took to accumulate them, equals the average earthquake disaster size in a given country, in units of fatalities per event. For calculating these two parameters, we have compiled a new catalogue of earthquake fatalities for the world, covering the period 856BC to March 2022, listing 2,795 reports. 117 countries have reported at least one earthquake with one fatality or more; 77 and 52 countries have reported more than 100 and 1,000 earthquake fatalities, respectively. The total number of fatalities recorded is 8,336,526. We estimate that the reporting of fatal earthquakes is complete for events with more than 16 fatalities since 1927. Caution has to be exercised in estimating what earthquake disasters are in store for a given country because the 95 year period of high quality recording is about an order of magnitude shorter than return times of great earthquakes. For rescue purposes, it is important to realize that small earthquakes, M 5 ± 0.5, can cause significant numbers of fatalities.

Advancing Science With Global Seismological and Geophysical Networks

Oral Session • Tuesday 18 April • 04:30 PM Pacific

Conveners: Andrew M. Frassetto, Incorporated Research Institutions for Seismology (andy.frassetto@iris.edu); Colleen Dalton, Brown University (colleen_dalton@brown.edu); Martin Vallée, Institut de Physique du Globe de Paris (vallee@ipgp.fr); Frederik Tilmann, GFZ Potsdam (tilmann@gfz-potsdam.de); David Wilson, Albuquerque Seismological Laboratory, United States Geological Survey (dwilson@usgs.gov); Robert Busby, Incorporated Research Institutions for Seismology (busby@iris.edu)

Continuing Detection and Location Using Continuous Long Period Data Recorded at Global Seismic Networks

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Earthquakes detections and location is routinely performed by picking body wave phases, their association and location of the source. This process is performed on relatively high frequency data and mostly rely on P and S waves. Since the 90s is however clear that long period (>20s) seismic waves are radiated by several geophysical processes, as landslides, rapid ice movements, volcanic eruptions and also some earthquakes. However, the detection of these events with classical seismological approaches is not trivial.

We here apply a method to detect and locate source of long period (30-100s) surface waves generate at the free surface of the Earth. This method employs continuously recorded seismological signal at global seismic networks, by long and very long period instruments. By applying our method to ~13 years of data we detected and located 33429 events, including ~1500 previously undetected events. These new events track environmental and volcanic processes occurring in remote places of our planet (e.g., Antarctica, deep oceans).

We will first present the method, its advantages and caveats. We will then discuss the results obtained by analyzing data from the year 2010 to the beginning of 2023. We will particularly focus on new sources, as the large number of new detections in the western antarctica, or the significant increase of new long period events we resolved offshore of eastern United States.

Our catalog of new detected events, is here presented as the base for future studies, aimed at quantify the physical processes generating the long period signals we record.

Global Trends in Microseism Amplitude on a Warming Planet

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Earth's microseism wavefield is incessantly excited by wave-wave and wave-solid Earth coupling processes and constitutes the dominant global long-period seismic source process in the absence of earthquakes. The primary and secondary microseism bands reflect integrated geographically extensive ocean wave forces applied to both the ocean floor and upon coastal regions and are uniquely integrative proxies for large-scale ocean wave state. Previous microseism studies have thus utilized microseism metrics to explore spatiotemporal trends in storm intensity, storm tracking, sea ice extent and ocean wave attenuation, and other variability in the weather and climate system. I will summarize results from a new and frequency-domain analysis methodology incorporating continuous long-operational calibrated global seismic data to the near present to extract frequency-domain primary and secondary microseism intensity metrics, and to assess and interpret their periodic and secular regional to global features. A number of atmospheric reanalysis and modeling studies now indicate that Earth's storm and ocean surface wind intensity is broadly increasing across multi-decade time scales under the influence of climate-change attributed storm intensification. This analysis shows that increasing storm intensity is also apparent in global microseism amplitudes. This is most apparent in the primary microseism band which most directly reflects wave amplitudes along Earth's coastal regions.

Wireless Collection of Environmental and State-of-Health Data in Seismographic Networks

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Seismographic networks frequently incorporate the acquisition of data sources of related interest. For example, the Global Seismographic Network combines data acquired from infrasound and meteorological sensors. As a matter of practice, the physical connection of multiple data sources to data acquisition equipment requires significant systems engineering not to compromise the quality of acquired data through the introduction of ground loops and electrical interference. Various geophysical and environmental sensors, in general, are not physically co-located, resulting in complicated wiring and the need to protect wiring against physical damage, especially voltage transients induced by lightning. Since the primary seismological data are acquired with a dynamic range exceeding 150dB, low electrical noise in the acquisition system must not be compromised by adding related inputs. Therefore, using a secure, error-correcting protocol, the Q8 data acquisition system integrates additional data sources using low-power wireless transmission from multiple nodes. The implementation includes precision timing in each node and the ability for nodes to "relay" traffic in a mesh topology. The physical connection to the central acquisition unit is thus eliminated. Moreover, the sensors for additional data can be placed in their optimal physical location, e.g., weather and magnetometers away from local interference, or monitoring of PV arrays may be positioned at an outdoor site. The implementation accommodates up to 16 channels of information from up to 8 nodes, totaling 128 channels at up to 1 sample/sec. The transmission distance is up to 100m or more, depending on the antenna. The power consumed is in the mW range, compatible with ultra-low-power cycled modes of the Q8.

The Minimus Digitizer Platform: A User-Friendly Ecosystem for Efficient Network Management and Seismic Station Configuration

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The Guralp Minimus broadband digitizer has led the way with introducing a number of innovative features to broadband digitizers including easy network configuration, compact form-factor, extensive State of Health (SOH) monitoring and low latency digitization. Since its introduction, there have been major technological advances in processing chips resulting in the power consumption of seismic digitizers decreasing drastically in the last few years. The next iteration of Minimus, Minimus2, takes advantage of modern chip power consumption to reduce overall nominal power consumption by over 50% whilst maintaining high functionality. This significant decrease in power consumption will facilitate far more simplified field deployments for offline deployments.

The Minimus platform also provides a high level of functionality for online stations, including the industry unique option of sending State of Health (SOH) data via the SEEDlink protocol. This makes SOH monitoring far simpler for larger networks as SOH data be managed using similar methods as waveform data. This also allows for time-series analysis of SOH data to be able to proactively maintain stations and advance diagnose any issues before they result in any loss of data. The Minimus platform seamlessly interfaces the Discovery software to seamlessly integrate new stations into existing networks. The management of large numbers of real-time seismic stations is further enhanced with Guralp Data Centre ("GDC") a cloud-based software package to build on the Discovery tool set.

The Minimus platform was built from the ground up to provide one of the lowest latency digitizers available with digitization latencies down to 40ms, making it well suited to Earthquake Early Warning applications. This is achieved with the use of causal decimation filters, high sample rates and Guralp's proprietary GDI protocol. The Minimus platform is built as a modular digitizer platform that is available within a number of different packages to suit a range of applications, including as a standalone digitizer or built within Broadband seismometer and Force Balance Accelerometer systems.

Reviewing How the Management and Operation of the Global Seismographic Network Has Evolved, With a Look Into the Future: A Partnership Between the Community, NSF, and the USGS

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The Global Seismographic Network (GSN) is a state-of-the-art facility consisting of permanent stations around the world with broadband and very broadband seismometers, which provide real-time, continuous, high-quality seismic data, along with ancillary sensors. The GSN has driven forward fundamental research in geophysics and geological hazard monitoring for decades. The network is the result of productive cooperation at the federal level between the National Science Foundation and United States Geological Survey and in management and operations by the EarthScope Consortium, Inc. (formerly IRIS), the USGS Albuquerque Seismological Laboratory (ASL) and UC San Diego's Project IDA over the last four decades. Continued vigor of the GSN over the last decade has been greatly aided by the contributions of the scientific community through a governance process facilitated by EarthScope and the exceptional diligence of the station operators at ASL and IDA. Here we summarize EarthScope's role as NSF facility operator and a science community consortium that provides stakeholder scientists with an up-front seat and input into network operations and potential scope change. Dedicated community governance through the GSN Advisory Committee has promoted collaboration between researchers and network operations, creating opportunities to improve the quality and breadth of observations made by these stations. We also preview the potential future evolution of the GSN, recognizing the need for innovation and continued scientific relevance. We will discuss potential ways to enhance the GSN's already robust observing capacity, optimize the network distribution through international collaboration, and modernize station design, moving toward higher quality and more complete data, robust operations, and lower operational costs. EarthScope is committed to the continued viability of this unique and high quality global observational network.

Advancing Science With Global Seismological and Geophysical Networks [Poster]

Poster Session • Tuesday 18 April

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A Truly Very Broad Band Borehole Seismometer With Flat Response Over 5 Decades of Frequency

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Decades ago new opportunities in seismology were opened by the development of broadband seismic sensors with feedback. The three defining characteristics of these instruments were the bandwidth extension to longer periods, a much lower intrinsic noise and a higher dynamic range. However, the goal of further extending their bandwidth to frequencies above 100 Hz has proven elusive, because these sensors are plagued by parasitic resonances leading to modes not controllable by the feedback system.Here we present a new low noise seismic borehole sensor with a truly very broad band flat response over five frequency decades from 2.7 mHz (360 sec) to 270 Hz. The instrument does not have mechanical resonances below 400 Hz. We achieved the bandwidth extension to high frequencies with improvements of the mechanical design, i.e. the arrangement of the pivots and the geometry of the spring.

The design is realized in a borehole arrangement, where three sensors are stacked in 90 degree angles to each other. Including a single jaw hole-lock as a clamping mechanism the complete stack has a diameter of 89 mm, is 625 mm long and weighs about 24.5 kg. We show test results from three co-located complete borehole sensors with identical frequency responses.

Ambient Seismic Noise Studies of the Alpine Fault, New Zealand

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The Alpine Fault has been identified as the primary seismic hazard in Southern New Zealand since it ruptures in M7-8 earthquakes as regularly as every ~300 years and last ruptured in 1717 AD. Empirical information about how the ground shaking will affect New Zealand after a large Alpine Fault earthquake does not exist as no such Alpine Fault earthquakes have yet been recorded instrumentally. Ambient seismic noise is a new field in seismology that allows us to study wave propagation in areas of interest without the need of an earthquake or explosions. Ambient noise typically appears random and incoherent in seismograms, but it has been demonstrated experimentally and theoretically that the cross-correlation of ambient seismic noise recorded at two seismic stations can reveal coherent energy travelling between stations. The resulting cross-correlation function can provide an estimate of the Green's function between those stations. This analysis allows us to retrieve the propagation properties of seismic waves over long paths using noise records alone. A good understanding of the ambient noise field is vital for both time-travel and amplitude measurements. We perform a noise analysis of the West Coast of New Zealand to characterise the ambient noise field using records from permanent and temporary networks, including SALSA (Southern Alps Long Skinny Array), a new temporary network of broadband seismometers deployed every ~10 km between Milford Sound and Maruia following the Alpine Fault trace. This analysis will allow us to perform travel-time analysis (ambient noise tomography) and amplitude analysis (Virtual Earthquakes).

Current Issues and Difficulties Being Faced by the Ukrainian Seismic Network

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The Ukrainian seismic network was in need of modernization in February 2022 and the war has exacerbated its critical issues, leading to the need for a fundamental reorganization. We will discuss the current status of the network and draft reconstruction plans. As of January, 2023, the war has caused damage to the network including destruction of facilities and infrastructure, inability to serve stations, destruction of the Zmiinyi Island infrastructure, migration of people involved in maintenance, and delayed standardization of existing stations.In order to effectively participate in data exchange and integration with the European and international community, it is necessary for the Ukrainian seismic network to have certified, industry-standardized instruments and updated digital infrastructure. However, the seismic network of the Institute of Geophysics of the NAS currently possesses outdated and non-certified equipment, which leads to poor quality instrumental data and hinders the exchange of observational materials and scientific analyses with the global scientific community. In 2019, efforts towards modernizing the Ukrainian seismic network began with the creation of a unified platform for data processing. To achieve this, the industry-standard SeisComP seismic network software was adopted. In November 2022, four low-cost Raspberry Shake Seismographs (RS3D) were purchased and will be tested in various locations throughout Ukraine. The deployment of these budget seismometers is a temporary solution for both data collection and education in Ukraine. Even though it is generally a seismically calm region, it is important for Ukraine to have a functional seismic network for both safety and research purposes. A modernized seismic network not only serves as a means of surveillance, but also as a fundamental infrastructure for academic geophysical research in Ukraine and will allow for better integration and data exchange with the European and international community.

Collective Impact in Earthquake Science

Oral Session • Tuesday 18 April • 08:00 AM Pacific

Conveners: Aaron A. Velasco, University of Texas at El Paso (aavelasco@utep.edu); Marianne S. Karplus, University of Texas at El Paso (mkarplus@utep.edu); Michael R. Brudzinski, Miami University (brudzimr@miamioh.edu); Susan Bilek, New Mexico Institute of Mining and Technology (sbilek@nmt.edu); Manuel Mendoza, University of Colorado (mame3278@colorado.edu); Alexandros Savvaidis, Bureau of Economic Geology (alexandros.savvaidis@beg.utexas.edu); Steven Jaume, College of Charleston (jaumes@cofc.edu)

Learning Past Disasters and Forecasting Future Earthquakes on the 100th Anniversary of the 1923 Kanto Earthquake

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The great Kanto earthquake occurred on September 1, 1923, and caused the worst earthquake disaster in Japan with ~105,000 casualties. The majority (~ 90 %) of victims were due to fire; a unique feature different from the 2011 Tohoku earthquake (>90 % by the tsunami) or the 1995 Kobe earthquake (~ 90 % by building collapse). The Kanto earthquakes (M ~ 8) occur along the Sagami trough, where the Philippine Sea plate subducts beneath the Kanto region. The penultimate Kanto earthquake, the 1703 Genroku earthquake, caused larger crustal deformation and worse tsunami disasters in the southern Boso peninsula. Recently, documents and tsunami deposits indicate that the 1293 Showo earthquake and the 1495 Meio earthquakes were also Kanto earthquakes, suggesting a recurrence interval of 210 +/- 9 years, while other candidates such as the 878 and 1433 earthquakes have been also pointed out.

In order to share such seismological knowledge and uncertainties with the general public, the Japanese government's Earthquake Research Committee (ERC) annually estimates and announces long-term forecasts, in terms of occurrence probability in the next 30 years. The probability of a future Kanto earthquake is calculated as 2 % if Brownian Passage Model is adopted, while it is 10 % if the Poisson model is assumed. The ERC also makes National Seismic Hazard Maps, which are also accessed through the Japan Seismic Hazard Information Station (J-SHIS) website. The Central Disaster Management Council of the Cabinet Office makes damage estimation, assuming the worst-case scenario. When a 1923-type Kanto earthquake occurs, 700,000 to 1,330,000 houses may be burned and 20,000 to 70,000 people may be killed. For smaller (M~7) earthquakes beneath Tokyo, the fire damage may be up to 610,000 houses and the casualties may be up to 23,000 people. Because of the higher probability of occurrence (70 % in the next 30 years), the countermeasure policies were targeted to the latter scenario and shared with local governments and the general public.

Developing Guidance to Communicate Global Aftershock Forecasts

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The U.S. Geological Survey (USGS) is responsible for public aftershock forecasts following US earthquakes. An automated system produces forecasts for most M≥5 earthquakes, with the first forecast posted online ~20 minutes after the earthquake. These forecasts are presented using automated templates, based on best practices around tiered communication. While this system is not operational for earthquakes outside the US, the USGS has received requests for forecasts following damaging earthquakes worldwide and plans to produce forecasts for global earthquakes with a high number of fatalities (orange or red PAGER level). However, aftershock forecasting globally has the inherent challenge of communication across different languages and cultures. Further, aftershock forecasts made from outside the affected region can be a challenge for local science communicators because they may need to respond to questions from the media and the public about a forecast that they may not be familiar with themselves. To support the communication of aftershock forecasts globally, the USGS is developing additional public tools to assist local science communicators in understanding the forecasts and communicating them within their communities. A two-page communication guide will accompany the forecast template and will be translated into multiple languages. To develop this communication guide, we are in the process of facilitating meetings with science communicators in different countries to solicit feedback on its components. Additionally, updates to the automated template are required, specifically regarding protective action information. We currently recommend "Drop, Cover, and Hold On", which is appropriate in the US, but not in other countries with poor building practices. By developing the communication guide and updating the current forecast template, aftershock forecasting will be more effective and accessible to reduce seismic risk worldwide.

Improving Family Resilience for Earthquakes in Hispaniola

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Due to its geographical and geotectonic characteristics, Hispaniola Island is exposed to considerable risk from seismic events. Rapid population growth and urbanization are causing a rapid increase in vulnerability of communities and disaster impacts in Haiti and Dominican Republic, which share the island. Land degradation and unplanned growth in urban and rural areas unsuitable for development, lack of compliance with building codes are the main drivers of most of the current vulnerability in the island. For years, stakeholders have been working in the development and implementation of strategies to provide practical family preparedness in vulnerable communities about the seismic risk but still these efforts are not enough to increase resilience. For that reason GeoHazards International (GHI) with support of USGS have been conducting a three-year program to supply families in Haiti and the DR with practical earthquake preparedness information based on robust earth science in four communities in the Cibao Valley in the DR and three communities in Haiti.

GHI and local partners are conducting family disaster preparedness activities, a public awareness campaign and focused community interventions designed to improve the safety of families from local natural hazards. Examples of interventions include support for basic, practical preparedness measures such as local and home hazard assessments, support to families to develop their emergency plans, technical advice and assistance with anchoring or relocating objects in the home that could fall or create hazards during earthquake. The program is also developing sourcebooks with practical family preparedness information in local languages and in English as a resource for disaster safety advocates interested in helping their communities build resilience.

Using a Collective Impact Framework in SZ4D to Build Equity and Capacity With Geoscience

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The BECG integrative group has been working to identify strategic activities to capitalize on the assets of the SZ4D initiative (i.e., geohazards, international, instrumentation, multi-institutional). BECG recommended six primary areas to concentrate broader impacts efforts: 1) building capacity for international collaborative research, training, and data sharing; 2) promoting equity in hazard mitigation; 3) supporting evidence-based education and training; 4) increasing effectiveness of public outreach; 5) strengthening interdisciplinary collaboration; and 6) improving BAJEDI. The overarching goal is to transform the mindset of our geoscience community to embrace these efforts as critically important for successful science.

A traceability matrix was developed to determine critical needs for each area. Needs identified in multiple areas that should be targeted to enable accelerated progress included: a common agenda, development of assessment tools, establishing partnerships, and improved communication. BECG identified that a Collective Impact (CI) framework could meet these specific needs. CI was developed in social science as the commitment of a group of people from different disciplines to solving specific social problems using a structured form of collaboration. CI would help to ensure BECG activities have meaningful staying power and not as fleeting or discretized as traditional PI-focused broader impacts. Through discussions with the SZ4D community, BECG developed an implementation plan for building a CI framework to accomplish SZ4D science and capacity building goals. These priorities emerged: 1) developing partnerships with key communities, 2) shepherding communities of practice, 3) coordinating international capacity building, 4) strengthening training partnerships, and 5) matchmaking between PIs and BECG efforts. The matchmaking component has resonated as the highest priority such that the other priorities can be seen as key steps to ensure the matchmaking to be successful.

Dealing With the Unexpected: South Carolina's Response to the 2021-2022 Elgin-Lugoff Earthquake Sequence

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Starting with a M=3.3 event on December 27, 2021, the Elgin-Lugoff, South Carolina region has experienced 80 felt events as of December 10, 2022. 19 of these generated 100+ "Did You Feel It (DYFI)?" reports (5 largest generated 1000+) and over 25,000 total DYFI reports resulted from this sequence. A review of historical earthquakes in the Midlands of South Carolina has revealed no evidence of previous seismicity associated with this source zone, making this a clearly "unexcepted" set of events. Multiple organizations in South Carolina responded to this sequence, primarily to inform state/local government agencies and the public regarding the nature and potential hazards associated with these earthquakes. We faced several challenges in doing so, in particular because of a lack of seismic stations near the swarm (closest network station >30 kilometers distance). Only 1 seismometer/telemetry system was initially available to redeploy close to the seismicity, which improved detection and location of events but was not sufficient to clearly delineate the geologic structure associated with this earthquake swarm. On a positive note, moment tensors for the larger (M 3.3-3.6) earthquakes determined by other organization (SLU/USGS) allowed us to quickly determine that these earthquakes were consistent with the regional stress field and not associated with the longer segments of the Eastern Piedmont Fault System that run through the area. This also helped combat public rumors that these events were human-induced and not natural. This earthquake sequence also exposed a vulnerability in earthquake response in South Carolina, in that no state agency had the ability to closely monitor this earthquake sequence adequately and answer all the questions posed by other state/local agencies and the public. Led by the South Carolina Geological Survey, we are currently proposing that the state acquire a set of portable, telemetered instruments that would fill this gap.

Collective Impact in Earthquake Science [Poster]

Poster Session • Tuesday 18 April

Conveners: Aaron A. Velasco, University of Texas at El Paso (aavelasco@utep.edu); Marianne S. Karplus, University of Texas at El Paso (mkarplus@utep.edu); Michael R. Brudzinski, Miami University (brudzimr@miamioh.edu); Susan Bilek, New Mexico Institute of Mining and Technology (sbilek@nmt.edu); Manuel Mendoza, University of Colorado (mame3278@colorado.edu); Alexandros Savvaidis, Bureau of Economic Geology (alexandros.savvaidis@beg.utexas.edu); Steven Jaume, College of Charleston (jaumes@cofc.edu)

A New Approach for Assessing Fragility Curves in Seismic Vulnerability and Risk Studies. an Application to Costa Rica

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To quantify the human and economic losses caused by these events, seismic risk studies must deal with different types of uncertainties whose assessment methods are still under development, such as those associated with selecting fragility curves (FCs). The appropriate use of FC allows a better approximation of the level of performance of a structural system in the face of seismic hazards. In this respect, an inadequate selection of the FC can mean a notably unreliable estimation of damages and losses. This research proposes a methodology approach for assessing and selecting FCs for seismic risk studies from a catalogue of existing proposals available in the literature. To this end, a bibliographic search of different vulnerability and seismic risk studies for the Central American region has been conducted. A database was constructed with the parameters of the capacity and FCs available for diverse construction typologies. A multidimensional index based on several variables divided into key dimensions is proposed to facilitate the creation of a rational ranking of fragility curves in terms of adequacy. Additionally, the specific criteria considered to build this index were validated from a survey of experts and the implementation of the fuzzy Analytic Hierarchy Process (AHP).The FCs used in different vulnerability projects in Costa Rica are explored, applying the methodology developed in this case. As a result, it is concluded that in the diverse vulnerability projects, FC with very different probabilities of damage is being used for buildings with the same attributes. Moreover, the proposed methodology permits knowing the reliability level of the FC used depending on the class the curve was classified into based on their score. Therefore, it allows establishing the adequacy and uncertainty related to the selected FC, a relevant subject that the researchers should consider in seismic vulnerability and risk studies.

Center for Collective Impact in Earthquake Science (C-CIES)

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The Center for Collective Impact in Earthquake Science (C-CIES), funded as a Track 1 planning grant by National Science Foundation (NSF)'s Centers for Innovation and Community Engagement in Solid Earth Geohazards program, aims to address fundamental science questions related to natural hazards through a novel approach of involving all stakeholders. The C-CIES mission is to advance hazard science with the aim of meeting the natural hazard mitigation needs for all communities in regions of low probability but high impact hazard risk. The vision for the center is to become a world-class research center dedicated to improving resiliency from geohazards in an equitable, accessible, and sustainable manner. The core values of the center are scientific integrity, equity, excellence, diversity, access, justice, inclusion, and collective impact. The goals of the center will be to 1) Advance basic hazard science and engineering; 2) Establish a foundation for a shared, value-driven understanding of science; 3) Be responsive to the needs of all communities through user-inspired research; 4) Grow to national prominence; 5) Recruit, retain, and train the next generation of diverse, interdisciplinary scientists; 6) Develop a framework for impactful geoscience that translates results of scientific discovery into actions that can improve resilience and reduce risk from geohazards. C-CIES has adopted the collective impact (CI) model, which develops a network of community members, organizations, and institutions through the development of a common agenda, centralized support, continuous communication, mutually reinforcing activities, and shared measurement. C-CIES science will initially fund pilot projects that will address faulting, earthquakes, and their impact, and upon evaluation, may be promoted to a full project as the center launches in two years. If promoted to a full center, C-CIES science questions will be expanded to other LPHI geohazards. Using CI, we aim to change the way geoscience is conducted by answering fundamental community-driven science questions that will have a broad, positive impact on all communities.

New Seismic Exposure Model for Guatemala City, a New Seismic Risk Approach

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Advances in seismic hazards in the Central American region have shown the need to develop new studies on the seismic vulnerability of all cities in the region. In recent years, a series of large magnitude earthquakes have occurred in Guatemala that has highlighted the lack of earthquake prevention and mitigation policies. In 2012 and 2017, two earthquakes of 7.3 and 7.0 respectively occurred in the San Marcos region in the southwest of the country, producing severe damage. Seismic vulnerability studies such as GEM (2018) and PREPARE (2021) have been developed for the country. This study proposes a new seismic exposure model for Guatemala City. A methodology is presented combining different sources of information and using new digital tools for data collection in the country. This exposure model has revealed the high level of buildings vulnerable to a possible large earthquake. Likewise, the results of the exposure model reveal some deficiencies in the prevention and mitigation plans of local public institutions.

Social Science and Education Research for ShakeAlert, the Earthquake Early Warning System for the West Coast of the United States

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As of May 2021, rollout of public alerting of the ShakeAlert Earthquake Early Warning (EEW) System, has been completed in Washington, Oregon, and California. Critical questions remain about what people understand and expect from ShakeAlert, including if they know what to do when they receive an alert. To evaluate whether the ShakeAlert System has been successful in answering these key research questions, the U.S. Geological Survey (USGS) collaborates with partners from universities, emergency management and other state agencies, the National Science Foundation, and USGS licensed alert distribution partners to implement a social science initiative focusing on three goals:

1. To understand earthquake risk perception, protective action knowledge, and basic earthquake preparedness across Washington, Oregon, and California populations. 2. How to apply social science research to inform the ShakeAlert communication, education, outreach, and technical engagement (CEO&TE) programs.

3. To develop a monitoring and evaluation plan for CEO&TE programs for ShakeAlert. The ShakeAlert social science initiative focuses on research that is currently underway and plans future directions to reach our goals.

We outline the various publications that have been published or are in draft, future projects, and how social science and educational research has been integrated into the ShakeAlert System to improve outcomes for users of the system.

The Launch of Seismica: From Early Career Researchers' Perspective

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Seismica is a newly developed community-run Diamond Open Access journal for seismology and earthquake science. The idea for Seismica started in late 2020 when Earth Scientists on social media came together in response to steep increases in article processing charges for Gold Open-Access journals. The need for a Diamond Open Access journal and the necessity to share seismology research for broader community benefits was evident. This led to collective action as a handful of early- and mid-career earthquake scientists came together, adopting the common agenda of founding and offering our community a new peer-reviewed journal that would be free to publish and read. This new journal's philosophy was developed through continuous communication among broader community members. Once an Editorial Team was recruited, an all-volunteer board of researchers prepared Seismica for launch within ten months, developing policies and structures for a journal that strives to be accessible, transparent, respectful, credible, and progressive. Seismica opened for submissions in July 2022.Here we highlight strategies and efforts to improve professional development opportunities for early-career researchers (ECRs) through Seismica and our lessons from this experience. ECRs make up a high share of volunteers in Seismica, and the time they dedicate to this community effort has professional value. Besides regular journal editorial and reviewer duties, ECRs have unique opportunities to gain experience in various stages of ongoing journal development in dedicated operational teams, such as preparing for the journal launch and handling the first set of journal submissions. The wide-ranging group of early-to-mid career researchers involved in Seismica means they have a greater say and stake in the decisions that affect the seismology community, ensuring Seismica adjusts well to the constantly-evolving career pathways and expectations in this field. These activities are all valuable parts of professional development and career advancements that showcase Seismica's unique contribution to the seismology community.

Visualization of Aftershock Forecasts Driven by User Needs

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The United States Geological Survey releases aftershock forecasts following large (M5+) earthquakes in the US and associated territories, using an automated system. Forecasts contain the expected number (and range) of aftershocks in a specified area for various magnitude thresholds and time windows. The numbers are released in an aftershock forecast product template, in tables and text. Visualizing these forecasts can better aid communication of aftershocks. In particular, we want to identify which forecast visualizations (including maps) can serve a variety of user groups, using a four-step research program. First, we hold workshops with members of target user groups, including emergency managers, civil/structural engineers, critical infrastructure operators, urban search and rescue teams, the media, public information officers/science communicators, and public health officials. In these workshops, users will perform small-group activities to elicit specific user needs on the types and dimensions of aftershock forecast information needed by their role (informational needs) and how this information would optimally be packaged (product needs). We will then develop a suite of forecast graphics and maps that align with these informational and product needs (step 2). In step 3, we plan to run a user experiment to test a subset of these forecast products. In the experiment, members of the target groups will use different forecast products to perform decision-making tasks based on common use cases of aftershock forecasts. The final step is to analyze the experimental data to reveal the characteristics of forecast products that can effectively communicate the forecast across user groups. Workshops and experiments will be held with participants from the United States, Mexico, and El Salvador to identify cross-cultural components of effective forecast communication. We present preliminary results from several user workshops and discuss next steps in the research agenda.

Constraining Seismic Hazard in the Cascadia Subduction Zone

Oral Session • Thursday 20 April • 02:00 PM Pacific

Conveners: Leah Langer, U.S. Geological Survey (llanger@usgs.gov); Max Schneider, U.S. Geological Survey (mschneider@usgs.gov); Erin A. Wirth, U.S. Geological Survey (emoriarty@usgs.gov); Diego Melgar, University of Oregon (dmelgarm@uoregon.edu); Valerie Sahakian, University of Oregon (vjs@uoregon.edu)

A Comparison of Foraminiferal and Diatom-Based Transfer Function Estimates of Coseismic Subsidence During the 1700 Ce Earthquake Along the Oregon and California Coast

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At the Cascadia subduction zone, quantitative foraminiferal-based coseismic subsidence estimates are most often used to constrain earthquake and tsunami source models. However, ecological factors affecting foraminifera such as dissolution in low pH environments, mixing across subsidence contacts, and limited supratidal and subtidal range can limit their application and accuracy. Diatoms have the potential to produce more accurate quantitative estimates of coseismic subsidence because they are composed of dissolution-resistant siliceous valves, do not burrow through sediment, have high species turnover in the intertidal zone, and are found in freshwater environments. Here, we develop a diatom-based Bayesian transfer function (BTF), which uses the empirical relationship between modern diatom assemblages and elevation within the tidal frame to estimate relative sea level (i.e., land level) changes from fossil diatom assemblages in cores and outcrops. We use a new modern dataset of >150 diatom samples from tidal wetlands along the Oregon and northern California coasts. We apply our diatom-based BTF to the 1700 CE earthquake contact at 13 Oregon and California coastal sites that also have existing foraminiferal-based BTF coseismic subsidence estimates. We find that at most sites diatom subsidence estimates are at the upper range (e.g., Salmon River) or exceed (e.g., Nestucca) foraminifera-based estimates. At Netarts Bay, the new larger diatom-based subsidence estimates are more similar to subsidence estimates at adjacent sites and help resolve ambiguities in rupture models for the 1700 CE earthquake. Future work will focus on understanding why foraminifera might underestimate subsidence and how diatom ecological factors can improve subsidence estimates, as well as determining the sensitivity of earthquake and tsunami source models to decimeter-scale increases in coseismic subsidence.

Investigating the Earthquake Rupture History of the Northern Cascadia Subduction Zone Using Lacustrine Diatoms, Lake Ozette, Washington, USA

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Offshore turbidites and onshore tidal wetland stratigraphy have provided exceptional geologic records of great (M_w >8) earthquakes along the Cascadia subduction zone (CSZ). Together, these geologic records document up to 19 great earthquakes at the CSZ over the last 10,000 years, however, most onshore evidence is concentrated in the central and southern CSZ where records extend thousands of years longer than the northern CSZ. The limited onshore record of past earthquakes and tsunamis in the northern CSZ leave questions about the spatial and temporal variability of events along the entire megathrust boundary. Coastal lakes located in the northern CSZ may provide a more complete picture of past megathrust earthquakes since earthquake magnitude thresholds for generating depositional signatures in lakes are typically lower (MMI ~5.5) than other environments (e.g., coastal marshes). A combination of extensive coring and chirp profiles collected from Lake Ozette, located on the coastal rim of the Olympic Peninsula in northern Washington state, has revealed more than 25 Holocene subaqueous mass transport deposits (MTDs), however, questions about the source of the MTDs still remain. Diatoms, a type of siliceous microalgae, preserved within lacustrine sediments may act as bioindicators for MTD origin (i.e., seismic versus hydroclimate). Here, we explore the diatom signatures within multiple MTD and river-inflow flood deposits to address questions about source mechanism. Preliminary results suggest diatoms record distinctly different signatures during earthquakes and high river inflow events, enhancing our ability to use diatoms to distinguish the source of deposits in the fossil record. The broad-scale implications of this research are to understand the recurrence interval of great earthquakes along the CSZ, improve spatial correlation of seismic events, and enhance the earthquake record for northern Cascadia.

Evaluating Turbidite Correlations for Paleoseismology

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Marine turbidite paleoseismology relies on inferring synchronous triggering of turbidity currents by earthquake shaking. Such inference commonly relies on uncertain age dating and correlation of physical stratigraphy over a wide area. We assess the subjectivity of lithostratigraphic correlations based on existing core photographs, X-Ray computed tomography (CT) images, and high-resolution magnetic susceptibility (MS) logs, which underpin current understanding of earthquake recurrence along the Cascadia Subduction Zone. We highlight the importance of considering depositional processes associated with turbidity currents when attempting to correlate their deposits, by visually evaluating the similarity of turbidite facies at mm scale in photos and CT images in these contexts. Results confirm established ideas about alteration of signals from source to sink by complex sedimentologic processes, and which imply not all deposits should be correlated. Even when correlating seems appropriate, not every correlation is meaningful. Thus, we use dynamic time warping (DTW) to correlate MS logs objectively and repeatably, and we quantify significance –by comparing observed DTW correlation coefficients and p-values to a distribution derived from randomly generated turbidite sequences. All our analyses show that turbidite correlation metrics degrade markedly with distance between cores >10 km apart, and analyses illuminate missing turbidites in some cores, from the previously inferred sequence. Lastly, our analyses reveal a promising paleoseismic turbidite signature, in the form of uniquely thick turbiditic mud caps in some cores. Thinner mud caps that are more characteristic of most turbidites are found in channels and at the base of slope, whereas the thickest mud caps are preserved in abyssal plain and slope basin cores. These thick mud caps suggest ponding of flows and might be indicative of anomalously large turbidity currents that may have been mobilized by great earthquakes.

Searching for Empirical Links Between Shaking and Turbidity Current Generation in the Cascadia Subduction Zone

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Seismic hazard estimates for the Cascadia Subduction Zone (CSZ) rely on geologic observations such as magnitude and recurrence intervals derived from offshore turbidites. These assume that shaking from CSZ earthquakes remobilizes seafloor sediment, but empirical observations of seismically-generated turbidity currents are lacking in the CSZ. Few quantitative estimates exist linking shaking intensity to turbidity current generation, challenging our ability to fully constrain past shaking and earthquake characteristics. The Ocean Networks Canada (ONC) cabled seafloor array in Barkley Canyon provides concurrent seismic, turbidity, and other oceanographic data in a seismically active portion of the margin. Multiple large regional (>M6) and moderate local (<M6) earthquakes occurred during the ONC operating period 2016-present, allowing us to search for direct observations of shaking and concurrent canyon system processes.We seek empirical observations of seismically-generated turbidity currents to determine if a threshold level of shaking is associated with turbidity currents. Using the Barkley Canyon (BACAX) oceanographic 2019 sensor data, we create a catalog of turbidity events at BACAX. We do so with a short-term average/long-term average (STA/LTA) algorithm to identify elevated levels of turbidity and require a subsequent exponential decay. We compare our catalog to characteristic oceanographic measurements (i.e., oxygen, temperature), and examine water velocities for each event. The combination of data suggests that all 17 events at BACAX are internal tide generated, and unrelated to shaking. We also present results for a chronologically expanded catalog, subsequently comparing any events that are unexplained by non-seismogenic triggers to measurements of shaking, to identify if there is a statistically significant link between ground motions and turbidity events. This method may be used at other sites where existing data may reveal such relationships.

Compilation and Assessment of Data Quality for Onshore and Offshore Paleoseismic Proxies of Great Cascadia Megathrust Rupture

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The quality of paleoseismic data for megathrust rupture along the Cascadia subduction zon0 (CSZ)e collected over the past three decades varies because analytical capabilities and data collection methodologies have evolved. Since 2019, the USGS Powell Center Cascadia earthquake hazards working group compiled published onshore and offshore paleoseismic data along the 1100-km long CSZ. Here we present our progress, spanning sites from Vancouver Island to the Mendocino triple junction, including a systematic reanalysis of coastal radiocarbon chronology for inferred megathrust ruptures. Evidence for megathrust rupture includes coastal land-level change, tsunami inundation, onshore shaking proxies such as landslides or liquefaction, and offshore shaking proxies such as marine turbidites. As part of the compilation, we also present a ranking scheme to assess the quality of age estimates and evidence for great megathrust rupture. With the age ranking scheme, we ask: "How well is a proposed paleoseismic event dated?" based on the materials and methods used. With the evidence ranking scheme, we ask: "How confident are we that a proposed event is, in fact, the result of a Cascadia megathrust rupture?" based on the sedimentological characteristics, correlation, and mapping. The evidence ranking scheme also helps to evaluate possible alternative mechanisms for creating paleoseismic evidence such as crustal fault, intraslab, or distant tsunamigenic earthquake. We envision the compilation as a “one-stop-shop” for paleoseismic data in Cascadia that was compiled and evaluated by a diverse group of researchers and designed with sufficient detail to be useful for a wide audience. For example, explicit values of coastal deformation with uncertainty, tsunami inundation, and ground motion constraints may be used by modeling colleagues to assess variability in past rupture characteristics. The compilation also identifies data gaps and future research opportunities.

The Role of Transient Deformation in Interseismic Coupling in Cascadia

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The Cascadia subduction zone is one of the most well studied regions for transient deformation. Slip reversals in Cascadia accompanied by non-volcanic tremor occur quasi-periodically depending upon the location along strike, and the slip tends to be concentrated at depths between 20-50 km along the subduction interface. The location of slow-slip, just downdip of the locked zone where great subduction earthquakes are generated, requires having a complete view of the interseismic cycle in order to fully characterize seismic hazards in the region. Fortunately, the Cascadia region has up to a three decade long record of daily deformation from geodetic-grade Global Navigation Satellite System (GNSS) stations that can be used to address the total transient slip budget in the region. In this study, I use daily position time series from over 270 GNSS stations between the Mendocino triple junction and northern Vancouver Island and determine the transient behavior at a number of scales on a station-by-station basis. I use a new detection algorithm that relies on the prominence of absement (absement is the integral of displacement and represents sustained motion over a time period). I classify transients based on different thresholds for absement prominence, and stack waveforms using 40 day windows around the transient detections. I then invert for slip using the three-component total transient displacement vectors, and compare the slip behavior from the different threshold values. I find that the slip models from lower threshold absement values have consistently more up-dip slip than the larger threshold absement values, indicating that the character of transient deformation shifts to smaller and more frequent events at shallower depths. From the transient slip models, I modulate the input interseismic velocities to account for the transient slip that is occurring and re-examine the coupling models in the region using a backflip approach. I examine the change in the downdip extent of strong coupling and finish by discussing implications for megathrust slip in the future.

USGS Tsunami Sources Powell Center Working Group on Tsunami Sources: Probabilistic Tsunami Hazard Assessment for the Cascadia Subduction Zone

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U.S. states and territories adjacent to the Pacific Ocean are subject to tsunami generated from the surrounding subduction zones. Probabilistic Tsunami Hazard Analysis (PTHA) is adopted as a process that helps society mitigate impacts along coastlines through improved products for decision making for evacuation planning and through informed engineering approaches for structural design in tsunami hazard areas. The PTHA process includes four basic steps: source characterization, logic tree development (e.g., source rate distribution), tsunami modeling, and tsunami hazard mapping.

The U.S. Geological Survey (USGS) John Wesley Powell Center’s working group on tsunami sources hosted a week-long meeting in May 2022 that focused on the characterization of the Cascadia subduction zone (CSZ), a primary disaggregated contributor for tsunami hazard along the west coast of the continental U.S. Meeting participants included subject matter experts from academia, private industry, and state and national government agencies. A major goal for the meeting was to draft a logic tree for CSZ tsunami sources based solely on peer reviewed literature.

We present a summary of the meeting that included presentations on how subduction zones slip and deform during earthquakes (rupture dynamics), the structural evidences that may reveal how the CSZ may coseismically deform (informed by estimates of variation in megathrust seismogenic locking, the potential for splay faulting, etc.), and the spatiotemporal variation of prehistoric earthquakes along the margin. Together these informed the design of a draft logic tree with branches representing the range of possibilities, from known to unknown instances of CSZ tsunamigenesis. Where there was not consensus, participants assigned branch weights via an anonymous online poll. Parts of the logic tree are aligned with the USGS National Seismic Hazard Model. Future work will include developing guidance for probabilistic tsunami hazard and risk assessments.

Analyzing Recent Splay Fault Activity in the Cascadia Accretionary Wedge Using High-Resolution Seismic Reflection Data

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Splay faults, which branch from the main plate boundary fault in the accretionary wedge with a steeper dip angle and a closer proximity to shore, can result in larger tsunamis with shorter warning times upon rupture compared to megathrust-only fault ruptures, posing an increased hazard to coastal communities. Slip occurred on splay faults during several of the last century’s biggest subduction zone earthquakes, but our understanding of potential active splay faults and their hazards in Cascadia remains limited. In order to identify the most recently active and therefore potentially seismogenic splay faults in the Cascadia accretionary wedge offshore Washington state, we conduct a detailed stratigraphic and structural interpretation of near-surface deformation in the wedge and in shallow slope basins. We use high-frequency sparker seismic data to examine the record of deformation in these basins and the upper ~1 km of the surrounding accreted wedge sediment packages. Observations of folded and faulted strata allow us to determine the history of deformation and develop an integrated stratigraphic and structural sequence of events for each basin. We find numerous basins that display near-surface deformation of the youngest sediments, indicative of recently active splay faulting in portions of the accretionary wedge. Several basins also contain splay faults which break to the surface with observable scarps on multibeam bathymetry. By observing basins that are crossed by multiple seismic profiles, specific prominent splay faults can be traced along the margin. We make a preliminary estimation of total displacement on prominent splay faults using average sedimentation rates to quantify how compression is partitioned to various portions of the accretionary wedge. This study connects deep fault structure in the accretionary wedge to near surface deformation, bridging the two scales of most previous work, and improving our overall understanding of splay fault activity in Cascadia.

Designing or Upgrading a Seismic Network to Meet Specific Performance Criteria Using Array Modeling, a Case Study for Puget Sound Washington State

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More science, particularly related to hazard reduction and earthquake forecasting, is enabled via the availability of rich seismic datasets and event catalogs. Deployment of high performing monitoring networks, which produce high quality datasets, is an investment that enables ongoing and future science advancements. One measure of network performance, magnitude of completeness (Mc), is determined by a number of factors including station density, network geometry, self-noise and passband of the system used, ambient noise environment and sensor installation method and depth. Sensor installation techniques related to depth are of particular importance due to their impact on deployment cost and station performance. It is well established that deploying seismic sensors at greater depths reduces their exposure to cultural and environmental noise, improving seismic signal detection. When extended to overall network performance, this noise suppression results in improved (decreased) magnitude of completeness for the network. Using modeling tools, we assess the theoretical improvement in performance associated with an upgrade to borehole installations, increasing sensor depth, for a real world network in the Puget Sound area of Washington State.

The goals of monitoring networks and science are overlapping and dependent. Establishing measurable and achievable performance metrics for these supported networks helps the community understand the present distribution of performance and converge on recommendations for government agencies that will benefit both science and monitoring. For example, datasets from monitoring networks with reduced Mc are likely to inform and enable earthquake forecasting research with the potential to benefit hazard reduction for the general population. Additional Authors: Tim Parker (Timparker@nanometrics.ca), Nick Pelyk (Nickpelyk@nanometrics.ca), Geoffrey Banibridge (Geoffreybanibridge@nanometrics.ca) Dan McNamara (mcnamara@usgs.gov)

Challenges in Assessing Site-Specific Seismic Hazards in Cascadia

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In site-specific seismic hazard analyses, a more rigorous approach to addressing epistemic uncertainties in seismic source and ground motion characterization needs to be taken than for large-scale assessments such as the USGS National Seismic Hazard Maps. Although originally developed for the nuclear industry, the principles behind Senior Seismic Hazard Analysis Committee (SSHAC) guidance have been applied to a wider range of critical and important infrastructures. This has been the case particularly in the Pacific Northwest, where it has been applied to numerous dams. As emphasized in the SSHAC guidance, analyses need to address the “center, body, and range of technically-defensible interpretations”. Despite the incredible advances that have been made in our understanding of earthquake hazards in the Pacific Northwest, many significant challenges in site-specific seismic hazard analyses remain. Although the Cascadia megathrust controls the hazard for much of the Pacific Northwest, particularly at long periods, crustal faults can still dominate the probabilistic hazard if the site is sufficiently close. Given that there remain significant uncertainties in the characterization of Quaternary faults in the Pacific Northwest, and the fact that Quaternary faults continue to be identified and characterized, site-specific seismic hazard analyses need to incorporate these rapid changes in our state of knowledge. Three case histories will be presented where recently recognized Quaternary faults - the Spencer Canyon fault (Sherrod et al., 2021), Mt. Hood fault zone (Madin et al., 2021), and Canyon River-Saddle Mountain fault zone (Bennett et al., 2017) - have resulted in the need to re-evaluate several high hazard dams due to their proximity to these faults and local communities. Hence, these faults and their significant associated epistemic uncertainties need to be characterized for seismic hazard analyses. None of these faults are included in the 2018 National Seismic Hazard Maps.

Constraining Seismic Hazard in the Cascadia Subduction Zone [Poster]

Poster Session • Thursday 20 April

Conveners: Leah Langer, U.S. Geological Survey (llanger@usgs.gov); Max Schneider, U.S. Geological Survey (mschneider@usgs.gov); Erin A. Wirth, U.S. Geological Survey (emoriarty@usgs.gov); Diego Melgar, University of Oregon (dmelgarm@uoregon.edu); Valerie Sahakian, University of Oregon (vjs@uoregon.edu)

Ambient Noise Seismic Imaging of an Urban Fault: A Citizen Scientist-Hosted Investigation of the Seattle Fault Zone

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Sedimentary basins amplify and prolong strong shaking during large earthquakes. The city of Seattle sits atop the Seattle basin, and faces high seismic hazard posed by both the regional-scale Cascadia subduction zone and crustal faults. The Seattle fault zone forms the southern border of the basin, presenting an actively deforming basin edge with a complex internal geometry and velocity structure. Resolving the location and character of this active, urban fault is necessary for rigorous seismic hazard assessment in the city of Seattle. We deployed 100 nodal seismometers across the Seattle fault zone and basin edge in four North-South transects for one month in July 2019. All instruments were hosted by Seattle residents, and installation included educational involvement with residents and students.

We process and perform auto-correlation and cross-correlation analysis of the continuous ambient seismic noise data. Correlations are contaminated by anthropogenic activities, particularly highways (I-90 and I-5), which causes spurious arrivals in all correlations. To select the optimal correlations (i.e., minimal spurious arrivals) for generating the stack, we perform Gaussian mixture model clustering on the waveform shapes, using the correlation coefficient as a distance metric. We automate the clustering of correlations that we attribute to daytime and quiet times (nighttime and weekends). We further investigate if the re-constructed single-station correlations enable us to observe subsurface geological interfaces. In particular, we attempt to characterize the structure of the Seattle fault zone. Using one-bit spectrally whitened cross-correlations of the “quiet time” cluster, we produce broadband dispersion curves for surface waves in the 1-10 Hz frequency band. With DSurfTomo (Fang et al. 2015), we then directly invert these dispersion curves to produce 3D shear wave speed models.

Analysis of the Seismic Noise Using PPSD for Non-Volcanic Tremors in Cascadia Prior the Onset of SSEs

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Non-Volcanic Tremors (NVT) are a low-amplitude seismic signal, with a dominant frequency content of 1-10 Hz, lasting a few hours to a few days that are commonly observed in subduction zones. NVT contains predominantly S-wave energy, and are thought to emanate from locations on or near the plate interface. NVT often coincides spatially and temporally with geodetically identified Slow Slip Events (SSEs) and is recognized as the seismic manifestation of deep slow slip events. Since 2009, the Pacific Northwest Seismic Network (PNSN) detects, locates, and catalogs tectonic tremor across the Cascadia Subduction Zone (CSZ) resulting in a catalog of ~500,000 tremors that can be used to determine when and where SSEs occur. In this work we explore the character of seismic noise near the onset of known SSEs. Our goal is to determine whether the frequency content or amplitude of noise immediately prior to SSEs is systematically different than background noise levels prior to the first arriving tremor event.To do this, we calculate the Probabilistic Power Spectral Densities (PPSD) at frequencies between 1 and 10 Hz. We calculate noise levels for both day-long time periods over the course of a year and for shorter hourly intervals since noise can have strong diurnal variations in character. In this manner, we are able to track the noise behavior throughout the course of the year and assign probabilistic values to the noise amplitude across the frequency band of interest. We then use the same process to determine the PPSD for the time period immediately prior to known SSEs from the tremor catalog. Preliminary results show that noise levels begin to grow prior to the SSE onset. For one event we analyzed in detail, noise levels were at or exceeded the 95th percentile in the 8 hours before the SSE. We plan to extend this analysis to multiple SSEs occurring along the margin but this initial result suggests that SSEs may have an extended nucleation process. The changes in noise character could be caused by smaller amplitude and/or less-frequent tremor that could signal precursory slip.

Characterizing Aftershock Dynamics in the Pacific Northwest Using Bayesian Etas

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The Pacific Northwest (PNW) has substantial earthquake risk, both due to the Cascadia megathrust fault and other fault systems under the region’s population centers. Forecasts of aftershocks following future large earthquakes will thus be desirable and require statistical models calibrated to a catalog of the PNW’s past earthquakes and aftershock sequences. This is complicated by the fact that the PNW contains multiple tectonic regimes hypothesized to have different aftershock dynamics as well as frequent swarms. We use the Epidemic-Type Aftershock Sequence (ETAS) model to describe the characteristics of earthquakes and aftershocks for the PNW, accounting for these different types of seismicity. Typically, maximum likelihood estimation (MLE) is used to fit ETAS to an earthquake catalog; however, the ETAS likelihood suffers from flatness near its optima, parameter correlation and numerical instability, making likelihood-based estimates far from robust. We present a Bayesian procedure for ETAS estimation, such that parameter estimates and uncertainty can be robustly quantified, even for small and complex catalogs like the PNW. We model the earthquakes of the continental PNW, using a new catalog formed by algorithmically combining US and Canadian data sources and then identifying earthquake swarms. We perform a completeness analysis that supports two complete subcatalogs split by latitude, and with differing start years and magnitudes of completeness. While ETAS parameter MLEs are unstable and depend on both the optimization procedure and its initial values, Bayesian estimates are insensitive to these choices. Bayesian estimates also fit the subcatalogs better than do MLEs. We use the Bayesian method to rigorously estimate ETAS parameters and their uncertainty when including swarms in the model, modelling across different tectonic regimes and complete subcatalogs, as well as from catalog measurement error. Many parameter estimates change substantially when considering these catalog issues, indicating their importance for seismicity rate modelling and aftershock forecasting in the PNW.

Constraining Basin Structure and Characterizing Ground-Motions in the Oregon Willamette Valley

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The Willamette Valley (WV) in Oregon is a sedimentary basin between the Coast Ranges and the Cascades, stretching from Eugene to Portland. Basins often amplify ground motions during earthquakes, increasing seismic hazard, but this region lacks the recordings of medium and large events that allow us to empirically constrain site response due to the shallow geologic, basin structure. Currently, the community standard velocity model of Stephenson et al. (2017) has limited representation of the WV shallow structure. We aim to use existing geologic data and 3D numerical simulations of wave propagation to create a preferred velocity model that is an improvement of the current standard velocity model of this region, with the ultimate goal of constraining likely site response in this populated region.

To this end, we have developed velocity models describing the shallow (<5km) structure of the WV to use in numerical simulations, constrained by oil and gas well logs, geologic and structural maps, seismic profiles and Vs30 values. We made four models, varying the characteristics of the basin's depth geometry and its sedimentary filling. We then test these models, to determine which best replicates observed waveforms from select recorded small, local crustal earthquakes. We assess performance using residuals between peak amplitudes, shaking durations and arrival times. With our final preferred model, we perform a validation up to 1-2Hz with all available recorded, high-quality waveforms in the region. Ultimately, assuming basin effects are magnitude-independent, we will use our preferred velocity model in a suite of regional numerical simulations of small to moderate (<M5) crustal earthquakes with varying depths and azimuth, to discern average site response in the region due to our shallow crustal structure. Here, we present our preliminary models and validation results for two local, ~M4, earthquakes, recorded throughout the WV. We also show our preferred model, and a comparison of synthetic waveforms from this model, with observed waveforms recorded from four other local crustal earthquakes.

The California Geological Survey Response to the 20 December 2022 Magnitude m6.4 Ferndale Earthquake Sequence

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Seismic hazard in coastal northern California (CA) has an annualized earthquake loss of over $30 million USD. While the two largest contributors to seismic hazard in CA are the San Andreas and Cascadia subduction zone fault systems, Gorda intraplate earthquakes are the largest source of annual seismicity in CA. In the Mendocino triple junction (MTJ) region, these two overlapping fault systems interact in ways that we are only beginning to understand. Based on seismicity, the 20 December 2022 magnitude M6.4 earthquake ruptured 40-50 km of a N70E striking intraplate fault zone within the subducted Gorda plate.

Understanding the potential impact from future earthquakes supports community preparedness and mitigation to protect lives and reduce potential damage to infrastructure. An essential part for estimating hazards from future earthquakes is the documentation of ground deformation following earthquakes to better develop relations between earthquake source parameters and the occurrence of surface effects caused by shaking and surface rupture.

The California Geological Survey (CGS) and U.S. Geological Survey (USGS) operate an earthquake field response program designed to collect field observations of fragile and perishable geologic evidence for earthquakes that impact the state. The CGS, with Federal, State, and non-profit partners, coordinates earthquake field investigations through the CA Earthquake Clearinghouse (CEQCH). The CEQCH activated a virtual clearinghouse following the M6.4 earthquake to support coordination and documentation of multi-agency field observations.

The CGS and the USGS have been collaborating closely since the 2019 Ridgecrest Earthquake to develop a data acquisition schema to collect ephemeral data and to create a field data acquisition system which can be deployed within 15 minutes for post-earthquake investigations. Field observations include landslides and cracks in sand dunes and road fill, though there was no evidence for liquefaction.

Variability in Diatom-Based Coseismic Subsidence Estimates Over Multiple Earthquake Cycles in a Southern Oregon Tidal Wetland, Cascadia Subduction Zone

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Along the Cascadia subduction zone (CSZ), foraminifera-based estimates of coseismic subsidence have enhanced our understanding of 1700 CE earthquake rupture dynamics by serving as the data base for models that constrain areas of relatively high and low slip along the megathrust. These coseismic subsidence estimates are produced through transfer functions (TF), which are statistical models that employ the empirical relationships between modern microfossil assemblages and their corresponding elevations relative to a tidal datum to reconstruct past sea levels using microfossils recovered in cores. However, dissolution of foraminifera in low pH environments limits the applicability of foraminifera-based TFs across some pre-1700 CE contacts, especially in southern Oregon where coastal marshes archive a ~7000-year record of CSZ earthquakes. Here we use diatoms, a microscopic algae composed of dissolution-resistant silica, to produce quantitative TF-based coseismic subsidence estimates across 6 earthquake contacts in cores collected along Fahys Creek, a tributary of the Coquille River. Inferred timing of these events ranges from the most recent earthquake of 1700 CE to ~4500 cal yr BP. Our diatom-based TF reconstructions of the pre- and post-earthquake environments are consistent with a sudden change from upland/high-marsh soils to low-marsh/tidal flat environments. Coseismic subsidence estimates across the 6 contacts show variable amounts of coseismic subsidence, ranging from ~0.5m to >2m. Future work will incorporate subsidence estimates from an additional site ~40 km to the south at Sixes River. A transect of correlative coseismic estimates in southern Oregon at the two sites will enhance understanding of temporal and spatial variability of deformation from CSZ ruptures and will inform how upper plate structures (e.g., Cape Blanco anticline) affect coseismic subsidence.

Coseismic Ground Failure: Advances in Modeling, Impacts and Communication

Oral Session • Thursday 20 April • 08:00 AM Pacific

Conveners: Alex R. Grant, U.S. Geological Survey (agrant@usgs.gov); Kate E. Allstadt, U.S. Geological Survey (kallstadt@usgs.gov); Laurie G. Baise, Tufts University (laurie.baise@tufts.edu); Eric Thompson, U.S. Geological Survey (emthompson@usgs.gov)

Post-Earthquake Response Application: A New and Improved Method for Data Collection Using Arcgis Field Maps

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Earthquake response coordination requires planning, practice, and cooperation, balancing a variety of needs including public safety and medical responses, utility repair, damage assessments, and scientific data collection. The scientific response, especially when documenting earthquake surface deformation (surface ruptures, slope movement and liquefaction) and structural damage, requires a rapid and well-coordinated effort to efficiently collect ephemeral data. These data are most useful to those analyzing field data and those focused on remote analysis if they are collected in a uniform and consistent format. The California Geological Survey (CGS) and the U.S. Geological Survey (USGS) – Earthquake Science Center, have been working together to develop an earthquake response schema to be used in ESRI's Field Maps which will allow for the quick acquisition of these perishable data. Previous versions of the schema have been tested and revised based on response efforts including, but not limited to, Ridgecrest (2019), Puerto Rico (2020), Monte Cristo (2020), and Taiwan (2022). The resulting feature service will also facilitate rapid communication through ESRI Dashboards during the event both within CGS and USGS and with external partners such as the Earthquake Clearinghouse, California Offices of Emergency Services, and other Federal, State, and local agencies participating in the earthquake response effort.

Insights From a New Global Coseismic Landslide Runout Length Dataset

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The hazard and possible impacts posed by earthquake-triggered (coseismic) landslides is a combination of triggering and the runout length (size) of each landslide. While landslide triggering models have benefitted from the continued development and sharing of landslide inventories after earthquakes, runout lengths are rarely mapped, forcing modelers to rely on simplified relationships from aseismic slides or computationally expensive runout simulations. We present an automated method for measuring the runout length developed and validated on 1579 coseismic landslides compiled from published inventories. Combining several readily computed geometric and topographic attributes, the proposed automated runout model closely matches manually mapped runout lengths for slides ranging from several meters to kilometers in length. We then apply this model to the USGS global coseismic landslide inventory repository to develop a database of over 80,000 landslides with runout length estimates. We find global coseismic landslide runout lengths do not follow established fall-angle or mobility relationships developed for aseismic landslides, suggesting the need for new models to better predict the extent, impacts, and therefore risk, associated with coseismic landslides. We will present the results of our runout model, as well as an analysis of the factors driving the non-linear behavior of coseismic landslide mobility as a function of landslide size and topography. These data and results provide the building blocks for new coseismic landslide runout models to improve hazard and risk forecast models as well as enabling new near-real-time estimates of the impacts of landslides triggered by earthquakes.

Updating Global Geospatial Liquefaction Models With a Focus on Feature Engineering

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This work updates the global geospatial liquefaction models developed by Zhu et al. (2017) by significantly expanding the database to include fifty-four earthquakes and thirty candidate geospatial predictors. Zhu et al. (2017) developed global geospatial liquefaction models using liquefaction inventories for twenty-seven worldwide earthquakes and seventeen candidate geospatial predictors. In order to develop multivariate logistic regression models for liquefaction classification, multiple feature engineering techniques are employed to find the best combinations of geospatial predictors. First, we apply the feature filter to remove low-correlated and redundant predictors based on different correlation measures. Also, we select optimal predictors from a group of geospatial predictors with the same physical meanings but derived using different geospatial products. After the feature filter, ten predictors are retained in the predictor pool for developing the multivariate models. Then, two feature engineering strategies, exhaustive feature selection and principal component analysis (PCA), are applied to select the best predictor combinations and investigate the information loss. The results suggest that the exhaustive feature selection method achieves less information loss and better interpretability than the PCA method for this case. Based on exhaustive feature selection results, we recommend three models that use different geospatial predictors representing site vulnerability to liquefaction and have good classification accuracies. We conclude that such feature engineering methods could be applied to other geospatial modeling tasks that can benefit from finding the optimal predictor combinations.

Global Geospatial Modeling of Earthquake-Induced Soil Liquefaction Using a System of Voting Machine Learning Classifiers

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Data-driven geospatial liquefaction models are useful tools for regional seismic hazard assessments. The models are based on liquefaction occurrence inventories, widely available geospatial variables, and earthquake-specific parameters. Our inventory is updated with geospatial data from non-liquefaction and liquefaction occurrence locations in 54 earthquakes around the world. Geospatial data includes 2 categorical and 28 continuous variables representing proxies for soil saturation, soil density, and earthquake loading. In our prior work, logistic regression was used to present an updated global geospatial liquefaction model. In this study, we evaluate the use of an ensemble of decision trees as an alternative advanced machine learning (ML) algorithm to find complex nonlinear patterns in a large dataset. The proposed methodology starts with an exploratory data analysis to remove highly correlated features and run feature transformations. Neighborhood component analysis is also implemented as an ML-based feature selection approach to remove the variables with low weight on the classification model. The liquefaction inventory is highly imbalanced in terms of liquefaction and non-liquefaction classes and in terms of the data provided by the event. The class imbalance issue is treated in an innovative manner by distributing the event datasets over several balanced subsets. On each data subset, the binary classification model is trained and validated via a K-fold cross-validation approach. Based on the designed voting system of classifiers, the final class assignment for each sample point is done by considering the majority votes of the classifiers as the final prediction. To check the model reliability and potential bias, the leave-one-out testing approach is used to independently test the model by removing one earthquake at a time. Comparing the results of the proposed method with the logistic regression model showed that the overall accuracy and spatial extent of the liquefaction predictions were improved for most of the earthquakes tested.

Integrating Regionalized Geotechnical Information Into the U.S. Geological Survey's Liquefaction Product Within a Bayesian Framework

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The U.S. Geological Survey's (USGS) Ground Failure (GF) product team has been tasked with estimating the extent of liquefaction (LF) and landslides (LS) following significant earthquakes worldwide since 2018. Because these models were calibrated against global LF and LS inventories, they are generalized and applicable to any earthquake globally. However, the USGS GF models are based only on geospatial proxies, and when regionalized geological and geotechnical information is available, better estimates of ground failure can be obtained by combining the GF models with this localized geotechnical information in a Bayesian manner. We expand upon a model previously developed to update liquefaction probabilities using such geotechnical information. This previous framework involved: (1) estimating the distribution of Liquefaction Potential Index (LPI), which is based on subsurface geotechnical measurements, 2) using a function defining liquefaction probability in terms of LPI, and (3) updating the USGS global model's liquefaction probability estimates given the distribution of LPI for areas within artificial fill. Having made several improvements, we present the enhanced updating framework and demonstrate the utility of integrating this LPI-based geotechnical information for the 2019 Anchorage, Alaska and 1989 Loma Prieta, California earthquakes (for which liquefaction inventories are available for model comparison and framework validation). This model, which can update liquefaction probabilities in several geologic units (including nonsusceptible hard rock units), provides improved estimates of liquefaction probability where units were reliably mapped. This framework represents a novel means of integrating information not present in the USGS GF model to get improved liquefaction estimates.

Determining Coseismic Landslide Hazard Using Regional-Scale Physics-Based Ground-Motion Simulation

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The influence of seismic ground motion on landslide hazards is vital to assess associated risks to settlements and infrastructure, especially to mountainous communities. Because several thousands of landslides may occur over a large area during and shortly after an earthquake, a statistical analysis must be performed to quantify the spatially distributed hazard and risk.

Using landslide inventories from three earthquakes (Haiti 2010, Iwate Japan 2008, and Hokkaido Japan 2018), we statistically analyze the main factors contributing to coseismic landslides occurrence. We determine ground motion intensity measures using physics-based shaking simulations with kinematic ruptures embedded in a 3D Earth model, which we calibrate using empirical ground motion models (GMM). The physics-based shaking simulations allow us to study how rupture properties and site effects, especially topographic effects, affect coseismic landslide occurrence. Ground-motion simulations generate time series for each point of the model domain, allowing for a more comprehensive analysis of shaking intensity than standard methods like GMM. For example, our simulations provide specific intensity measures (IM's) of shaking, like Arias intensity (Ia), cumulative absolute velocity (CAV), peak-ground motion (PGV, PGA), and spectral acceleration (SA_T), as well as the ground-motion frequency content.

We test the benefit of the ground-motion simulations in explaining the coseismic landslide distribution. Specifically, we propose a methodology to better use results of ground motions simulations to explain landslide occurrence based on the Newmark sliding-block model approximation. We conjecture that the new methodology can be further explored to build future earthquake scenarios and associated coseismic landslides.

Macro-Level Study of Seismically Induced Slope Stability in Kashmir Himalaya

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The necessity for efficient solutions to minimize the damage caused by seismically-induced landslides has prompted recent advances in methodologies for slope displacement mapping at the regional scale. However, the time horizon of hazardous occurrences is essential in rational hazard management. Kashmir Himalaya suffered tremendously from slope failure due to seismic activities, complex lithological and tectonic settings. In order to identify terrain stability, the Newmark displacement model has been applied to estimate the Factor of Safety (FOS) and displacement in the Kashmir Himalaya. The data set include a digital elevation model, landslide inventory, geotechnical database and surface-consistent peak ground acceleration. All the data have been rasterized into 30*30m grid cells on GIS. Combining these data sets in a dynamic model based on Newmark's deformation analysis yields estimates of coseismic landslide displacement. The predicted FOS and displacement exhibit that the sliding blocks are unstable due to gravity sliding and/or seismic shaking. The displacements have been compared with the earthquake-triggered landslides to construct a probability curve relating predicted displacement to the probability of failure. This probability function can be applied to predict and map the spatial variability in failure probability in any ground-shaking conditions of interest.

The Application of a Liquefaction Probabilistic Models to South Italy: A Case Study

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The study of the incidence of the coseismic phenomena at the ground surface is becoming an increasingly demanding and fundamental need in terms of civil protection agencies, immediately after a strong earthquake, in near real-time. In this work, we test the reliability of statistical procedures developed globally to quantify the occurrence of liquefactions in probabilistic terms when applied to Italy. With this in mind, we used two models available in the literature: one from Zhu et al. (2017), currently implemented by the USGS, and one from the European project LIQUEFACT. We evaluated their reliability using a historical earthquake for which documented evidence of liquefaction is available. We parameterized the source of the earthquake of the 7th February 1783 in Calabria, Southern Italy, with the most up-to-date seismological and historical information available in the literature and tested sources with variable parameters to have an approach that would also cover the uncertainties associated with an ancient event. The two statistical models were built using global and detailed datasets. The latter was compiled explicitly for the area under investigation, to assess whether more specific and punctual information would bring a better constraint to the estimation. We used the historical data confirming liquefaction only as a validation benchmark, excluding them from the constraint of the models.

How Do Creeping Landslides Respond to Earthquake Shaking?

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Ground shaking in the near field of large earthquakes can instantly turn stable steep hillslopes into catastrophic slope failures. This type of immediate response of earthquake-triggered, first-time landslides has been widely observed and recorded around the globe. However, less well known is how slow-moving landslides respond to seismic shaking. Long-term creeping landslides are dominantly located on gentle hillslopes and their kinematics are often tied to slope hydrology; however, few have been documented to accelerate into catastrophic failure by earthquake shaking. Does this indicate earthquake shaking barely affects the stability of large creeping landslides?

Here, we use the M6.4 Ferndale, California earthquake on 12 Dec 2022 near the Mendocino Triple Junction as a typical example to answer this question. By utilizing ground deformation maps generated from the ALOS-2 Stripmap and ScanSAR satellite radar images between 2016 and 2022, we find that the Ferndale earthquake reactivated or accelerated seven large creeping landslides within 35 km of the epicenter, though none of them failed

catastrophically. Five other known landslides within the same range did not show apparent acceleration immediately after the earthquake, possibly owing to their topographical setting or their delayed response to seismic shaking caused by shear-zone material compaction/dilation and pore-pressure redistribution. Potentially, earthquakes also increase surface cracking and create void space in the landslide body, thereby promoting post-earthquake rainwater infiltration and landslide movement. To validate these hypotheses, we are conducting studies using more incoming ALOS-2 ScanSAR data with 14-day revisit, which are scheduled for acquisition throughout 2023. The tectonically active U.S. West Coast hosts hundreds of large creeping landslides, and it is essential to better understand how earthquakes may impact the future of these unstable hillslopes.

The Great Alaska Inventory: A Digital Compilation of Ground Failures Triggered by the 1964 Great Alaska Earthquake

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The M9.2 1964 Great Alaska earthquake is the second largest earthquake in the historical record, involved nearly five minutes of shaking, and generated deep and shallow landsliding and widespread liquefaction over an area exceeding 200,000 km^2. This important event has been extensively studied, yet no digital compilation of ground failures from the event exists. Data from consequential historic events like the Great Alaska Earthquake are valuable not only for understanding the extent of impacts, but also for improving the accuracy of predictive ground failure models. Ground failure data from historic events are not often digitized and are therefore relatively inaccessible for quantitative analyses. Herein, we present a digital compilation of about 1500 published ground failure observations from the 1964 earthquake, merged into a single inventory with comprehensive metadata reported as feature attributes. We also examined how the observed ground failure data compare to current ground failure models of this event. The largest challenges with this effort were in handling large uncertainties in the feature locations and in the variability of the data quality. To address these issues, we compared the published information to historical topographic maps and local records. We also included attribute fields to delineate different types of data and their accuracy, such as maps of different scales and/or detail. These attributes were essential for understanding the limitations of the dataset and for using these observations appropriately in model development and/or assessment. We encourage their use in future inventories. Our new consolidated inventory will contribute to the USGS repository of earthquake-triggered ground failure inventories.

Coseismic Ground Failure: Advances in Modeling, Impacts and Communication [Poster]

Poster Session • Thursday 20 April

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A Machine Learning Approach for Landslide Mapping of the 2016 Kumamoto Earthquakes From Geospatial and Image Data

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A series of earthquakes, with 7.3 Mw highest intensity, hit Kumamoto, Japan, over a period of two days in April 2016. The earthquakes caused numerous landslides and surface ruptures in the steep volcanic geological environment. In this study, pre- and post-event sets of high-resolution aerial (Geospatial Information Authority of Japan) and satellite (DigitalGlobe) imagery, paired with the USGS preferred geospatial model for landslide probability and individual geospatial inputs including elevation, surficial geology, slope, precipitation and landcover layer provided by National Mapping Organization of Japan, were used to develop a machine learning (ML) approach for landslide mapping. The ML approach was trained and validated using an inventory of human-drawn landslide occurrence polygons of the area as ground-truth labels provided by Kyoto University's Disaster Prevention Research Institute and the Japanese National Research Institute for Earth Science and Disaster Resilience. The goal of this work is to improve automated image-based landslide mapping by adding data of physical parameters as well as temporal difference indices calculated from pre- and post-event imagery using ML algorithms. The selection of geospatial effective parameters was done via the supervised Bhattacharyya feature ranking method. The pixel-based ensemble classification algorithm used in this study not only learns from the color channels of the imagery, but also analyzes additional RGB-derived parameters, data of selected geospatial variables, and change information (vegetation and grayscale difference) derived by comparing pre-event and post-event imagery. Different combinations of input parameters were tested, and the results showed that adding data of selected geospatial parameters plus change indices to the imagery lead to the highest classification accuracy. Landslides in these formations are common throughout Japan and have been triggered by heavy precipitation as well as seismic events. Therefore, such data-driven, efficient and fast mapping methods can be effective for landslide prevention, mitigation and reconstruction operations.

How to Quantify Uncertainties for Logistic-Regression-Based Geospatial Natural Hazard Models?

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Global natural hazard models are data-driven models that take advantage of broadly available geospatial proxies to predict natural hazard phenomena and are wildly used in both pre-disaster planning and post-disaster responses. It remains less explored on how to quantify uncertainties for such geospatial natural hazard models. Taking the logistic regression based global geospatial liquefaction model (GGLM) (Zhu et al., 2017) as an example, we propose an uncertainty quantification (UQ) framework that consists of uncertainty source characterization, global sensitivity analysis, and forward uncertainty quantification. The GGLM predicts the liquefaction probability using the ShakeMap's PGV, slope-based V_{S30}, distance to water body, water table depth, and annual precipitation as explanatory variables. First, we characterize three sources of uncertainties: parametric uncertainty, model error, and geospatial input uncertainty. We use Bayesian inference to quantify the posterior distribution of model parameters and their variations with the sample size, and find that the parametric uncertainties are small when a large dataset is used to learn the model parameters. Model errors are calibrated as a normal distribution based on a novel classification residual analysis. The geospatial input uncertainties are characterized using the literature and expert judgement. Second, we use the Sobol's method to investigate the sensitivity of model output to different uncertain inputs and find that the variance of model output is largely contributed by the geospatial input uncertainties and model errors. Last, we propose an approximation-based forward uncertainty propagation (FWD) method, which shows consistent results as the Monte-Carlo-Simulation-based method but much better computational efficiency. Given that the logistic regression models are wildly used in the earth science filed, we conclude this UQ framework could also be applied to other geospatial modeling problems.

Liquefaction or Liquefiction? Anthropogenic Regulation and the Influence of Evaporite Dissolution on Ground Failure in the 2019 Ridgecrest Earthquake Sequence

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Optical remote sensing observations of the 2019 Ridgecrest, California, earthquake sequence revealed a significant amount of surface ejecta in the nearby Searles Lake, including one area where the surface ejecta was arranged in a repeating hexagonal "honeycomb" pattern. This pattern is collocated with injection wells from a solution mining operation, suggesting anthropogenic activities influenced the spatial distribution of surface ejecta. Geologic cores

throughout the lakebed reveal massive evaporite units interfingered with clay and silt units, and a notable lack of traditionally liquefiable sand-dominated units. Soil behavior types acquired from cone penetration tests (CPT) on the periphery of the lakebed, where more sand-dominated united are expected, estimate less than 3% of traditionally liquefiable contractive sand layers. Satellite-based Interferometric Synthetic Aperture Radar (InSAR) data show highly localized subsidence signals in the same hexagonal pattern in the four years leading up to the earthquake sequence. The lithology, CPT-derived soil behavior, and spatial distribution of long-term subsidence indicate that surface ejecta in Searles Lake is not likely related to liquefaction. Instead, we propose a process, similar to liquefaction, that would also result in the observed surface ejecta: (1) mining-related dissolution of evaporites increases the void/cavity space that is filled with fluid, (2) ground shaking causes void/cavity collapse (i.e., a volume reduction), (3) the collapse increases the fluid pressure, and (4) the increased pressure results in sediment-laden fluid to flow to the surface. This study is an excellent example of how remotely sensed optical and InSAR data can assist in rapid identification and evaluation of spatially distributed ground failure features and their effects across a variety of geologic deposits and terrains.

Crustal Deformation and Seismic Hazard in Western Canada, Cascadia and Alaska

Oral Session • Thursday 20 April • 08:00 AM Pacific

Conveners: Richard H. Styron, GEM Foundation (richard.styron@globalquakemodel.org); Tiegan Hobbs, Geological Survey of Canada (thobbs@eoas.ubc.ca); Christine Regalla, Northern Arizona University (christine.regalla@nau.edu); Lydia Staisch, U.S. Geological Survey (lstaisch@usgs.gov)

Examining Possible Links Between Tectonic Tremor and Crustal Earthquakes on the Leech River Fault System in Northern Cascadia

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Along the Cascadia margin, tremor occurrence related to episodic tremor and slip (ETS) events are modulated by the structure of the continental plate. In particular, tremor is generally spatially anticorrelated with major crustal faults and forearc earthquakes; however, the Leech River fault (LRF)—a major fault zone on Southern Vancouver Island—coincides with two high-density tremor clusters. In this study we examine the relationship between tremor and crustal earthquakes in the LRF system. The tremor catalogue is computed using our recently-developed differential-traveltime Bayesian inversion method and includes events during the 2003-2006 deployment of the Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity (POLARIS) array, and the relocated catalogue in the LRF system is provided by Li *et al.* (2018). With enhanced resolution of tremor depths, we show that most tremor is coincident with the surface of the low-velocity zone between 20 and 35 km depths where the LRF zone terminates.Preliminary results show that the shallowest tremor events are preferentially colocated with deeper seismicity in the vicinity of the LRF, which may be evidence that fluid-driven tremor-genic processes exist on this forearc fault system away the subduction fault. Alternatively, what appears to be shallow tremor may in fact be microseismicity induced by changes to the stress field resulting from slow slip on the megathrust. Evidence of a widely-eroded subduction fault zone and/or underplated forearc in northern Cascadia suggests that ETS is a multifaceted phenomenon resulting from complex structures at depth. Considering the proximity of the LRF to metropolitan areas and recent evidence that it has hosted large events in the last ~10,000 years, the relationship between this fault and periodic slow slip events directly beneath it may help unify our understanding of the tectonic setting and its associated seismic hazards.

Geologic-Geodetic Block Modeling of Northwestern North America for Seismic Hazard Assessment of Western Canada

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The northwestern plate margin of North America is complex, alternating between subduction and transform configurations, and with distributed crustal faulting extending for hundreds of kilometers inboard of the margin. Data to characterize faulting and earthquake occurrence in the region is unevenly distributed, and sparse in large swaths. Though this presents challenges to seismic hazard analysis, recent work documenting Quaternary paleoearthquakes in southwestern British Columbia demonstrates the need to create a fault-based seismic hazard model for western Canada and the vicinity. In order to build this model, we first create a database of probable active faults in Canada, with ~50 fault traces, as well as similar databases for Alaska and the northwestern contiguous US. Then, we build a block model upon the fault data that inverts geologic slip rates and GNSS velocities to find internally-consistent fault slip rates for all faults in the databases, as well as spatially-variable partial locking on the Cascadia and Aleutian megathrusts. The preliminary model predicts deformation rates of significance for seismic hazard (i.e., ~1 mm/a) on faults throughout western Canada with lengths suitable for generating large-magnitude crustal earthquakes, including the Rocky Mountain Trench and frontal thrusts, as well as the Fraser and Thompson River faults. Faults closer to the Cascadia subduction zone (and metro Vancouver) may have higher slip rates. However, when fitting the GNSS data there is a substantial tradeoff between permanent strain the model allocates to crustal faults and interseismic strain accumulation on the subduction interface, and the model may not be finding the most accurate solution; more geologic slip rate data would help resolve this. Slip rates throughout the US Cascadia region are generally slower, as strain is distributed on a large number of closely-spaced faults. Fault database and model refinements are ongoing, and a preliminary fault-based hazard model is forthcoming.

Geologic Evolution of the Denali Fault System and Associated Crustal Structure

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The Denali fault is an active right-lateral continental strike-slip fault that transects the North American Cordillera from northern British Columbia to the Bering Sea shelf. Along the ~1,100 km on-land section of the fault, the strike changes by over 100º and as a result the fault system complexity changes along strike, ranging from a multi-stranded fault with a well-defined locus of master faults in southwestern Yukon to a highly localized master strand bordered by splay thrust systems through central Alaska, then to a multi-stranded fault system in western Alaska. The structural evolution of the Denali fault as a major continental fault system that has accommodated hundreds of kilometers of displacement implies that the fault is a significant geophysical feature. However, the complex and diverse geology surrounding the fault and variability in geologic and geophysical data resolution related to the difficulty of access cause the perceived geophysical signature of the fault to be spatially variable.

Here, we aim to review the geologic evolution of the Denali fault system by blending new advancements with established ideas that have held up over time. We integrate the regional geologic framework with a series of new P-receiver function (PRF) profiles that cross the Denali Fault. The new PRF profiles use all available data (1999-2022) from both temporary and permanent broadband seismometers available from the IRIS DMC to image the crust. These data include the seven recently deployed ICED array stations that targeted the eastern Alaska Range and adjacent section of the Denali Fault that had previously been under-resolved by the TA and other deployments. Geophysical information from this section of the fault corroborates the geologic observations indicating that the Denali fault is a primary lithospheric-scale boundary, with some sections that clearly indicate a step across the Moho. However, in the west some sections of the fault there is no clear evidence in the PRFs of a change in crustal thickness.

Distribution and Focal Mechanisms of Incoming Plate Earthquakes Along the Alaska Subduction Zone

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We analyze the variation in earthquake locations and focal mechanisms along the Alaska subduction zone using ocean-bottom seismic data from the Alaska Amphibious Community Seismic Experiment (AACSE), EarthScope

TA, and other land-based seismic networks. Earthquake locations are determined with a nonlinear relocation program (Lomax et al., 2000) incorporating a three-dimensional velocity model based on ambient noise Rayleigh wave tomography. Focal mechanisms are determined using a waveform inversion (Herrmann, 2013) for the largest events. We manually pick P and S first motions to determine the focal mechanisms for the smaller events (Snoke, 2003). Seismicity is higher in the Shumagin Gap, with extensional faulting as deep as 30 km below the seafloor, and predominantly normal faulting. These earthquakes are mostly confined within 50 km of the trench, matching the region of fault scarps observed in bathymetric profiles. A swarm of over 50 earthquakes occurred along one of those faults over several days in April 2019 with magnitudes ranging from 2 to 3.25. This swarm could be caused by fluid circulation along a plate-bending fault extending into the mantle, promoting mantle serpentinization and the subduction of water at the Shumagin Gap. Downdip of the trench at the Shumagin Gap, some normal faulting earthquakes are deeper than the plate interface, indicating that plate-bending faults are reactivated after subduction. The Semidi Segment to the east has less seismicity and more diverse focal mechanisms. There are strike-slip earthquakes with north-south oriented left-lateral fault planes in addition to normal faulting events. This change in the dominant faulting mechanism coincides with other changes across the Alaska subduction zone including incoming plate curvature, fabric orientation, and sediment thickness. These incoming plate variations are also reflected in the changes in megathrust coupling, which is higher in the Semidi Segment than the Shumagin Gap.

Towards Adjoint Tomography of Northern Alaska

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Northern Alaska features diffuse seismicity and large-scale deformation far from the plate boundaries. However, the structures and processes involved are not well understood. Due to its remoteness, northern Alaska has exhibited historically sparse coverage, resulting in difficulties in mapping and monitoring in this region. This has changed following the deployment of the EarthScope Transportable Array in Alaska, with years of high quality seismic data now available for a comprehensive study. In this study we investigate deformation and structure in northern Alaska using adjoint tomography, a seismic imaging method that minimizes differences between observed and synthetic seismograms to generate high-resolution images of Earth structure. The result of this tomographic study is expected to yield structural models of the subsurface which can then be used to refine earthquake catalogs and perform detailed interpretations of tectonic processes in and around northeastern Alaska. We present ongoing research and preliminary findings related to the tomographic imaging portion of this research.

Crustal Deformation and Seismic Hazard in Western Canada, Cascadia and Alaska [Poster]

Poster Session • Thursday 20 April

Conveners: Richard H. Styron, GEM Foundation (richard.styron@globalquakemodel.org); Tiegan Hobbs, Geological Survey of Canada (thobbs@eoas.ubc.ca); Christine Regalla, Northern Arizona University (christine.regalla@nau.edu); Lydia Staisch, U.S. Geological Survey (lstaisch@usgs.gov)

Catalog of Coseismic Displacements Across Alaska

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A significant number of moderate to large earthquakes have occurred across Alaska over the last two decades, with each event causing permanent coseismic and/or transient postseismic displacements over a large area. At the time of the 2002 Denali fault earthquake, there were very few continuous GNSS sites across Alaska, so most data for that event came from campaign surveys. The development of the Plate Boundary Observatory (now Network of the Americas, NOTA) starting in 2004 substantially increased the number of continuous sites, making it much easier to resolve the effects of these earthquakes through space and time. For example, the recent Simeonof (2020, MW7.8) and Chignik (2021, MW8.2) events on the subduction interface offshore the Alaska Peninsula caused detectable coseismic displacements as far north as the Seward Peninsula. Prior to the installation of NOTA, this deformation would not have been captured. Without a robust network of continuous GNSS sites along the Alaska Peninsula, it would have been extremely difficult to separate the coseismic and postseismic effects from the closely spaced Simeonof, 2020 M7.6 Sand Point, and Chignik events. Capitalizing on the improved data resolution, we present a catalog of observed and model displacements from the most important earthquakes in Alaska over the last two decades.

Crustal Stress in Continental Alaska and the Yukon

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The crustal stress field controls active fault orientations and the style of deformation. In continental Alaska, ponderous topographic relief, complex interactions between the lithosphere and subducting material, and a mosaic of inherited terrane boundaries may all exert strong influences on crustal stress and deformation. To map the state of stress in continental Alaska, we compile regional moment tensors from earthquakes in the North American Plate and then conduct formal stress inversions and forward modeling of frictional fault slip potential. While the availability of data vary across the state, both first-order patterns active across thousands of km and second-order anomalies spanning a few hundred km are resolved. Overall, horizontal maximum compression directions fan roughly radially about the Yakutat Microplate, from ENE-WSW in the Seward Peninsula and western Alaska and Brooks Ranges, to SSE-NNW in the central Alaska and Brooks Ranges, N–S in the Yukon Flats Basin, and NE–SW in the Wrangell, St. Elias, Ogilvie, and Mackenzie Mountains. The radial orientations are sustained across multiple independent stress provinces for up to 1000 km inland from the microplate. Consistent with models of indenter tectonics, however, the relative magnitude of horizontal compression decreases with distance from the Yakutat indenter: Evenly mixed reverse-oblique faulting in the Alaska, Wrangell, and St. Elias Ranges transitions to strike-slip between the Denali and Kaltag Faults, and strike-slip with secondary extension in the western Brooks Range, Seward Peninsula, and southwestern Alaska. Superposed ~15° variations in stress directions and small differences in faulting styles between stress provinces may be due to glacial rebound and other isostatic adjustments, gravitational potential energy variations, or mantle processes.

High-Resolution Seismic Catalog for Minto Flats Fault Zone, Central Alaska, Based on Waveform Cross-Correlation of Events Between 2014–2019

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Accurate catalogs of earthquake locations, magnitudes, and origin times provide a foundation for the study of fault dynamics, brittle-ductile transition zones, earthquake migration, and structural seismology. Environmental noise such as from bodies of water and urban development can negatively impact the detection of low-magnitude earthquakes, and therefore it is beneficial to incorporate other methods such as waveform correlation to aid in the detection process. We use network-matched filtering and relative relocation techniques to compile an enhanced earthquake catalog of the Minto Flats fault zone (MFFZ) in interior Alaska. MFFZ is a left-lateral strike-slip fault system situated between the Denali and Kaltag faults and is associated with Nenana basin. It produced a magnitude-6 earthquake in 1995 and has potential for a magnitude-7 earthquake. Our enhanced catalog for MFFZ is, as expected, dominated by small-magnitude (M ~ 0) events below the traditional detection limits. The results of this study provide the most complete catalog available for the MFFZ from September 2014 to December 2019 and include deeper events, clusters of seismicity and a complex, and segmented fault structure not present in the regional catalog. We are also able to more strongly identify a third fault strand within the zone that was previously unstudied.

Shallow Deformation in the Central Seattle Fault Zone, Washington State, From Land-Based High-Resolution Seismic-Reflection Imaging

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The detailed structure of the Seattle fault zone is laterally complex along its ~70 km length, including through the Seattle, Washington, urban area. Much of what is known about the fault zone has come from lidar imaging, paleoseismological investigations, gravity and aeromagnetic modeling, and multiscale marine seismic reflection imaging. Only a limited number of land-based high-resolution seismic imaging profiles crossing the fault zone have been acquired. We analyze 24 km of land-based P-wave seismic reflection profiles that fill in critical gaps in the Seattle fault zone in West Seattle, central Seattle, and Mercer Island. These data were acquired with either mini-vibroseis or accelerated weight-drop sources with nominal 5 m geophone spacings. The seismic profiles image tectonic deformation in the upper 1 km, including upwarped Tertiary rock and deformed Quaternary strata. The base of the Quaternary strata is a prominent reflector throughout the three sets of profiles. The West Seattle seismic profiles show a weaker impedance contrast at the base of Quaternary strata but provide evidence in the upper 500 m for the location of the northern fault strand currently implemented in the National Seismic Hazard Model. Deformational patterns interpreted on several profiles in the central region and Mercer Island are consistent with south-directed backthrusting with apparent dislocation on bedding planes. In the central Seattle area, an interpreted backthrust trends at approximately 45° NW compared to the nearest main thrust that trends generally east-to-west. The seismic profiles on Mercer Island provide evidence for the westward extension of both the Newcastle Hills and Newport anticlines to at least Mercer Island. The variability in thickness of the Quaternary deposits across the Seattle fault zone has implications for ground motion focusing and resonance effects.

Crustal Imaging of High Seismic Hazard Regions

Oral Session • Thursday 20 April • 08:00 AM Pacific

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Subduction Zone Interface Structure Within the Southern M9.2 1964 Great Alaska Earthquake Asperity: Constraints From Receiver Functions Across a Spatially Dense Node Array

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Kodiak Island is an exposed part of an accretionary complex along the Alaska-Aleutian subduction zone that formed as the Pacific plate subducted below the North American plate. Subduction of the Pacific plate beneath Alaska has produced more >M8 earthquakes than any other plate boundary system during the last ~100 yrs, including the 1964 M9.2 Great Alaska earthquake. Kodiak Island lies on a section of the subduction zone that ruptured in the 1964 event and experiences seismic tremors, suggesting multiple modes of plate interface slip. Unconsolidated sediment thickness and fluid distribution along the subduction zone interface are some of the factors thought to affect slip stability. We conduct a high-resolution teleseismic receiver function investigation of the subducting plate interface within the Alaskan forearc beneath Kodiak Island using data collected as part of the Alaska Amphibious Community Seismic Experiment in 2019. The Kodiak node array consisted of 398 autonomous three-component 5-Hz Fairfield Nodal Zland geophones deployed at ~200-300 m spacing on northeastern Kodiak Island within the southern asperity of the 1964 M9.2 Great Alaska earthquake. Receiver function images at frequencies of 1.2 and 2.4 Hz show a coherent, slightly dipping velocity increase at ~30-40 km depth consistent with the expected slab Moho. In contrast to studies within the northern asperity of the 1964 rupture, we find no evidence for a prominent low-velocity layer above the slab Moho thick enough to be resolved by upgoing P-to-S conversions. These results support evidence from seismicity and geodetic strain suggesting that the 1964 rupture connected northern (Kenai) and southern (Kodiak) asperities with different plate interface properties.

3D Crust and Upper Mantle Velocity Structure of India and Surrounding Regions Using Rayleigh Wave Dispersion Analysis.

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We model the 3D shear-wave velocity structure of crust and upper mantle of India, Himalaya, Tibet and surrounding regions. This highly resolved lithospheric velocity structure upto a depth of 200 km provides detailed understanding and improved clarity on key evolution and deformation aspects. 2D group velocity tomography maps, resolvable laterally at 3°, are produced from 1D event-raypath dispersion curve between 10-120 s. They provide first order insights about the high velocity persistent in cratons of the Peninsular Indian shield, Eastern Himalayan syntaxis, Pamir, Hindukush and other regions representing high grade metamorphic rocks. Similarly, the Mahanadi and Godavari rift, Bay of Bengal basin, Himalayan foreland basin, Afghan Tadjik basin, Makran subduction zone, and Andaman islands represent the sediment-laden low group velocity structures. The shear-wave velocity (Vs) structure obtained by isotropic inversion is presented as depth sections and profiles to study its lateral variations across the entire region. Focal mechanisms of moderate-to-large earthquakes, Moho depth computed from Airy's isostatic compensation, free-air gravity anomaly data from previous works are investigated in-tandem to discuss the Vs structure. Salient insights include flexural bending, underthrusting of Indian plate till Altyn-Tagh fault in western Tibet and till Jiasha suture in central and eastern Tibet, crustal thickness of each tectonic unit, and sediment thickness of major sedimentary basins. Very high velocity in upper mantle region of Indian cratons, Tibet and Hindukush-Pamir is speculated to be due to eclogite facies rocks unlike the Deccan Volcanic Province and eastern Dharwar craton where this high velocity layer is absent, possibly due to plume volcanism related thermal anomaly or metasomatism. The coherence between the convergence rate, deformation of topography, and the earthquake records discloses this regional scale velocity model as a baseline model that can be considered for disaster mitigation and research studies of local extent within the highly seismic Indo-Eurasia region.

Ambient Seismic Noise for Imaging and Monitoring Volcán De Colima

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Understanding the shallow magma storage and magmatic plumbing system of a volcano is key to its monitoring. We have gained new insight into the internal structure of Volcán de Colima by generating a high-resolution three-dimensional shear-wave velocity tomography using ambient seismic noise recorded on the Colima Volcanic Complex and a neighborhood technique. Our findings show a network of NE-SW low-velocity zones that are oriented along a local fault system. The overlap of a negative radial anisotropy with the low-velocity zone indicates that magma follows vertically oriented structures, such as interfingered dikes or faults and cracks with a significant vertical component. The difference between the currently active system, connected to a network of fluid-filled dikes, and the former active system, filled with solidified sills and dikes, is highlighted by the contrast between the low-velocity anomaly under Volcán de Colima and the distinct high-velocity anomaly under Nevado de Colima. This velocity model has directly impacted the monitoring of the volcano using ambient seismic noise. Cross-correlations of ambient noise can be used to measure temporal fluctuations of relative seismic velocity in various frequency bands, which reveal information about stress or strain perturbations at various depths. We precisely and quickly retrieve the velocity variations in many frequency bands at once by monitoring seismic velocity variation using wavelet transforms. This improves the depth localization of the source of velocity change in the shallow crust, finely constrained by the high-resolution velocity model.

In Situ Vp/Vs Ratios During the 2019 Ridgecrest Earthquake Sequence

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The ratio of compressional- to shear-wave velocity (Vp/Vs) is directly related to Poisson's ratio and can provide insights into characterizing crack and fluid properties and analyzing the effect of pore fluid pressure. In this study, we apply a high-resolution estimation method using waveform cross-correlation data to calculate in situ Vp/Vs ratios in the near-source regions of the 2019 Ridgecrest seismic sequence and to investigate the spatial and temporal patterns in Vp/Vs ratio. We take advantage of the waveform cross-correlation relocation catalog and differential times for 29,462 earthquakes from January 1 to August 31, 2019 from an earlier study originated from the seismic data at the Southern California Earthquake Data Center. Over 164 million P- and S-wave differential times and the corresponding correlation coefficients for 1 million event pairs are available for the estimation of in situ Vp/Vs ratios. The most prominent feature in our results is the relatively homogeneous ratio throughout the majority of the rupture zone of the earthquake sequence. Slightly lower values are seen in the areas where the seismic activity ceased. An intriguing observation is the relatively high Vp/Vs ratios surrounding the source regions of the Mw 6.4 and 7.1 earthquakes. The Coso Geothermal Field is dominated with very low Vp/Vs values. From there, the Vp/Vs ratios gradually increase to the northwest direction. We will compare our results with the tomographic models and other geophysical data to investigate the fault zone material and associated stress characteristics of near source regions.

Site Amplification Variability in Yangon, Myanmar Tracked by Regional and Local Seismic Phases From a Dense Nodal Array

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Yangon, the largest city in Myanmar is located at the convergence of the Yangon and Bago rivers and is home to more than 7 million people. As a part of the Irrawaddy delta system, this densely populated city sits on young water saturated alluvium that can amplify earthquake ground motions. The city is surrounded by several seismically active faults including the Sagaing fault, a major right lateral strike-slip fault that has historically produced M>7.0 earthquakes. In the west, active subduction of the India plate also has the potential to generate a megathrust earthquake of M>8.0. Assessing site response is critically important to understanding and elucidating the seismic hazard potential and necessary building codes that can minimize the loss of property and life from a large seismic event. We investigate site amplification beneath the city of Yangon using data from 110 three-component nodal seismometers that were deployed along three densely spaced profiles during the Myanmar Universities Seismic Experiment (MUSE). Isolating the site term is often difficult since seismic amplitudes depend on the source, path, attenuation (Q), and velocity structure of the earth. However, MUSE has such a small aperture where the source and path effects have a negligible impact on relative changes in the amplitudes for frequencies below 5 Hz. We use this fact to investigate both regional and local Lg and Sg amplitudes and measure the relative site amplification in different frequency bands. Our preliminary results show which parts of Yangon city have significantly higher site amplification (by close to two orders of magnitude). We observed coherent site response characteristics between both the Sg and Lg phases. We also found that the site terms correlate well with the shallow geological structure of the city. Our model of site amplification is important for mapping the seismic hazard potential and the high-resolution seismic micro-zonation of Yangon at the scale of city blocks.

Seismic Imaging of the Solfatara Volcano (Southern Italy) and Characterization of the Very Shallow Fluids Accumulation Zone.

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Nowadays, the use of active seismic is fundamental and particularly challenging for the imaging of volcanic structures. The use of refraction and reflection phases allows for imaging the shallow structures and sometimes even determining the characteristics of the fluids.The case study of the Solfatara crater was particularly challenging for these purposes. The Solfatara is a quiescent volcano belonging to the Campi Flegrei (Italy), a resurgent nested caldera that has been extensively investigated through active seismic investigation. During the active experiment RICEN (Repeated Induced Earthquake and Noise) performed in the context of the EU project MEDSUV between May and November 2014, two 400 m long profiles were acquired. The seismic arrays were deployed along the NE-SW and NW-SE directions within the crater across the zones of the fumaroles and the "fangaia". The main fumaroles, Bocca Grande and Bocca Nuova represent some of the most apparent evidence of deep magmatic-hydrothermal activity. In particular, we first performed a refraction non-linear tomographic imaging to characterize the very shallow layer of the crater using a Bayesian estimation of the P-wave velocity model. Subsequently, seismic reflection imaging was performed to investigate the subsoil at greater depths and locate the main structure and possible pathways for the gas ascent. In particular, we got advantages of the seismic attributes such as energy, root mean square, envelope, and sweetness for determining the maximum and minimum values of amplitude zones on the migrated, post-stack seismic sections. Finally, to better characterize the reflectivity of shallow events, enhanced by the post-stack attributes, the Amplitude Versus Offset (AVO) technique has also been used to discriminate and identify shallow gas pockets. The final multi-2D seismic profiles were combined into a final structural image of the Solfatara subsoil. This shows clear evidence of the fluids contact trapped zones at 10-50 m depth beneath the crater's surface and their migration paths down to 150 meters depth.

3D Mapping of Scattering Attenuation for the Central Italy 2016–2017 Seismic Sequence

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Between August and October 2016, the Central Apennines (Italy) was struck by a cascading seismic sequence known as the Amatrice (Mw 6.0) - Visso (Mw 5.9) - Norcia (Mw 6.5), which has been associated with fluid circulation in the normal fault network. Seismic attenuation parameters (e.g., scattering and absorption) are powerful tools for detecting fluid presence and fracturing. The aim of this work is to investigate with 3D images, in space and time, the scattering contribution to the total attenuation of two datasets, one before the mainshock of Amatrice (March 2013-August 2016) and a second during the sequence (August 2016-January 2017). To measure scattering, we used peak delay mapping. A comparison between the 3D mapping of the pre-sequence and sequence shows a dissimilarity in scattering, with a general increase of it over time after the Amatrice main event. Main structural elements (e.g., Monti Sibillini and Acquasanta thrusts) and lithologies are strongly controlling the scattering losses, with changes from low to high scattering around 4 and 6 km depth, west of the Norcia basin and of the Monti Sibillini thrust, suggesting an increment of fracturing due to the intense seismic activity. Monti Sibillini and Acquasanta thrusts act also as rheological barriers, creating contact between different geological domains. This causes a scattering contrast due to different responses in fracturing and compacting before and during the seismic sequence. Low scattering anomalies are located at the footwall of the thrusts during a pre-sequence phase, replaced by high scattering after the mainshocks. Low scattering can be associated with increased pore pressure due to fluid circulation in Triassic deposit layers; the movement and release of the pressure starting from this formation possibly provoked the movement of the thrusts, triggering the main events of the 2016 sequence.

Tomography of Crustal Seismic Attenuation in Switzerland and Surrounding Regions: A New Input for the Next Generation of Seismic Hazard Models

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We present a 3D attenuation model of the upper crust for the Swiss Alps. The 3D inversions derive the quality factor Q (1/attenuation) using path attenuation t* observations for > 4500 earthquakes recorded on permanent and temporary stations for the period 2002-2022. We followed a procedure in which a series of inversions are performed on decreasing size grids. Re-gridding is done using a nearest-neighbor approach. This method allows to obtain a reasonable Q model everywhere despite the spatially varying data distribution and to resolve deeper parts of the model thanks to including longer distances phases. The resulting Qs and Qp models show large-scale features in the upper crust, which are consistent with a recently improved high-resolution velocity models of the same region and serve to refine the interpretations of crustal structures from Vp and Vp/Vs. For example, at depths ranging between 2.0-6.5 km, low Q is imaged along the Rhone valley in the Valais region in southwest Switzerland. This region locates in the transition zone between the Central and Western Alps and represents one of the most hazardous areas within the Alpine Arc, which hosts the presently seismically most active fault zones. As the attenuation of fractured rock volume is enhanced by fluids, the low Q values observed in this area may relate to distributed microfractures that produce greater fracture connectivity and permeability in a relatively higher strain-rate zone. This is also confirmed by low-velocity anomalies imaged by recent high-resolution tomography efforts aiming to image the fault-zone structures in this region. Thus, in combination with recently developed Vp and Vs velocity models, the developed 3D attenuation models not only advance our understanding of seismotectonic processes in Switzerland, but will also provide additional constraints in terms of composition and physical properties of the uppermost crust of the Swiss Alps as well as crucial input for next generation seismic hazard models of Switzerland. This new acquired information can be used for a more realistic prediction of earthquake related ground motions.

3D Seismic Attenuation Model: Scattering and Absorption Imaging Beneath the Los Angeles Metropolitan Area

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In high seismic hazard regions, modelling seismic attenuation and combining it with velocity models is a powerful tool for imaging crustal features, such as complex fault systems, sedimentary layers and fluids. A frequency-dependent attenuation model is also critical for improving wavefield predictions in ground motion studies.In the northern Los Angeles area, sedimentary basins may act as a waveguide producing large amplifications from an earthquake rupture on the southern San Andreas Fault. While the Southern California Earthquake Center community models provide P and S wave velocities for this region, a 3D attenuation model has to be incorporated into Earth models for more accurate wavefield simulations. This work aims to develop the first high-resolution, physics-based attenuation model across the Chino and San Bernardino basins using local earthquakes recorded by eight nodal arrays (410 stations), deployed during the Basin Amplification Seismic Investigation (BASIN) experiment. We perform high-frequency attenuation analysis using the peak-delay and coda attenuation methods to measure the scattering and absorption contributions, respectively. We present seismic scattering and intrinsic attenuation tomography at 12, 18, and 24 Hz (down to 10 km depth with a horizontal and depth resolution of 3 km and 1 km, respectively). The results show that the main structural discontinuities, such as the Fontana fault in the Chino basin, control the scattering anomalies allowing for the discrimination between relatively compact and fractured media. High absorption anomalies across the basins mark sedimentary layers and suggest the presence of fluids, i.e., groundwater, in agreement with recent ambient noise tomography. We thus present imaging results of both elastic and anelastic properties that aim at constraining the effects of sediments, fluids, and fractures on seismic wave propagation beneath the Los Angeles metropolitan area.

Attenuation of the South American Lithosphere

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Using the amplitudes of regional phases (Pg, Pn, Lg, Sn), we have developed a comprehensive attenuation model of the lithosphere in South America. By using seismic data recorded by stations from multiple networks, we obtain excellent path coverage of the whole continent, including in the eastern portions that are relatively aseismic. We then use a multi-phase amplitude tomography to determine Qp and Qs in the crust and upper mantle over a broad frequency band (0.5-10 Hz). We observe many expected features, including lower Q (higher attenuation) in the active Andes orogenic belt and higher Q (lower attenuation) in the stable craton. Beyond this, however, we see less expected results, including significant variations along the Andes (such as a trend of high Q in the Peruvian and Pampean flat slab regions) and low upper mantle Q extending north from the Rio de la Plata craton along the Chaco and Pantanal basins, which is associated with thinner lithosphere than adjoining regions of the South American platform. Our preliminary results suggest regional variations within the Amazon craton: relatively lower average Q values in the Guyana shield compared with higher average Q in the Central Brazil shield (north and south of the Amazon river, respectively). This is also consistent with the average lithospheric thicknesses inferred from surface-wave tomography. As in other areas of the world, we find that attenuation is highly sensitive to the thermal structure, with warmer regions of more recent tectonic activity having lower Q than older and colder stable continental regions.

Crustal Imaging of High Seismic Hazard Regions [Poster]

Poster Session • Thursday 20 April

Conveners: Chiara Nardoni, Louisiana State University (cnardoni@lsu.edu); Simona Gabrielli, Istituto Nazionale di Geofisica e Vulcanologia (simona.gabrielli@ingv.it); Patricia Persaud, University of Arizona (ppersaud@lsu.edu); Eric Sandvol, University of Missouri (SandvolE@missouri.edu)

Ambient Noise Interferometry to Obtain Images of the Mid- and Lower Crust

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Conventional seismic reflection imaging techniques using ambient seismic noise require extraction of seismic reflection response using seismic interferometry. Additional processing steps include CDP sorting and migration are required to obtain a reliable image of the subsurface. However, these traditional techniques have difficulty in imaging the mid and lower crust.We use the data from a large-N seismic survey conducted in March 2014 near Sweetwater, TX, which consisted of 2639 receiver locations using Z-land 1C nodes from Nodal Seismic. These short period instruments recorded signals from a Vibroseis source truck for 11 days. We identify the period when Vibroseis sources were active and split the data into two subsets: data recorded with and without Vibroseis sources. We further split the data without Vibroseis sources into three smaller subsets with an increasing recording period of 4, 5, and 6 hours starting at 11:00 pm CST. We experiment with different processing parameters including frequency range, time/frequency normalization, cross-correlation and step length, and maximum time lag to find optimum parameter values and obtain virtual source gathers for all subsets of data.We used stacks of near-offset traces from virtual source gathers to form a gather equivalent to a zero-offset reflection section. Various sizes of the stacking bins were tested to determine trade-offs between lateral resolution of the image and contamination from random noise. A P-wave reflectivity image was then obtained by minimizing the masking effect of the effective source time function. A comparison between primary results obtained for the data subsets with and without Vibroseis sources indicates that comparable images of the deeper subsurface can be obtained without the use of Vibroseis sources. Images improve, in the sense that they become better and better approximations of the Vibroseis image, upon increasing the recording duration.

Constraining Geologic Structure of the Rock Valley Fault Zone: Dense Gravity Analysis for the Rock Valley Direct Comparison Experiment

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Direct comparisons of seismic wave observed from earthquake and explosion sources through similar geologic structure are sparsely available. Discriminating the signals produced by shallow earthquakes versus explosions is thus challenging. The Rock Valley Direct Comparison experiment addresses this by proposing to record explosive sources collocated with historic shallow earthquakes. To understand the historic data and to directly compare the signals requires a detailed characterization of the underlying geologic structure. A Geologic Framework Model (GFM) of the Rock Valley region has been generated with data inputs from regional gravity surveys. However, these regional surveys are sparse compared to the scale of the study region. To improve our GFM and better understand the underlying fault structure, we collected a densely sampled gravity dataset spanning Rock Valley Fault Zone (RVFZ). We took gravity measurements along 5 fault perpendicular lines totaling 218 sites, including reoccupation of several regional sites, with ~150 m spacing, and 200-700 m separating each line. Relative gravity measurements are calibrated to an absolute gravity station south of RVFZ in Mercury, Nevada. Gravity data corrections are applied including instrumental drift, latitude, tide, terrain, free air, and Bouguer corrections. The resulting Bouguer anamoly maps clearly highlight the RVFZ structure with gravity lows in the center of the valley where alluvium fill is thickest and gravity highs on the flanks where Paleozoic sedimentary units and Tertiary volcanic rocks are exposed. We run a series of froward models to test the validity of various fault zone permutations and the ability of the data to constrain such models. The gravity observations are also compared to recent tomographic inversions. The seismic data from the region will be integrated with the gravity information in a joint inversion as a part of future work on the project. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Imaging the Deformation Belt of Western Hispaniola Using Multi-Component Ambient Noise Cross-Correlations

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Hispaniola Island is located at a complex boundary between the North American plate and the Caribbean plate, resulting in a series of fold-and-thrust belts and active fault zones. In order to solve the regional structure of western Hispaniola, several seismic imaging studies have been conducted using receiver function and local earthquake tomography. These studies combined with geological observations give the outline of crustal structure in the area, showing a thinner crust (~20 km) in the northern and southern domains and a thicker crust (~40 km) in the central part of western Hispaniola. However, the resolution of these results is limited. Receiver function is only sensitive to the structural discontinuities beneath stations, whereas local earthquake tomography is restricted by the earthquake observation, in which event detection in this region has been shown to be a challenging task due to high background noise. Therefore, in this study, to investigate the crustal structure across western Hispaniola, we perform multi-component noise cross-correlation and measure Rayleigh wave phase velocity and ellipticity (i.e., horizontal-to-vertical (H/V) amplitude ratio) between the period of 2-20 s. The data used in this study are mainly from 27 broadband stations in western Hispaniola that were deployed from April 2013 to June 2014 during the Trans-Haiti project. Additionally, we include all available stations within 1,000 km from the target area to provide constraints on longer-period signals. The preliminary results of H/V show consistent patterns related to geology, in which sedimentary basins show high H/V whereas mountain areas show low H/V, implying different elastic responses of Rayleigh waves in different geological units. We will then combine H/V and phase velocity measurements to invert for a 2-D shear velocity across western Hispaniola. The results from this study will provide useful insights into seismic hazard assessment in this area, which has recently experienced two devastating earthquakes in 2010 and 2021.

Imaging the Oceanic Crust in Remote Areas Using Existing Datasets

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Imaging of the crust in offshore environments presents challenges that limit our ability to evaluate large-scale crustal deformation. Seismic reflection imaging has proven to be an effective tool for imaging the crust, but it is expensive and relatively slow to acquire, limiting its use in remote areas, where care must be taken to target surveys effectively and efficiently. These limitations may make it cost prohibitive or difficult to acquire regional images of the crust.

In this study we use a combination of satellite-derived gravity data and global density models to estimate the elevation of the top of the Pacific Plate on a continental scale along the Queen Charlotte Fault, which sits west of British Columbia and southeast Alaska. Within this area there are extensive seismic reflection data which image the crust and are used to validate our estimated surface. Furthermore, we use the magnetic anomaly dataset to identify faulting within the crust, allowing us to build a regional model of the crustal surface. This method represents a valuable tool for crustal imaging that can be used in remote and data-poor regions that are seismically active using existing datasets, allowing us to build first-order models of the oceanic crust, which can be used to effectively target higher-resolution imaging in locations where access acquisition costs are prohibitive.

Locating an Urban Fault Along the San Francisco Peninsula Using High-Resolution Active-Source Seismology

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In July 2021, the U.S. Geological Survey conducted a series of seismic surveys in San Carlos, California across suspected traces of the Quaternary-active Serra Fault, a poorly mapped fault trending subparallel to the San Andreas fault along much of the San Francisco Peninsula. We deployed a series of seismic profiles along suburban streets, consisting of 3-component nodal seismometers spaced at 5-m intervals, and co-located seismic sources (shots). Here, we present results from a 61-node, 300-m-long profile along Graceland Avenue. P-wave shots were generated using a 500-kg weight drop mounted on a Bobcat tractor, and S-wave shots were generated by horizontally striking an anchored metal block with a 3.6-kg hammer. We developed 2D tomographic velocity models from P- and S-wave data separately and combined the models to create 2D Vp/Vs and Poisson's ratio models. Our P-wave model shows a zone of high velocities (> 3500 m/s) in the upper 30-m depth, centered near the western end of the profile. Our S-wave model shows a large increase in velocities (600 to > 1200 m/s) east of the same area. Our Vp/Vs and Poisson's ratio models indicate a zone of high ratios (Vp/Vs > 3.5; PR > 0.48) in the upper 30-m depth, centered near meter 180 of the profile. We interpret the velocity differences and high ratios near meter 180 as resulting from the presence of the Serra fault, which is likely a water-saturated fault barrier at that location.

Preliminary Imaging Results From a Nodal Array to Investigate the Structure of the Southern Cascadia Forearc

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Numerous variations in the tectonic and seismogenic behavior of the Cascadia forearc appear linked through subduction-mediated processes, such as non-volcanic tremor density, episodic tremor and slip (ETS) recurrence interval, uplift and exhumation rates, intraslab seismicity, slab dip, plate locking, and topography. These correlations are particularly pronounced in Southern Cascadia, where the shortest slow slip recurrence intervals, the highest amount of non-volcanic tremor, and the broadest forearc topography are found. Despite this, the southern Cascadia forearc has been relatively under-instrumented with modern passive seismic equipment. As such, better seismic images are needed before robust comparisons with other portions of the forearc can be made.

From March - April 2020, the Southern Cascadia Earthquake aNd Tectonics ARray (SCENTAR) was deployed to investigate the forearc structure in northernmost California. This array consisted of 60 continuously operating 3-component nodal seismometers (an ~8-fold increase compared to long-term seismic monitoring in the area) with an average station spacing of ~15 km. Analysis of the noise spectrum on these instruments are comparable to nearby broadband instrumentation down to ~0.1 Hz, which overlaps with frequencies commonly used for passive seismic imaging. Teleseismic vertical P-waveforms are nearly identical on nodal and broadband instruments, allowing for the computation of receiver functions to image the local discontinuity structure. Despite only 1-month of data, the preliminary receiver function images show a very similar structure to what has been collected in the prior decade of permanent and temporary seismic stations. In addition, ambient noise interstation cross-correlations show reliable surface wave arrivals up to 15 second periods, which will allow for higher lateral sampling and shallower sensitivities than previous datasets could obtain. This dataset highlights the feasibility of using short-term nodal arrays and passive imaging techniques to recover the seismic structure in hard-to-reach regions at a relatively low cost.

Receiver Function Imaging of Erebus Volcano via Joint Bayesian Inversion With Spatial Weighting

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Erebus volcano, located on Ross Island, Antarctica, is one of few examples of an open convecting lava lake. It features Strombolian style eruptions among various forms of ambient seismicity and has a complex magmatic structure with sparsely resolved continuity between the crust and mantle related to a hypothesized hot spot upwelling. Previous active source tomography and coda interferometry studies have noted strong shallow scattering structures associated with low velocities, but the Moho depth has only been regionally constrained to an estimated 18 - 20 km depth. To better resolve this and corroborate other large-scale crustal structures, we use twenty-seven seismic stations distributed on the Erebus edifice from the Tomo-Erebus, MEVO, and GSN seismic networks with a total of two hundred and eleven earthquakes between 2007 - 2010 to compute P-wave receiver functions (PRFs) with individual and multi-station Bayesian Markov chain Monte Carlo (MCMC) inversions. By using multi-station inversions, we assume the deeper structures are similar across stations but have greater variance closer to the surface to account for edifice heterogeneity. After inverting, we note a strong shallow discontinuity between 4 - 7 km, corroborated by ongoing icequake coda images, and a Moho depth between 17 - 22 km. Dispersion information is planned as part of an eventual joint inversion for the entire dataset.

Seismic Experiments in the Kumaon Himalaya: Do We Expect a Great Earthquake?

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The Kumaon segment is a part of the central Himalayan seismic gap that is thought to be capable of hosting a future great earthquake. A series of seismic experiments were performed based on data from a local seismic network to study the seismogenesis in the region. Initial receiver function (RF) studies identified a relatively shallow crust (~40 km). The Lesser Himalaya is the most widely spread lithology in the area and is divided into the Outer and Inner Lesser Himalaya (OLH and ILH respectively). Both stacked RFs and velocity models identify a double ramp structure on the decollement (or MHT) separating the Indian and Eurasian plates. This north-dipping MHT serves as the sole thrust to an overlying hinterland dipping duplex in the ILH. Seismotectonic study reveals steep-dip imbricate faults with coincident seismicity between shallow to mid-crustal (ramp) depth. Seismic imaging also reveals a lower crustal low-velocity zone with a high Poisson's ratio (~0.28) in the ILH. The ductile nature of the lower crust supports the decreasing events with depth. The number and correlation of gravity lineaments with the local anisotropy show the upper crust to be more brittle in the ILH. The region is anisotropic (delay time ~0.18 s) with fast polarization directions both along and orthogonal to the convergence direction. This indicates the combined effect of tectonic stress and local geological features in generating stress-aligned micro-cracks. Stress inversion of earthquakes shows a perturbed stress field and low friction coefficient in the ILH. These earthquakes also report low source parameters compared to that in other segments, showing incomplete dissipation of accumulated stress. The concentration of shallow-focus earthquakes is a result of the presence of a fluid-rich zone, strain localization, and large stress build-up due to locking in the ramp. The high seismicity with a low-stress drop ($\sigma \leq 40.6$ bar) and *b*-value (~0.64) makes this segment a seismically hazardous zone.

The Crustal Structure of Southwestern Turkey Using Local Seismic Data

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In this study, we explore the crustal structure of southwestern Turkey (35°N-39°N and 26°E-32°E) using double difference travel time tomography. Travel time data were obtained from three different earthquake catalogs: International Seismological Centre (ISC), Kandilli Observatory and Earthquake Research Institute (KOERI), and The Disaster and Emergency Management Presidency of Turkey (AFAD). The ISC data was collected between the years 2000 and 2022, KOERI data from 2013 to 2021, and AFAD data from 2010 to 2022. Based on the location of intermediate depth seismicity in this region, the Hellenic slab is dipping to the west and the Cyprean slab is steeply dipping to the northeast. We have chosen 5437 very well-located earthquakes out of 191024 earthquakes. These events were relocated using the double difference approach (HYPODD). The Cyprean slab appears to become nearly vertical (or >80° dip angle) after relocation, while the Hellenic slab is still dipping to the west. The relocated earthquakes are concentrated on a line starting from the east of Kos Island and extending to the Fethiye-Burdur fault zone. This line of earthquakes might be evidence of an unnamed rift zone. In general, we observed evidence of the brittle-ductile at around 20 km depth, consistent with a fairly steep crustal geotherm. The seismic velocity structure of the region was obtained by applying the double difference seismic tomography technique. Our preliminary tomographic model shows a low-velocity zone in the region extending from the east of Kos Island, which is the region with the most intense crustal seismic activity, to the Fethiye-Burdur Fault Zone. In addition, high Vp/Vs ratio and low Vp/Vs ratio anomalies were observed at the eastern edge of the Menderes Massif and in the northern part of the Menderes Massif, respectively. The accuracy of the results of the seismic tomography study has been evaluated using a large number of resolution tests. In addition to the resolution tests, we have utilized a bootstrap resampling scheme to estimate the velocity uncertainty.

De-risking Deep Geothermal Projects: Geophysical Monitoring and Forecast Modeling Advances

Oral Session • Tuesday 18 April • 08:00 AM Pacific

Conveners: Federica Lanza, Swiss Seismological Service, ETH Zurich (federica.lanza@sed.ethz.ch); Kristine Pankow, University of Utah (kris.pankow@utah.edu); David Eaton, University of Calgary (eatond@ucalgary.ca); Ryan Schultz, Stanford University (rjs10@stanford.edu); Nori Nakata, Lawrence Berkeley National Laboratory (nnakata@lbl.gov); Annemarie Muntendam-Bos, Delft University of Technology (A.G.Muntendam-Bos@tudelft.nl)

Assessing the Relative Contributions of Fluid Pressure and Elastic Stress to Induced Seismicity

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Induced seismicity may involve complex triggering mechanisms that significantly complicate subsurface energy extraction. While both pressure and elastic stress effects have been linked to induced events, the relative contribution of these effects to total seismic-moment-release remains to be understood. One key component in determining the importance of pressure vs. elastic stress effects are more robust constraints on crustal hydrology. We examine processes that govern fault hydrology and slip at various scales from centimeter lab-samples to kilometer reservoirs. We use tidal responses and lab core measurements to estimate permeability changes in a shallow geothermal reservoir near Winnemucca, Nevada, where geothermal operations take advantage of hydrothermally-altered and fractured rocks. The reservoir formed within a sequence of normal and strike slip fault in the basin and range tectonic province.

We integrate results from InSAR, pressure, temperature and seismicity analyses. We generate a high-resolution seismicity catalog based on waveform cross-correlations and relative event relocations. The seismicity with ML -2.0 to 1.0 forms spatial clusters close to injection wells, although reservoir deformation is dominated by compaction and pore-space collapse. We test reservoir cores from intact (porosity~0.4 %) and fractured phyllites (porosity~4%) as well as felsic intrusive rocks (7 – 15 %) and determine permeability and poroelastic coupling during stepwise pore (<40 MPa) and confining pressure changes (<45 MPa). Permeability values from seismicity migration are compared with direct permeability measurements from lab tests and tidal analysis. Corresponding peak fault zone permeability is ~50 milliDarcy at 1 km depth. These values suggest that direct pressure effects are likely limited to near-well regions. Deep and distant induced events associated with geothermal and hydrocarbon operations likely require more complex mechanisms such as poroelastic stress transfer and aseismic slip.

The Effect of Correlated Permeability on Fluid-Induced Seismicity

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Fluid-induced earthquakes are a side effect of industrial operations such as hydraulic fracturing and enhanced geothermal systems, where high-pressure fluids are pumped into the earth's crust to increase oil and/or gas flow to a well from petroleum-bearing rock formations or to improve permeability in underground geothermal reservoirs. One of the challenges associated with subsurface high-pressure fluid injections is the estimation of the seismic hazard and its spatial footprint: how far away from the injection site can seismicity be induced? Field data have shown that the spatial footprint typically varies significantly between injections into the basement and injections above basement. If the fluids are pumped into the crystalline basement, the occurrence of the seismicity is typically very localized in space. Here, we show that varying degrees of spatial correlations in porosity or log(permeability) can explain this observation. By analyzing high-quality permeability data, we first directly show that the degree of correlations in the crystalline basement is indeed significantly different from formations above the basement. Then, using this in a novel conceptual model, we show that the degree of correlations controls the spatial footprint of fluid-induced seismicity explaining the field observations. Our findings are independent of the presence or absence of viscoelastic effects typically responsible for aftershocks. Our findings can be directly incorporated in any seismic hazard assessment.

Transient Evolution of the Relative Size Distribution of Earthquakes as a Risk Indicator for Induced Seismicity

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Seismicity induced by human activity has gathered significant scientific attention in the past two decades, however the physical mechanisms driving induced earthquakes is yet to be fully understood. The injection of fluid in the subsurface in particular has been shown to cause changes in the stress field leading to the triggering of earthquakes. Events in engineered geothermal systems, like the ones recorded in Switzerland (Basel 2006, St-Gallen 2013) and Korea (Pohang 2017), have shown that such injection operations can have dramatic consequences. The hazard associated with these earthquakes needs to be managed to prevent infrastructure damages and protect both the population and economic viability of the project.

The b-value of the Gutenberg-Richter power law has been used as a proxy for the state of stress in the subsurface. We propose to use the temporal evolution of the b-value as a statistical tool to evaluate the changes in the stressing of the injection region. In the case of Basel, the b-value has been observed to drop a few days before the series of events leading to the shut-in and subsequent bleed-off of the geothermal well. We use a numerical model coupling a 3D fluid flow simulator and a stochastic geomechanical model to investigate temporal changes of the b-value and understand the observations made in Basel.

By comparing the observations in Basel and our numerical models, we establish a highly systematic behaviour of the b-value during an injection cycle. We show that the temporal evolution of the b-value is controlled by site specific conditions and pre-existing faults as well as the injection pattern. Our results open up new approaches to assess and mitigate seismic hazard and risk through careful site selection and adequate injection strategy, coupled to real-time monitoring and modelling during reservoir stimulation.

An Ensemble Approach to Characterizing Trailing Induced Seismicity

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Earthquakes caused by human activities can pose significant risks, and lingering seismicity that trails the stopped anthropogenic operation is a particular challenge for risk management. To address this concern, we characterize cases where induced seismicity stops. Five competing models are fit to 56 trailing seismicity cases that span injection operations including: hydraulic fracturing, enhanced geothermal systems, wastewater disposal, and gas storage. Models are ranked based on a suite of statistical performance metrics. We find that the Omori and Stretched Exponential models are typically the best fitting; however, since there are cases where each model is best, we advocate for the use of an ensemble. We discuss a framework for a weighted ensemble that updates based on model performance and then demonstrate with a *post hoc* 'forecast' of trailing seismicity. We also find some cases (~23%) that misfit all the models. Residual analysis of these outlier cases shows common themes, including productive trailing sequences that abruptly cease. Such outliers suggest room for more physically motivated models that can encompass phenomenon such as operator mitigation, stress shadows, or poroelasticity. The results of our study provide a quantitative framework for quantifying trailing seismicity, including both forecasting, and observable mitigation criteria.

Assessing Potential Hazard and Risk from EGS Projects in Nevada and Oregon

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As part of the development of Induced Seismicity Mitigation Plans (ISMPs) for four proposed enhanced geothermal system (EGS) sites in Nevada and Oregon, we are evaluating the potential for induced and triggered seismicity and the associated seismic hazard and risk at each site. ISMPs are being developed in line with the seven steps described in DOE's *Protocol for Addressing Induced Seismicity Associated with Enhanced Geothermal Systems* (Majer *et al.* 2012). In Step 1, we performed preliminary screening-level risk analyses. We collected readily available information and data that could be used to assess the potential impacts on the local communities and stakeholders and performed a simplified analysis to evaluate those impacts during routine operations, including a possible worst-case scenario. Step 2 is an outreach and communications program, developed by the EGS owner. In Step 3, we reviewed and selected criteria for ground vibration and noise, assessing the existing environments in areas of potential impacts to establish a baseline, then evaluating the anticipated impacts. Step 4 is seismic monitoring being performed by Lawrence Berkeley National Laboratory. In Step 5, we estimated the seismic hazard at each project site due to both natural and induced seismicity. The former provides a baseline from which to evaluate the additional hazard that may be imposed by induced earthquakes. In Step 6, we developed a robust estimate of the seismic risk prior to the project and associated with the stimulation. Risk here includes the potential for: 1) structural and non-structural damage to residential housing, community facilities, and infrastructure of industrial, commercial, research, and medical facilities; 2) socioeconomic impacts from damaged infrastructure and operations interference in business and industrial facilities; and 3) nuisance (human perception of the ground shaking). The risk analysis helps evaluate alternative operational procedures, including those that could mitigate negative effects and minimize the risk from induced seismicity. Finally, Step 7 is the development of the ISMP.

Factors Characterizing Stable Seismic Energy Release During Hydraulic Stimulations: Egs Helsinki and Experimental Perspective

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Near-realtime high-frequency seismic monitoring of fluid injection allowed mitigating induced seismicity during two hydraulic stimulations performed in 2018 and 2020 in a deep geothermal well near Helsinki, Finland. Using near-realtime information on the evolution of seismic and hydraulic energy, pumping was either stopped or varied, following the theoretical predictions from a physics-based model of maximum magnitude, avoiding occurrence of project stopping large earthquakes.

We present factors contributing to the project success: 1) adaptive stimulation strategy, 2) structural inventory of the reservoir and 3) limited stress transfer. Seismic injection efficiency, the ratio of radiated-to-hydraulic energy, allows to identify whether evolution of induced seismic events is stable as predicted by existing models of maximum magnitude or not possible indicating upcoming run-away rupture. Tracking structural inventory of the reservoir with relocated earthquake hypocenters, focal mechanisms and source parameters gives information on potentially hazardous localization processes on major pre-existing structures also indicating potential for significant stress transfer. Finally, seismicity passively responding to injection operations, as in the case of the Helsinki project, is well described by a non-stationary Poisson process modulated by the hydraulic energy input rate. However, observable clustering in space and time, or deviation from random distribution of magnitudes in time and space may suggest emergence of instability in the stimulated reservoir. In the talk we will discuss a pool of physically explainable seismo-mechanical and statistical parameters that could be potentially used in developed ML/AI frameworks to analyze the stability of the seismic release during geothermal stimulations.

De-risking Enhanced Geothermal Energy Projects: Insights from the DEEP Project

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Enhanced Geothermal Systems (EGS) require balancing seismic ;risk and economic output, and past failed EGS projects demonstrate that this is a delicate balance to achieve. To develop an EGS, induced seismicity, which is not an undesired by-product but a necessary tool to create a productive heat exchanger, needs to be adequately managed and controlled. These are the key goals of DEEP (Innovation for De-risking Enhanced geothermal Energy Projects, www.deepgeothermal.org), an international collaborative project aimed at establishing a full-scale, real-time test bench for innovative seismic monitoring, processing, seismicity forecast modelling, and risk assessment. DEEP develops largely automated, data-driven and fully probabilistic approaches to assess seismic hazard and risk, so-called Adaptive Traffic Light Systems (ATLS). The primary field test site of DEEP is the DOE's Frontier Observatory for Research in Geothermal Energy (FORGE) in Utah (USA). Key to the project is also the definition of next-generation good-practice guidelines and risk assessment procedures to reduce commercial costs and enhance the safety of future projects, We will provide an update on the progress of the DEEP project, highlighting results from the past FORGE stimulations in 2019 and 2021. We will show the performance of different event detection and location algorithms using machine learning and Distributed Acoustic Sensing (DAS), as well as a performance assessment of forecasting models, performed both on synthetic and real data. We also will present how ATLS approaches will be tested and validated in upcoming stimulation at FORGE, and how this knowledge can be used to optimize seismic safety procedures for future EGS projects, such as the upcoming one in Haute-Sorne (Switzerland).

Clustering Analysis of Microseisms Generated During Hydraulic Fracturing Recorded by Downhole Geophones

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Statistical properties of microseismic signals induced during hydraulic fracturing could help us better understand the correlation between seismic recordings and injection activities. Clustering-based machine learning algorithms demonstrate great potential to identify changes in fracturing processes by searching for systematic differences in spectral properties of microseisms (e.g., Holtzman et al., 2018). In this study, we apply a Hierarchical clustering algorithm to power spectral density (PSD) of microseismic waveforms generated during hydraulic fracturing simulations. For each event, we average PSD calculated over three components and nearby downhole geophones to increase the signal-to-noise ratio. Then, the attenuation effect is corrected from the PSD using a best-fitting quality factor Q estimated from the linear trend of frequency spectra. The Wasserstein distance is used to quantify the difference in PSD between events. Applications to data collected from the Montney Formation and the April 2022 simulation at the FORGE site in Utah indicate event clusters with clear differences in spectral properties. The grouping results could potentially provide information on important topics, such as the characterization of fracture complexity, degree of fracture connectivity, and monitoring of fracture growth.

Noise Characterization of Surface DAS in Monitoring the April 2022 Stimulation at Utah FORGE

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The Utah FORGE site is an underground field laboratory for testing innovative technologies and methods aimed at advancing the development of enhanced geothermal systems (EGS). In April 2022, FORGE performed its first deep well hydraulic stimulation to reactivate pre-existing natural fractures and/or create new ones. Borehole geophones located thousands of microseismic events that delineated the successful creation of the reservoir at more than 8,000 ft deep in hot dry crystalline rock. Other instruments were also present during the stimulation, such as borehole distributed acoustic sensing (DAS) arrays, and surface geophone arrays. We participated by deploying a 2 km long DAS cable along the surface in a L-shaped configuration, with a channel (sensor) spacing of 1.5m. The surface DAS array was purposefully designed to evaluate source-sensor directional sensitivity and enhance the probability of detecting seismic events occurring at different locations relative to the array.

We present a preliminary analysis of seismic signals captured by the surface DAS array and characterize noise as it varies in amplitude, time, and space along the array aperture. The strongest and most perpetual signal we identify in the DAS records is cultural noise that we infer to be generated by operations at the injection site. We find that the surface array was also able to detect several microseismic events likely correlated to periods of injection. The unexpected observation of microseismic events right below the array is remarkable given the well-known insensitivity of DAS to high-angle body waves. This could potentially be attributed to the use of the interrogator that natively measures particle velocity instead of strain rate along the sensing fiber; thus, enhancing the system's response, especially to S waves with high incident angles. This analysis provides a basis for evaluating the overall performance of surface DAS, and demonstrates its value for seismic monitoring at EGS sites.

Towards Best Practices for Egs Seismic Monitoring: Insights Gained at Utah Forge

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The Department of Energy Frontier Observatory for Research in Geothermal Energy (FORGE) program has a mission to enable research and advances in drilling and technology to facilitate a pathway for commercial Engineered Geothermal Systems (EGS). In January 2021 at Utah FORGE, an ~3 km deep horizontally deviated well was drilled through basement rock at temperatures over 220ºC. In April 2022, the horizontal deviated section of this well was stimulated in three stages. At the Utah FORGE site multiple scales and types of seismic instrumentation are utilized to monitor background seismicity and reservoir stimulation phases. The Utah FORGE site has a local seismic network of broadband and accelerometer sensors and four deep vertical boreholes (three at reservoir depth; two with DAS cemented into the casing) where 3C sensor arrays were deployed during stimulation phases. During the 2022 stimulation, the local seismic network was utilized for a magnitude-based traffic light system, while data from the multiple boreholes were integrated to generate a near-real-time catalog to monitor reservoir development, and the near-real-time catalog and hydraulic data were used to test adaptive traffic light systems. In addition, two dense surface geophone experiments were conducted—one focused on event detection and the second for velocity model development. There was also an experiment utilizing horizontal DAS at the surface and following the stimulation a walk away vertical seismic profile experiment. In September 2022, a post-stimulation seismic workshop was held on the University of Utah campus. Groups that had participated in seismic monitoring of the stimulation or that had conducted other seismic related experiments participated. The meeting was structured to cover four key topics: (1) seismic instrumentation, (2) seismic network design, (3) seismic monitoring protocol, and (4) development and implementation of adaptive seismic traffic light systems. Here, we describe the 2022 monitoring effort and thoughts on future seismic monitoring at Utah FORGE and the monitoring of EGS systems more generally.

De-risking Deep Geothermal Projects: Geophysical Monitoring and Forecast Modeling Advances [Poster]

Poster Session • Tuesday 18 April

Conveners: Federica Lanza, Swiss Seismological Service, ETH Zurich (federica.lanza@sed.ethz.ch); Kristine Pankow, University of Utah (kris.pankow@utah.edu); David Eaton, University of Calgary (eatond@ucalgary.ca); Ryan Schultz, Stanford University (rjs10@stanford.edu); Nori Nakata, Lawrence Berkeley National Laboratory (nnakata@lbl.gov); Annemarie Muntendam-Bos, Delft University of Technology (A.G.Muntendam-Bos@tudelft.nl)

Applying Waveform Correlation Analysis to Microseismicity at the Forge Sites to Detect and Characterize Fractures

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The Frontier Observatory for Research in Geothermal Energy (FORGE) is a geothermal project located at Milford, UTAH, providing pioneer research in Enhanced Geothermal Systems (EGS). Microseismic monitoring is essential during stimulation that aims at creating a permeable fracture network. During hydraulic fracturing, different fractures are activated, some of which have low seismogenic potential while others can host large seismic events. Waveform cross-correlation is a powerful tool to identify events originating from the same faults and long-term monitoring with matched filter detection can identify the early onset of fault activation, which is an essential step for developing a proactive traffic light system. Waveform cross-correlation can also identify isolated asperities that generate events with nearly identical waveforms. Application to the 2019 stimulation found several similar event clusters that correspond to different stimulation stages and repeated activation of asperities. The 2022 stimulation features over 2000 microseismic events over three stages. Applying a machine-learning- based clustering algorithm to the microseismic event catalog found several fracture planes. However, different algorithms identify different sets of fractures, likely due to uncertainties in event location. Here, we apply waveform correlation analysis to microseismic events during stage 3 of 2022 stimulation to further detect fractures via similar event clusters, and asperities with nearly identical waveforms. We will measure precise relative magnitude based on principle component analysis of aligned waveforms, which will be used for magnitude calibration. The improved magnitude will be used to characterize the seismogenic potentials of different fractures, and their relationship with injection history. Analysis of the waveforms will provide the basis for the end goal of developing a proactive traffic light system to detect the early onset of fault activation.

Bidirectional Displacement Waveforms of Hhz Induced Microearthquakes - Evidence for Volumetric Shear-Slip Distributions in Ambient Crust Hydraulic Stimulation

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We examine HHZ displacement waveforms of microearthquake (MEQ) emissions induced by fluid injection into crystalline rock at 6 km depth and recorded at 2kHz rates by seismic sensors at 2.5km depth above the stimulation volume. The HHZ displacement waveforms for magnitude $-1 < m < 1$ MEQ are bidirectional, inconsistent with the standard unidirectional fault-zone-like planar slip distributions. While the HHZ waveforms are dominated by scattering for up to four-second codas, there is little intrinsic amplitude attenuation (Q_{absorb} ~ 3000). We find that the unscattered leading 10-20ms P-wave displacement wavefields is commensurate with dislocations on ambient fractures activated by fluid injection. Our HHZ event data set includes examples that show multiplets with several or more bi-directional dislocations.

The observed HHZ bidirectional quasi-sinusoid P-wave first motion displacements can be modeled by using Haskell's elastodynamic integral over radially directed source-slip emissions including over-pressured volumetric permeability structures. Far-field MEQ HHZ bidirectional displacements waveforms arise from summing over radially expanding distributions of slip velocity. Arrivals emitted by radial slip towards sensors at slip sites nearer the sensor are followed by later-arriving reversed-sign displacements from radial slip away from sensors, as emitted by sites further from the sensors. Hypothetically, EGS stimulation of the ambient crust proceeds via high-pressure fluid breakouts causing slip dislocations that increase the pore connectivity (permeability). Our poster will discuss this connection, which is expressed by the poro-perm relation $\kappa(x,y,z) \sim \exp(\alpha\varphi(x,y,z))$, and how this relates to the relative size distribution of the observed HHZ events.

Developing a Machine Learning Model to Pick Phase Arrivals on DAS Data at the Forge Site

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The UTAH FORGE site is a field laboratory for enhanced geothermal system with comprehensive geophysical monitoring network. The downhole DAS array recorded complete full wavefield of microseismicity occurred during the 2019 and 2022 stimulation, where clear P, S and S-P converted phases can be identified. The S-P converted phase occurred at the granite contract, where the seismic velocity significantly changes. We developed an interactive tool to manually pick and interpolate phase arrivals, and then analyze the frequency content and signal-to-noise ratio of different seismic phases. The phase picks with high signal-to-noise ratio are used to train a PhaseNet machine learning model using pytorch. Preliminary analysis of the predicted phase picks shows good agreement with manual picks, however, random noise was picked at channels further away from the microseismic events. Further improvement will be made to the training model. The delay time between S-P converted phase and P-phase will be used to better constrain event depth for microseismic events with nearly repeating waveforms (multiplets or repeating events) to identify spatial distributions of asperities. The current analysis is focused on the 2019 stimulation, and the machine-learning model will be applied to the 2022 stimulation to check the accuracy of predicted phase arrivals, and investigate the applicability of locating multiplets or repeating sequences during 2022 stimulation.

Time-Lapse Changes in Velocities at Patua Geothermal Fields Using Seismic Ambient Noise

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Geothermal resources and Enhanced Geothermal Systems (EGS) have the potential to provide clean energy, and the understanding of subsurface stress and strain changes becomes crucial for EGS operations. In this study, we analyze continuous recordings from five pairs of co-located surface and shallow-borehole seismometers deployed at the Patua Geothermal Field since June 2021. Patua is a conventional (non-EGS) geothermal field; however, a near-field EGS project is planned in an idle at the southern margin of the natural geothermal reservoir. The ambient-noise data recorded by this local array is used to detect time-lapse changes of subsurface velocities using coda-wave interferometry. Time-lapse changes in velocities provide a unique view of subsurface elastic changes between each receiver pair. We will jointly interpret the obtained time-lapse changes of subsurface velocities with observations from earthquakes, surface deformation (InSAR and GPS), and numerical modeling for characterizing subsurface stress and strain.

Deciphering Earthquake Clustering for the Better Understanding of Crustal Deformation Mechanisms

Oral Session • Thursday 20 April • 02:00 PM Pacific

Conveners: Eric Beauce, Lamont-Doherty Earth Observatory, Columbia University (ebeauce@ldeo.columbia.edu); Patricia Martínez-Garzón, GFZ Potsdam (patricia@gfz-potsdam.de); Piero Poli, Università di Padova (pieropoli85@gmail.com)

Aftershock Triggering and Spatial Aftershock Zones in Fluid-Driven Settings

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Aftershock cascades play an important role in forecasting seismicity in natural and human-made situations. While their behavior including the spatial aftershock zone has been the focus of many studies in tectonic settings, this is not the case when fluid flows are involved. Using high-quality seismic catalogs, we probe aftershocks dynamics in five settings influenced by fluids: (a) induced seismicity in Oklahoma and Kansas, (b) natural swarms in California and Nevada, and (c) suspected swarms in the Yuha Desert (California). All settings exhibit significant aftershock behavior highlighting the importance of event-event triggering processes. The spatial aftershock zones scale with mainshock magnitude as expected based on the rupture length. While (a) and (b) show a rapid decay beyond their rupture length, (c) exhibits long-range behavior suggesting that fluid migration might not be the dominant mechanism. We also find that the scaling of aftershock productivity with mainshock magnitude together with the Gutenberg-Richter b-value might allow to distinguish between natural swarms and induced seismicity.

Spatio-Temporal Dynamics of Earthquake Swarms in the Yellowstone Caldera

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It is generally believed that earthquake swarms are driven by either aseismic slip or the migration of fluids through a preexisting fault network. However, the factors that control swarm evolution remain unclear. We present a new high-resolution earthquake catalog for the Yellowstone caldera, built using deep-learning algorithms. We detect about 4 times more earthquakes than the routine catalog and estimate precise relative earthquake hypocenters using cross-correlation differential time measurements. We perform cluster analysis to characterize the spatio-temporal dynamics of swarms in the region. Roughly 70% of the seismicity in our catalog occurs in a highly clustered mode, where punctuated episodes of hypocenter expansion and migration characterize most clusters. We perform a systematic statistical analysis to characterize swarm duration and spatial migration patterns. Our results suggest that swarms tend to migrate laterally, vertical migration is also observed, but less common.

Ubiquitous Earthquake Dynamic Triggering in Southern California

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Earthquakes can be dynamically triggered by the passing waves of events from distant faults. Observations of frequent dynamic triggering offers tangible hope in revealing earthquake nucleation processes. However, the physical mechanisms behind earthquake dynamic triggering remain unclear and contributions of competing hypotheses are challenging to isolate with individual case studies. Therefore, developing a systematic understanding of the spatio-temporal patterns of dynamic triggering can provide fundamental insights into the physical mechanisms, which may aid mitigation of earthquake hazards. Here we investigate earthquake dynamic triggering in Southern California from 2008 to 2017 using the Quake Template Matching catalog and an approach free from assumptions about the earthquake occurrence distribution. We develop a new set of statistics to examine the significance of seismicity rate changes as well as moment release changes. We show that up to 70% of global M≥6 events may have triggered earthquakes in Southern California and that the triggered seismicity often occurred several hours after the passing seismic waves. This triggering rate means that earthquakes are triggered about every 4 days in the region, albeit at different locations. Although adjacent fault segments can be triggered by the same earthquakes, the majority of triggered earthquakes seem to be uncorrelated, suggesting that the process is primarily governed by local faulting conditions. Further, the occurrence of dynamic triggering does not seem to correlate with ground motion (e.g. peak ground velocity) at the triggered sites. These observations indicate that nonlinear processes may have primarily regulated the dynamic triggering cases. We investigate one such process, material fatigue, using the duration of elevated strain recorded by strainmeters in southern California. In contrast to peak ground motion values, strain energy dissipation is a relatively strong diagnostic of triggering conditions.

Quantifying Space-time Earthquake Clustering on a Given Fault Network

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Earthquake clustering is a fundamental component of seismicity that reflects various forms of earthquake triggering mechanisms. Zaliapin and Ben-Zion (SRL, 2021) introduced a simple and robust measure of space-time clustering, using the receiver operating characteristic (ROC) diagram, that allows disentangling effects related to concentration of events around a heterogeneous regional fault network (marginal space distribution of events) from coupled space-time fluctuations (joint space-time distribution). Their analysis has shown that the overall observed earthquake clustering is high, with the marginal space clustering playing a dominant role in the catalog clustering for a variety of regional catalogs and the global seismicity. At the same time, when one removes the marginal clustering and focuses on the coupled space-time clustering, different catalogs show different degrees of clustering, reflecting a variety of specific triggering conditions and mechanisms. Here we discuss what degree of clustering one should expect in a spatially inhomogeneous non-stationary process, assuming that its time and space components are independent, and how to assess observed deviations from this null hypothesis. We apply the discussed approach to examine the raw and background seismicity in various seismically active regions. We discuss robustness of the results with respect to the lower magnitude cutoff and spatio-temporal resolutions of analysis, and relative importance of the marginal space clustering vs. coupled space-time clustering in different environments. Reference: Zaliapin, I. and Y. Ben-Zion (2021) Perspectives on clustering and declustering of earthquakes. Seismological Research Letters, 93 (1): 386–401 doi:10.1785/0220210127

Anatomy of a Fault Zone: Space-Time-Magnitude Patterns of Microseismicity in the San Jacinto Fault Zone, Southern California

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We present key space-time-magnitude patterns of microseismicity observed in an updated catalog for the San Jacinto Fault Zone (SJFZ)—the most seismically active region in Southern California—during the period 2008-2022. We deploy an automated procedure to process raw waveform data from five seismic networks and capture a more complete representation of the space-time-magnitude distribution of events in the SJFZ than the standard catalog for the region. Seismicity patterns in our new catalog delineate the geometry of the locked region of the fault and the brittle-to-ductile transition zone (BDTZ)—features bearing important implications on the maximum potential magnitude of future ruptures in the area. Spatiotemporally diffuse seismicity characterizes semi-brittle deformation in the BDTZ, in contradistinction to the tightly clustered nature of seismicity in the overlying brittle crust. We observe transient clustering of seismicity in the BDTZ following some, but not all, moderate-sized events (M>4.5) in the region. Our high-definition catalog also helps constrain complex internal geometry of fault zone structures such as (1) anastamosing braids of deep seismicity in the Hot Springs Area; (2) conjugate networks of shallow fractures flanking the core fault zone; (3) the extent of the Anza Seismic Gap; and (4) branching structures in the Trifurcation Region. We will present an overview of these features and plans to further improve the SJFZ catalog using new tools.

Structural Control on the Distribution of Earthquake Clusters Along the Northern Ecuadorian Margin

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High resolution studies reveal the complexity and diversity of structure and physical properties in subduction zones. Studies to date, particularly after the 2016 Mw 7.8 Pedernales megathrust rupture, indicate earthquake clustering and slip behaviors that host frequent seismic swarms and repeating earthquakes along the Ecuador subduction margin. Structure in the subducting and upper plate and frequent aseismic release of accumulated stress seem to play an important role in megathrust rupture. The HIPER Project (High Resolution Imaging of the Pedernales Earthquake Rupture Zone) is a large multidisciplinary international collaboration to image the plate interface in the megathrust region. As part of the Project, temporary deployments recorded passive and active sources over two years to study lateral heterogeneity downdip and along strike in the forearc. The passive recordings included the deployment of 59 broadband stations across the forearc from the coast to the foothills of the Andes. Two linear arrays of nodes spaced about 1 km apart during 1-month: 158 nodes along strike near the coast crossing the Punta Galera, Cojimíes-Atacames and Jama earthquake clusters and 141 nodes along a dip direction across the forearc above the subducting Carnegie Ridge. In 2022, active sources from a dense 2-D grid of marine airgun were recorded by 483 nodes deployed near the coast. This provides an exceptional opportunity for onshore/offshore multiscale 3D imaging of the northern Ecuador. Here we focus on the margin from Punta Galera to Jama. Using the dense deployments, we present the spatio-temporal distribution of seismicity during this period in context of long-term observations. The ultimate goal of these deployments is to obtain precise locations of seismic sources along the northern margin of the subduction zone to better characterize deformation and its potential connection to rheology and structures that appear in part to control megathrust rupture and earthquake clusters.

Linking Fault Roughness at Seismogenic Depths to Earthquake Behavior

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Fault geometry affects the initiation, propagation, and cessation of earthquake rupture, as well as, potentially, the statistical behavior of earthquake sequences. We analyze 18,250 earthquakes comprising the 2016-2019 Cahuilla, California swarm and, for the first time, use high-resolution earthquake locations to map, in detail, the roughness across an active fault surface at depth. We find that the fault is 50% rougher in the slip-perpendicular direction than parallel to slip. Roughness estimates are spatially variable, and fluctuate by a factor of 8 over length scales of 1 km. We observe that the largest earthquake (M4.4) occurs where there is significant fault complexity and the highest measured roughness. We also find that b-values are weakly positively correlated with fault roughness. Following the largest earthquake, we observe a distinct population of earthquakes with comparatively low b-values occurring in an area of high roughness values within the rupture area of the M4.4 earthquake. Finally, we measure roughness at multiple scales and find that the fault is self-affine with a Hurst exponent of 0.52, consistent with a Brownian surface.

Micro-Seismicity Clustering, Aftershock Decay and b-Values During Laboratory Fracture and Stick-Slip Experiments

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Earthquakes rarely occur in isolation but rather as sequences of events, clustered in space and time. We study seismic event clustering in controlled laboratory experiments where fault zone properties and stress can directly be monitored. We employ recently-developed statistical methods (e.g., nearest-neighbor clustering, R-statistic, Bi-statistic) to resolve seismic event interactions in series of experiments on in-tact and faulted Westerly granite samples. The samples exhibit different heterogeneity and roughness which strongly impact seismicity clustering.

Our result show that heterogeneity in intact-samples promotes spatial clustering of seismic events albeit without temporal (Omori-type) correlations. Aftershock-like clustering is absent even during fracture nucleation and propagation close to peak stress. Aftershock-like triggering occurs during stable sliding on freshly formed fractures and in the presence of large-scale stress heterogeneity. The detected aftershocks in these cases can be described by standard seismological relationships such as a modified Omori-Utsu relation and its associated inter-event time distribution and productivity relation. Similarly, stick-slip on rough faults is associated with notable spatial-temporal seismicity clustering and Omori-decay mirroring natural seismicity statistics. Homogenous, planar surfaces, on the other hand, produce few aftershocks after unstable slip. Fault roughness also governs *b*-values and focal mechanisms variability. Rough faults lead to more heterogeneous focal mechanisms, spatially distributed seismicity and high *b*-values. The variability in focal mechanisms can be explained by heterogeneous, underlying stress fields which limit rupture size and promote high energy release within aftershock sequences. We conclude that roughness and heterogeneity strongly affect events sizes, clustering and seismic energy partitioning between fore, main and aftershocks.

Why Do We Need New Models of Earthquake Occurrence?

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While modelling the coseismic phase is relatively simple, a comprehensive, effective theory of seismic occurrence is difficult because of strongly nonlinear long-range interactions taking place in the brittle crust, so that fault systems cannot be reduced to simple non-interacting «planes of slip». Moreover, earthquake dynamics not only depends on the rheological properties of rocks, but also on their structural complexity and on intricate stress patterns inside the crustal volumes. Therefore, seismicity showcases different behaviours depending on the spatial and temporal scales of investigation because each level of complexity of the seismogenic source is associated with emergent properties that cannot be derived from the elementary laws ruling the system at a fundamental level. So, we need to set up new models able to reproduce well-known results and having predictive power. Here, we introduce a simple toy model to embrace some crucial features of seismicity at both coseismic and seismic-sequence scales. The key paradigm of our model is that seismicity is driven by the optimization of energy needed to mobilize crustal volumes given some mechanical constraints (i.e., strain rate and physical properties of rocks). Our model can reproduce several properties of seismicity such as the dependence of b-value of the Gutenberg-Richter law on the tectonic setting, spatial and temporal clustering of large and small events and the statistical differences between in-fault and off-fault seismicity, being the first featured by lower b-value, fractal dimension of spatial time series and higher seismogenic potential. Differences between tectonic settings are described using the same framework. Our approach can provide information about the long-term seismic behaviour of fault systems, which may be of interest in regions equipped with recently developed seismic networks and where paleo-recordings are poorly constrained.

Seismic Magnitude Clustering Is Prevalent in Field and Laboratory Catalogs but Absent in Synthetic Catalogs

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Clustering of earthquake magnitudes is still actively debated, compared to well-established spatial and temporal clustering. Magnitude clustering is not currently implemented in earthquake forecasting but would be important if larger magnitude events are more likely to be followed by similar sized events. Investigating many laboratory and field catalogs, we observed magnitude clustering at a wide range of spatial scales (mm to 1000 km). Filters based on magnitude of completeness and interevent times were applied to address previous study concerns of network detection limitations and short-term aftershock incompleteness. This phenomenon was still observed after various filters were applied, demonstrating that magnitude clustering is not an artifact but a widespread phenomenon. Field results demonstrate it is universal across fault types and tectonic/induced settings, while laboratory results are unaffected by loading protocol or rock types and show temporal stability. The absence of clustering can be imposed by a global tensile stress environment in the lab, although clustering still occurs when isolating to triggered event pairs or spatial patches where shear stress dominates. Restricting the analysis to triggering-triggered pairs creates the most significant magnitude clustering patterns, far exceeding that of solely spatial or temporal clustered events. Both the lab and field analyses found magnitude clustering is more prominent at short time and distance scales, and we seek to characterize the decay in clustering over time and distance to help provide clues about the governing physical process. Synthetic catalog modeling using both ETAS and Gutenberg-Richter probability density methods indicates >20% repeating magnitudes would be necessary to explain some cases, implying it can help to narrow physical mechanisms for seismogenesis.

Deciphering Earthquake Clustering for the Better Understanding of Crustal Deformation Mechanisms [Poster]

Poster Session • Thursday 20 April

Conveners: Eric Beauce, Lamont-Doherty Earth Observatory, Columbia University (ebeauce@ldeo.columbia.edu); Patricia Martínez-Garzón, GFZ Potsdam (patricia@gfz-potsdam.de); Piero Poli, Università di Padova (pieropoli85@gmail.com)

Automated Detection and Characterization of Swarms and Mainshock-Aftershock in Southern Mexico

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The Mexican subduction zone is considered a natural laboratory for studying slip processes due to the relatively short trench-to-coast distance which brings broad portions of the seismogenic and transition zones inland. Fasola et al. (2019) found that SSEs also occur correlated with swarms on a crustal sliver fault that accommodates partitioning of oblique convergence into dip-slip and strike-slip. Hence, this region provides an opportunity to pursue detailed characterizations of potential relationships between seismicity and aseismic slip on a complex plate boundary system. Considering that previous detection of swarms was focused on 2012 and earlier, we use an automated detection algorithm to characterize sequences in the catalog from 2006 to 2022. The algorithm identifies clusters of events using the nearest neighbor distances in the space-time-energy domain (Zaliapin and Ben-Zion, 2013). The algorithm then characterizes sequences on a spectrum from swarms to traditional mainshock-aftershocks using quantitative forms of these characteristics: (1) the magnitude difference between the largest event and the next largest events, (2) the percentage of the sequence after the largest event, (3) the slope of seismicity rate over time, and (4) the magnitude range divided by the number of events in the sequence. The algorithm has been fine-tuned via comparison to manual inspection and discernment based on prior work (Ventura-Valentin and Brudzinski, 2021). Given the larger number of sequences detected and categorized via automated processing, we will describe the statistically significant spatial, temporal, and magnitude-frequency patterns associated with these swarms and aftershock sequences. For example, we find that the majority of newly detected swarms cluster along the trace of the sliver fault.

Closing the Gap Between Local and Regional Observations of Segmented Ocean Plate Boundaries With a New 25-Year Earthquake Catalog of the European Arctic Seas

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Oceanic ridges and transform faults comprise nearly 45% of the Earth's plate boundaries. Even though they have lower seismic moment release rates than convergent plate boundaries, these intricately segmented oceanic plate boundaries host a large part of Earth's seismicity. Analyzing how their segmentation is expressed through their seismic behavior has not been commonly possible due to limited observations compared to plate boundaries on land. Even with ocean bottom deployments, a challenge is that there is often no overlap between event catalogs produced routinely from regional networks (typically with M>3.5) or from short local deployments (M<3). To close this gap, we apply a sensitive earthquake detection pipeline to complement a regional catalog over 25 years through template matching. We focus on the 3000 km of oceanic plate boundaries and adjacent areas in the European Arctic (68° - 87°N, 20°W - 40°E). For our initial catalog of 35000 earthquakes, we merge data from local to global observations and consolidate phase picks, hypocenters, and probabilistic location errors with BayesLoc. The waveforms of a well-observed subset with 15500 events form the templates that we correlate against continuous seismograms recorded at up to 300 stations (incl. 8 arrays). We use optimized versions of the software packages RobustRAQN (preparation and quality control), EQcorrscan (template matching) and fmf2 (GPU vendor-agnostic correlation) on a GPU-powered cluster. We set strict thresholds for robust event detections based on correlations and picks at >6 sites and in 3 independent time windows. From >200M initial detections, we filtered out, picked, and relocated >400K earthquakes, revealing oceanic seismicity at an unprecedented scale (25 yrs, Mc<2.5, relative error <2 km). A preliminary analysis shows that earthquake swarms, aftershock sequences, and persistent sites of seismic activity (including repeaters) characterize a complex segmentation of the plate boundary. We relate the activity to the boundary's tectono-magmatic character which includes (ultra-)slow spreading ridges, volcanic centers, and transform segments.

From Foreshock Outset to Aftershock Decay: High-resolution Analysis of a Recent Earthquake Sequence in the Ecuadorian Subduction Margin

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It is quite rare for an earthquake sequence to be recorded at high resolution from its early preparatory phase throughout mainshock and aftershock decay. This is even more unusual for less explored subduction zones such as the Ecuadorian margin. Producing such detailed studies could lead to a better understanding of the physical mechanism behind rupture initiation and earthquake triggering in active margins.On 27 March 2022, a Mw 5.8 earthquake occurred on the northern coast of Ecuador, near the town of Esmeraldas. Here we take advantage of a dense temporary seismic network in place at the time as part of an active seismic experiment (HIPER marine campaign, PIs A. Galve, A. Rietbrock), in order to detect and locate the whole of the local seismic sequence at high resolution. The continuous recordings of 100 short period seismometers are processed with a state of the art earthquake detection/location pipeline based on recently developed artificial intelligence methods. We also accurately relocate the whole sequence using a recently published local velocity model and relative relocation based on cross-correlation phase arrivals.The results show more than 900 events within the first three days following the mainshock. The sequence starts with three small-magnitude (M<2) foreshocks 40 to 2 minutes before the mainshock, all of them within 1 km from the mainshock epicenter. The ensuing seismicity spreads over 10 km along the subduction interface, nicely delineating the SE-dipping megathrust. Early aftershocks (first 12 hours) nucleate near the mainshock hypocenter and down-dip of it, while later aftershocks nucleate mostly up-dip of the mainshock. Aftershock productivity quickly decreases during the first 16 hours following the mainshock, after which the seismicity rate sharply increases again due to the occurrence of the largest aftershock (Mw 5.2). Our study provides a unique opportunity to study in detail the spatio-temporal relationship among seismic events throughout all different stages of an earthquake sequence at an unprecedented scale for this region of the world.

Intermittence of Transient Slow Slip in the Mexican Subduction Zone, as Seen by Tectonic Tremors

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The Mexican subduction zone hosts a variety of slow slip events, both in the states of Guerrero and Oaxaca, favored by the flat geometry of the plate interface. Previous studies using GNSS data revealed Mw 7-7.5 Long-term Transient (LT) accompanied by a microseismic activity of Tectonic Tremors (TT) and/or Low Frequency Earthquakes (LFEs), highly clustered in time. Short-term Transients (ST) of smaller amplitude were also identified in Guerrero between 2005 and 2007 using approaches combining GNSS data and LFEs catalogs.

In this study, we used the TT catalog published by Husker et al. [2019] to investigate, over a 10-year time period, how TT activity can help to characterize the dynamic of transient events over shorter time scales than accessible with GNSS data only. We analyzed separately the periods corresponding to LTs, and periods inter-LTs during which Short-Transients (ST) can be detected.

From the TT catalog (covering 2009-2019), we extracted TT bursts (events clustered in time). We decomposed the GNSS time series using the timing of TT bursts, providing for each GNSS time series a surface velocity during and in-between TT bursts. These velocities are then inverted to locate the associated source on the plate interface.

Our decomposition results during LTs reveal that, 80% of the surface motion during LTs is occurring during TT times, which represent only 30% of the LTs duration. These results highlight the intermittence of slip during long-transients, as most of the slip occurs during TT activity.

The decomposition during inter-LTs periods unveiled the occurrence of 29 STs in the Guerrero area, with a source at the location of previously identified STs. In Oaxaca, our result reveals for the first time the occurrence of 18, with a source located in the tremor zone. Our joint analysis of TT and GNSS data reveals that STs of small amplitudes occur regularly in Guerrero and Oaxaca. Consequently, short-term plate coupling is higher than previously estimated.

Intraplate Omori Decay Parameters and Spatiotemporal Distribution 145 Recent Central and Eastern North American Sequences

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Aftershock clusters are transient so must be identified and culled—”declustered”—from earthquake catalogs to calculate the long-term earthquake rates that are used to map seismic hazard in intraplate areas such as central and eastern North America (CENA). Despite this importance and the known differences between aftershock behavior in low strain-rate settings like CENA and tectonically active regions, estimates of aftershock sequence duration and the epicentral radius affected are based on California-type plate-boundary sequences. Here, Omori parameters for 145 intraplate CENA earthquake sequences (1974–2021, mainshocks M_w3.65–5.84) demonstrate significantly slower aftershock rate-decay than existing plate-boundary models, with major regional variations. The slope of log-rate vs time—Omori’s parameter *p*—averages 0.86±0.03 in the central/eastern U.S. sequences and 0.87±0.02 in the Charlevoix Seismic Zone, yet the rest of southeastern Canada averages *p*=1.02±0.05 similar to generic California behavior (*p*=1.07±0.03). Post-mainshock earthquake rates are only significantly elevated within ~15 km of the CENA mainshocks (up to 25 km for M5+ mainshocks) and remain so for $10^{3\pm1}$ days—months to a decade or two. While California declustering models may clip events within 0.15 years and 30 km of a M4 mainshock (0.3 years, 40 km for M5), windows of 4 year and 15 km (8 years, 20 km for M5) appear more appropriate for CENA. Using these longer-duration yet smaller aftershock windows would reduce hazard bulls-eyes adjacent to historical earthquakes.

Temporal Clustering of Earthquakes in the Canadian Arctic on a Regional Scale

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There has long been a perception that Arctic Canada experiences periods of enhanced seismicity on a regional scale. Following the 2017 M_W 5.9 Barrow Strait earthquake, which preceded a period of apparent enhanced activity, a preliminary attempt was made to determine whether there was any statistical significance to back up these observations (Bent et al., 2018, SRL). This earlier analysis, covering a time period of twenty-five years, found evidence for statistical significance. The current study expands on that work using a sixty year earthquake catalog extending back to the mid-1960s when a national seismograph network was established in Canada. Prior to that, the catalog for the Arctic region is not complete enough for reliable statistics. The raw data show several periods where the occurrence of moderately large earthquakes is significant at the 2-3 sigma level. Whether earthquake catalogs should be declustered for seismic hazard assessment is a subject of debate but declustering is useful in separating events for which there is a known or at least strongly suspected causal relation, such as aftershocks and swarms, from those with no expected relation. When declustering is undertaken, the statistical evidence for enhanced seismicity remains. Although a viable physical mechanism to explain the regional clustering has yet to be established, several possibilities can be ruled out. The earthquakes analyzed are all below M_W 6.0 and separated by 100s of km, suggesting that stress transfer on nearby faults is not the cause. Dynamic triggering from distant earthquakes can also be eliminated. Incidentally, dynamic triggering is also ruled out as the generating mechanism for swarms, whose cause has also not been established. There is no evidence for an overall increase in seismic activity in the Canadian north. The periods of increased activity tend to be short, 1 to 2 years in duration, after which the seismicity returns to its background level.

Variation of Fault Creep Along the Overdue Istanbul-Marmara Seismic Gap in NW Turkey

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Strain energy from tectonic loading can be partly released through aseismic creep. Earthquake repeaters, repeatedly activated brittle fault patches surrounded by creep, indicate steady-state creep that affects the amount of seismic energy available for the next large earthquake along a plate contact. The offshore Main Marmara Fault (MMF) of the North Anatolian Fault Zone represents a seismic gap capable of generating a M>7 earthquake in direct vicinity to the mega-city Istanbul. Based on a newly compiled seismicity catalog, we

identify repeating earthquakes to resolve the spatial creep variability along the MMF during a 15-year period. We observe a maximum of seismic repeaters indicating creep along the central and western MMF segments tapering off towards the locked onshore Ganos fault in the West, and the locked offshore Princes Islands segment immediately south of Istanbul in the East. This indicates a high degree of spatial creep variability along the Istanbul-Marmara seismic gap.

Detecting, Locating, Characterizing and Monitoring Non-earthquake Seismoacoustic Sources

Oral Session • Wednesday 19 April • 08:00 AM Pacific
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Using Seismic Methods to Monitor Bedload Transport Along a Desert Environment Ephemeral Tributary

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Use of seismic monitoring and data analysis techniques in recent years have allowed for improved understanding of several shallow earth processes, such as glacial motion, subsurface water flow, and bedload transport. Early applications using seismic data collected at high energy alpine rivers suggest that seismic energy within certain frequency bands is linked to bedload discharge. However, study of other river systems have been more limited, even though some of these systems, such as ephemeral streams in arid environments, transport large quantities of sediment during short-lived flash flood events. Here we present seismic and hydrologic data collected in a unique sediment observatory within an ephemeral tributary to the Rio Grande River, in the desert southwest of the U.S., combining dense seismic observations with a variety of in-channel bedload and water monitoring measurements. We have seismic records for more than a dozen floods ranging in depth from a few centimeters to over one meter, encompassing bedload flux as high as 12 kg s^{-1} m^{-1}, two orders of magnitude higher than in most perennial settings. Our efforts to date focus on identifying the noise sources within the seismic record, characterization of the seismic properties of the site, and determining the seismic frequency ranges best correlated with the automatically measured bedload flux. Within the 30-80 Hz frequency range, we find a linear relationship between seismic power and bedload flux. We hypothesize that variations in linear fit statistics between flood events are due to varying bedload grain size distributions and in-channel morphological changes.

Generating Green's Functions for Use in Seismic Monitoring of Debris Flows Using the Ambient Seismic Field

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Efforts to utilize seismic monitoring networks to study mass flows that generate seismoacoustic waves, such as debris flows, face challenges such as poorly known near-surface velocity structures, complicating efforts to separate path and site effects from the waves produced by mass flows. Ambient noise cross-correlation techniques have been successfully used to determine empirical surface-wave Green's functions and resolve velocity structures for remote regions that experience earthquakes. In this study, we use the same approach to retrieve Green's functions for the purpose of seismic monitoring of debris flows. We installed three-component nodal seismometers for month-long deployments in the summers of 2020-2022 along part of the Tahoma Creek drainage on the southwest side of Mt. Rainier, USA. We used ambient noise cross-correlation techniques to create impulse response functions between the nodal seismometers. While no debris flows occurred during 2020-2022 in the drainage, our impulse response functions may help interpret seismic waves from future debris flows. Additionally, we generated impulse response functions with a force hammer for a roughly 90 m section of the drainage to compare an alternative technique for creating impulse response functions. Our results show that the force hammer generated seismic waves with relatively high-frequency content compared to the ambient noise cross-correlations, with energy concentrated between 20-60 Hz and 5-50 Hz, respectively. We filtered the impulse response functions from both techniques between 25-50 Hz and found that the surface waves have similar arrival times and structure. However, the amplitudes for the waveforms were significantly different. As relative amplitudes for impulse response functions are not preserved during the ambient noise cross-correlation, we are exploring techniques such as modeling surface wave amplitudes and mathematically computing Green's functions to constrain the amplitudes.

Incorporating Numerical Landslide Models Into Broadband Synthetic Seismogram Simulations of Large, Rapid Landslides

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The ability to generate broadband synthetic seismograms of large, rapid landslides would be useful for forensic analysis of real events, and to generate test data of landslide scenarios for detection and early warning systems. Depth-averaged numerical landslide models are increasingly being used to model and try to match observed seismic data, but only for the simplest, lowest frequency (less than ~0.1 Hz) part of the spectrum. Depth-averaged models do not explicitly model the higher-frequency source processes (e.g., individual impacts), yet most of the energy in a landslide seismic signal is at higher frequencies. In this study, we establish a quantitative way to empirically model the higher frequency energy by examining the relationship between radiated higher frequency seismic energy from real landslides, and flow parameters from numerical landslide models. We do this using two depth-averaged numerical landslide models: SHALTOP, unique in explicitly outputting the entire basal traction field, and D-Claw, which can model two-phase flows (water and solids). We calibrate the models to the runout and the force-time history derived from long-period seismograms of well-characterized landslides from the Exotic Seismic Event Catalog (ESEC), focusing primarily on the 2019 11 million m^3 Iliamna, AK ice and rock avalanche, and the 2009 48.5 million m^3 Mount Meager, BC landslide. Once we establish a good model fit, we examine the relationship between the observed intermediate and high frequency (> 0.1 Hz) wavefield and spatiotemporally varying bulk flow characteristics that each model can produce (e.g., the distribution of basal tractions, frictional work rate, momentum, and inertial number). We then examine these findings in context of a greater set of empirical data of large, rapid landslides from the ESEC to propose a general approach for relating the higher frequency part of the spectrum to bulk landslide dynamics and characteristics.

Classifying Landslide Seismic Signals With Unsupervised Machine Learning From Multiple Locations

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Creating a reliable landslide early warning system is one of the main goals of landslide scientists. Seismometers are used to monitor landslides since they have high temporal resolution and an exceptional ability to record subtle vibrations from internal cracks caused by landslide movements. Because landslides are complex, it should be monitored at multiple locations. When this data is available, it is often impossible to understand every signal recorded. Recent advances on unsupervised machine learning mainly classify the time periods of continuous seismic signals of a single station but when multiple stations have different classifications at the same time, it can be challenging to interpret the overall behavior of an area since it is preferable to be consistent between stations. For slow-moving large-scale landslides, this is particularly true because different blocks of the landslide could behave distinctly. For this reason, we combine signals from seismometers of an array to build a spatial feature for classification, as a network response rather than a single-station response. We used an unsupervised machine learning method called K-means to do the classification and cross-validate our results. We used collocated GPS stations to study classes of seismic signals related to landslide movement and investigated the cause of movement from external forces. Finally, we compared our results to the common single-station classification approach. Our results reveal classes of seismic signals related to landslide movement and rainfall, where we can identify first-order spatiotemporal characteristics. We believe our approach has the potential to issue landslide alerts based on multiple stations in a landslide region.

Rapid Seismic Assessment of Potentially Tsunamigenic Landslides

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As the climate warms and glaciers retreat, the flanks of glacial valleys lose their support. These unsupported slopes increase the chance of failure, creating new landslide hazards and, in some cases, the potential to initiate catastrophic local tsunamis. This hazard is an emerging concern in much of coastal Alaska, a region dominated by a steep, glaciated mountain range landscape. Little is known about the potential for future hazards from these events, threatening human life in nearby communities. Currently, no systems are in place to detect, locate, and assess the size of landslides sufficiently quickly to inform potential tsunami warnings.We examine a selection of landslides across coastal Alaska over the past decade using the existing seismic network to demonstrate the potential for rapidly determining a landslide's tsunamigenic potential. We exploit the long-period waveform similarity observed in these events and develop an approach to assess landslides rapidly. Our strategy demonstrates the ability to detect and locate landslides with volumes as low as ~100,000 m3 using data recorded within one minute of occurrence. In the presence of good seismic network coverage, location errors are no more than a couple of kilometers. We also develop a simple amplitude relationship to approximate a slide's volume within an order of magnitude. This rapid landslide assessment approach provides a foundation for eventual coastal landslide monitoring systems on a real-time basis.

Landslide Monitoring with a Local Infrasound Array in Barry Arm, Alaska

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Large surficial mass movements generate energetic, low-frequency sound waves in the atmosphere, or infrasound, that can propagate and be detected tens to hundreds of kilometers from source areas. The recent proliferation of infrasound sensors in regional networks provides event databases with a growing variety of sources and drives improvements in signal detection and classification algorithms. Yet challenges remain in automated, real-time detection and characterization of infrasound from small to moderate mass movements due to the often emergent, low-amplitude signals from these events.

Here we present results from the first 5 months of local infrasound data from a 6-element array installed in summer 2022 just 2 kilometers from a recently identified, large (500 M m3) landslide in Barry Arm, Prince William Sound, Alaska. The array recorded signals from a wide variety of sources in the acoustically rich environment such as rockfalls, calving signals from multiple local glaciers, and snow avalanches. We process the array data in real-time using a least-squares beamforming algorithm to distinguish coherent signals from noise and to constrain source back-azimuths. Investigation of infrasound detections in 2022 indicate an increase in small mass movements from a portion of the landslide during September and October, coincident with heavy rains and high rates of landslide motion detected by terrestrial synthetic aperture radar. We investigate individual events from the dominant infrasound sources (landslide, glacier calving, snow avalanches) that were also captured in radar data and imagery to better understand how they generate infrasound. Identification of signal characteristics unique to the various infrasound sources active in Barry Arm is a necessary next step toward an automated detection and classification workflow to better monitor this potentially hazardous landslide. While the current focus is on Barry Arm, the techniques and lessons learned here should be applicable to other locations and will also provide insights into how best to monitor similar mass movement processes at regional scales.

The Land, Air, and Water Signature of Large Calving Events at Barry Glacier, Alaska

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Large glacier calving events share many geophysical properties in common with landslides. Both exhibit emergent waveforms with durations of several tens of seconds. Both produce energy across a wide range of frequencies (<0.01 to >10 Hz). Both can be observed across regional seismic networks. And in areas such as coastal Alaska, landslides and glacier calving happen in the same places. Landslides are a rare occurrence, while glaciers calve all the time. These high rates of calving significantly complicate efforts to monitor landslides.

We attack this problem, in part, by characterizing the full variation in calving events at Barry Glacier, Alaska. We examine several hundred large calving events observed in seismic, infrasound, and tide gauge data. Seismic stations close to the fiord show a long period (~0.01 Hz) seismic and/or tilt response lasting tens of minutes after calving has ceased. This signal closely tracks the wave heights observed on tide gauges and reflects the oscillation of water waves (i.e., seiche) within the fiord. We assume that the amplitude of the water waves scale with the volume of subaerial ice released in calving events. By contrast, we examine the seismic energy of the actual calving process and find little relationship to the size of the water waves. Local infrasound array data produce highly reliable backazimuths that point to the glacier terminus. Like the seismic data, the infrasound energy shows no meaningful relationship to the ensuing water waves. The water waves can be observed on tide gauges at distances of 8 to 16 km. These travel at speeds of 10-20 meters per second and exhibit significant dispersion and reverberation. The water waves travel about 4% faster during periods of high tide than low tide. Together these observations help characterize the signature of large calving events on land, in the air, and in the water and demonstrate multiple ways to distinguish them from similarly sized landslides.

An Unsupervised Machine-Learning Approach to Understanding Seismicity at an Alpine Glacier

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It is critical to understand the dynamic conditions of Earth's cryosphere, yet the subglacial and englacial environments that control many aspects of ice behavior are inherently difficult to observe. The study of seismicity in glaciers and ice sheets has provided valuable insights about the cryosphere for decades, more recently aided by tools from machine learning. Here, we present an unsupervised machine-learning approach to discovering and interpreting cryoseismic patterns using 5 weeks of seismic data recorded at Gornergletscher, Switzerland. Our algorithm utilizes non-negative matrix factorization and hidden Markov modeling to reduce spectrograms into characteristic, low-dimensional "fingerprints," which we reduce further using principal component analysis, then cluster with k-means clustering. We investigate the timing, locations, and statistical properties of the clusters in relation to temperature, GPS and lake-level measurements, and find that signals associated with lake flooding tend to occupy one cluster, whereas signals associated with afternoon and evening melt-water flow reside in others. We suggest that the one cluster contains signals that include the true initiation of the flood's englacial and subglacial drainage components. This work demonstrates an unsupervised machine-learning approach to exploring both continuous and event-based glacial seismic data.

Using Seismoacoustic Modeling to Infer Source Parameters of the 2020 Beirut Explosion

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The 2020 accidental explosion of the Port of Beirut provides a study case for regional propagation of the seismoacoustic wavefield, which is particularly relevant in a monitoring context. Additionally, the presence of the Mt. Meron infrasound array and the MMA0B seismic station, collocated about 100 km south from the event gives a full seismoacoustic observation of the event at regional scale.

It is well-known that there is a strong coupling between seismic and acoustic wavefields for near surface events, and both signals associated with the Beirut explosion are recorded above the background noise. The infrasound signal shows a high SNR tropospheric arrival, despite the station being in the conventional shadow zone for infrasound, due to penetrating diffracted/creeping waves, and the vertical and radial seismic components presents a well-developed crustal Rayleigh wave (Rg).

We infer the source characteristics by means of a waveform-based inversion procedure, which rely on the computation of full seismoacoustic Green's functions up to 1 Hz, using a 3-D spectral element method solver. It allows to take into account effects of a fine topography (90 m), 3-D elastic properties in the ground and to study the effects of variations in wind and sound speed in the atmosphere from various weather models.

We discuss the simulation results according to seismoacoustic coupling phenomenology, interaction of weather models and topography, and the inverted source properties through explosion yield estimation.

Single-Channel Infrasound Detection Using Machine Learning

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Infrasound, low frequency sound less than 20 Hz, is generated by both natural and anthropogenic sources. A source exerts a force on the atmosphere, generating infrasonic waves. These waves have the potential to travel thousands of kilometers due to their low frequency nature, making infrasound particularly useful for explosion monitoring. Regional and global networks of infrasound arrays are sparse, but many single-sensor infrasound stations exist. However, current processing methods rely on the presence of an infrasound array for signal detection and event association, location, and characterization efforts. Here we present a method using machine learning to detect infrasound arrivals at single-channel infrasound stations. We show that single-channel infrasound detection is possible and reliable as well as discuss efforts by the University of Utah to create a standardized and automated infrasound event catalog. This event catalog will be used as ground truth to verify single-channel infrasound detections, serving as a test for model generalization.

This research was funded by the National Nuclear Security Administration, Defense Nuclear Nonproliferation Research and Development (NNSA DNN R&D). The authors acknowledge important interdisciplinary collaboration with scientists and engineers from LANL, LLNL, MSTS, PNNL, and SNL. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Infrasonic Noise From Lava Eruptions at Nyiragongo Volcano, D.R. Congo

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During eruptions, volcanoes produce air-pressure waves inaudible for the human ear called infrasound, which are very helpful for detecting early signs of magma at the surface. Compared to violent ash-rich explosions, recording more discreet atmospheric disturbances from effusive eruptions remains a practical challenge. Wind and human activity are other powerful sources of unwanted infrasound noise masking volcanic ones. At Nyiragongo volcano (D.R. Congo), close to a one-million urban area, the drainage of the world's largest lava lake concomitant with short-duration lava flows on its flank and the renewal of an effusive eruption within its crater a few months later were a series of major volcanic events in 2021, all monitored with infrasound sensors. First, we explore these records for characterizing the temporal and spatial evolution of the flank eruption on May 22, 2021. In a second step, we show evidence of the infrasonic rumbling of a nascent lava lake starting a few months later detected up to the volcano observatory facilities in Goma city center about 17 km from Nyiragongo's crater. These results show remarkable local recordings of eruptive infrasound from rural and city-based stations and have significant implication for optimizing future monitoring efforts in a harsh field environment.

End-to-End Numerical Simulation of a Bolide's Reentry, Impact, Cratering, Fireball and Cloud Generation: Local and Global Consequences

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Simulations of a 1 to 2 km bolide striking Earth on solid ground and on ocean waters have been conducted. Models include hydrostatic equilibrium profiles of temperature, pressure, and densities for atmosphere and ocean, in order to accurately predict impact consequences. Phase changes, such as melting and vaporization, combined with the material's tensile, shear, and compressive strength responses, under high temperature and high strain conditions, along with anisotropic responses, are considered in greater detail than previous work. Our simulations illustrate the erosion of the bolide and the creation of a dusty tail, the breakup of the bolide into fragments, the erosion of some of the fragments, and the survival of others. The reentry of fragments into the stratosphere and their flattening is also demonstrated. For the first time, we present results of an integrated simulation of water and ground impact, the resulting crater formation, fireball evolution and cloud generation and transport of dust and debris to hundreds of kilometers from the impact site. We illustrate the seismo-acoustic signature of the asteroid impacting Earth. Computations were conducted on LLNL HPC using SME++ framework developed last 7 years.

The Upcoming Re-Entry of the Osiris-Rex Return Capsule: Plans for a Coordinated Seismo-Acoustic Observational Campaign

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Upon entering the Earth's atmosphere at hypervelocity, meteoroids and asteroids (>1 m in diameter) undergo complex processes as they encounter denser regions of the atmosphere. The resultant visual phenomenon is called a meteor, with very bright meteors known as fireballs and bolides. Meteoroids and asteroids are of broad scientific interest, from planetary sciences to hypersonic physics. However, impacts into the Earth's atmosphere are sporadic and unannounced, making it impractical to plan a multi-instrument observation campaign aimed at studying and characterizing these objects. Arriving from interplanetary space at hypervelocity, Sample Return Capsules (SRCs) are considered analogues for low velocity meteoroids and asteroids, and as such provide an unprecedented and unique opportunity to perform detailed studies. The next opportunity will present itself on 24 September 2023 with the re-entry of the OSIRIS-REx SRC that will bring samples of the carbonaceous near-Earth asteroid Bennu. Landing is planned over the region enclosed by an 80 km long and 20 km wide ellipse at the Utah Test and Training Range, Utah, USA. This re-entry presents a unique and exceptional opportunity to observe a well-defined artificial meteor, to perform detailed studies of hypersonic entry and event characterization, to test sensors, and to validate and improve models. Sandia National Laboratories will organize and lead multi-instrument observations of the OSIRIS-REx SRC re-entry. Instruments will include infrasound and seismic sensors strategically positioned in the immediate and extended region around the projected re-entry trajectory to maximize the scientific output. Data collected during this observational campaign will be made freely available to the broad scientific community following pub-

lication.SNL is managed and operated by NTESS under DOE NNSA contract DE-NA000352.

Feature Engineering and Clustering for Single-Station Seismic Waveform Classification in an Urban Environment

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To improve seismic event detection and classification in our increasingly urban and often sparsely-instrumented environment, it is important to expand our single-station methods to detect small seismic events in highly-fluctuating, high-amplitude background noise. In this study, we aim to identify effective waveform features which can detect and discriminate small local earthquakes, explosions such as quarry blasts, recurring industrial activity, and other sources of environmental and anthropogenic noise in urban seismic data. Some explored features include measures of power spectral density (PSD) misfit and modified STA/LTA ratios using skewness and kurtosis in the frequency domain. To assess the ability of our features in detecting transient events in urban seismic data, we apply a simple unsupervised learning model (K-means clustering) to continuous feature data from a single broadband station in the Chicago area. We systematically investigate how the findings of our clustering model change with additional features and processing steps. For instance, we explore how filtering our waveforms at characteristic frequency bands of environmental and anthropogenic noise can improve our model performance. We will present a few notable clusters of seismic events in the Chicago area and discuss their characterizing features and possible sources. To assess the efficacy of our features in different urban environments, we also apply our clustering model to continuous data from a single station in Singapore and present our preliminary findings. We conclude by discussing additional features and methods that will be explored in the future to improve our model performance and analysis.

Development of a Cots-Based Platform for Real-Time Seismic and Acoustic Vehicle Detection and Characterization

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We are developing a system for real-time seismic and acoustic detection and characterization of vehicles utilizing Artificial Intelligence at the computing Edge (Edge AI). Seismic and acoustic sensors deployed in urban and industrial environments can capture information related to pattern of life as well as operational events (e.g., machinery operation, vehicle traffic, and environmental control units). In particular, signals from approaching vehicles can be observed at very local distances (few tens of meters) as short pulses of energy (lasting a few seconds) with spectral content from a few 10s of Hz to a few kHz. Given the broad bandwidth features of these signals and the potential of high number of events, processing at the sensing point is preferable to storing or transmitting full data for post-processing. Furthermore, processing at the collection point can exploit multi-channel data analysis (e.g., array processing or polarization) for movement tracking. Our system utilizes an inexpensive Commercial-of-the-Shelf Linux-box computer with an acquisition card to collect multichannel seismic and acoustic waveform data and apply tensorflow (TF) lite models for vehicle detection and type identification. The workflow for the unit is based on running an anomaly detection (i.e., short-term-average-over-long-term-average) algorithm to capture the pulses and apply TF for the characterization. We are collecting data at an industrial environment for the development of the TF models focused on utility vehicles. As running TF required significant computational resources, we are testing the performance of the hardware and software under different computational loads (e.g.: number of channels and sampling rate) for the operation of the full workflow of the system: multichannel acquisition, detection, and characterization.

Detecting, Locating, Characterizing and Monitoring Non-earthquake Seismoacoustic Sources [Poster]

Poster Session • Wednesday 19 April

Conveners: Ezgi Karasözen, Alaska Earthquake Center, Geophysical Institute, University of Alaska Fairbanks (ekarasozen@alaska.edu); Kate E. Allstadt, U.S. Geological Survey (kallstadt@usgs.gov); Liam Toney, Alaska Volcano Observatory and Wilson Alaska Technical Center, University of Alaska Fairbanks (ldtoney@alaska.edu)

Explosive Energy Release of Gas Emission Craters in the Russian Arctic and Their Associated Seismic Magnitudes: Estimates and Implications

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Explosively formed permafrost craters located in the Russian Arctic have only recently been investigated by targeted, scientific expeditions (Kizyakov et al., 2015). Since their discovery, satellite images have helped identify such craters that formed as early as 2011 (Zolkos et al., 2021). In a few cases, local observations can constrain the formation date of craters to less than a day, but other craters have formation date uncertainties that span months to years. Here, we hypothesize that seismic detection may constrain crater formation dates for craters already identified by satellite imagery. Published descriptions of any crater-sourced seismicity are restricted to 1) hypotheses that small seismic events in the Barents-Kara region recorded by the Norwegian Seismic Array associate with craters (Bogoyavlensky et al., 2020, 2022), or 2) one report in a Russian journal that a temporary seismic network recorded a crater-forming event (Titovsky et al., 2018).

Our work estimates the explosive size of such crater-forming events to quantify their seismic detectability, with current sensor deployments. These estimates use published parameters like crater depth and diameter for some craters. We leverage research on maars (craters formed as shallow magma interacts with water, e.g., Valentine et al., 2014) and explosive craters on planetary bodies (e.g., Mitri et al., 2019), which exploit similar parameters and assumptions about the explosive reaction. Following these methods, we use scaling relationships derived from Holsapple & Schmidt (1980) to estimate the energy of crater formation. It is important to correctly screen these crater events from active-source or other gas explosions (natural gas development wells and transport pipelines), as well as track changes in crater formation timing and/or frequency under a changing climate. Continued study of these explosive events has implications for disciplines ranging from permafrost stability to nuclear explosion monitoring.

Full Moment Tensor and Source Characteristic of Remote Nuclear Explosions at the Lop Nor Test Site, China

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We investigate historical nuclear tests from the Lop Nor region, China, using waveform-based source inversions and three-dimensional waveform modeling. Despite sparse data distributions and low signal-to-noise ratios, we recover isotropic moment tensor solutions for historical explosions and obtain detailed uncertainty information from likelihood evaluations over magnitude, depth, and the entire space of moment tensor source type and orientation parameters. We identify a one-dimensional Western China Earth model that provides improved waveform fits, reduced cycle skipping, and drastically improved uncertainty estimates compared with spherical-average Earth models. Preliminary three-dimensional forward modeling results show yet further promise for improving source constraints. By exploring the entire source parameter space, we account for tradeoffs that become important for the determination of source type, depth of burial, and yield in sparse monitoring scenarios. Subsequent likelihood-based uncertainty analysis shows the importance of accounting for differences in data variance between body waves, Rayleigh waves, and Love waves and allows for straightforward data fusion between waveform, travel time, and polarity measurements.

Monitoring Vehicle Traffic With Seismoacoustic Data Using Machine Learning

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Vehicle traffic generates detectable seismic and acoustic signals that can be recorded by nearby sensors. These recorded seismoacoustic signals allow us to monitor the movement of vehicles. Using seismoacoustic data for traffic monitoring has advantages over traditional methods, such as the use of cameras, in industrial or research facilities. Seismic and acoustic sensors have a small footprint and can be less obtrusive, as well as being less affected by light conditions than cameras. The sensors can be easily deployed in a variety of locations, making them well-suited for monitoring traffic. We demonstrate the use of machine learning for traffic monitoring using seismic and acoustic data collected from a network of sensors deployed on an industrial facility in northern Texas. Traffic-related events were detected using the short-term-average over long-term-average algorithm. These signals are characterized by short pulses (few to several seconds) with energy concentrated above 100 Hz. Because each detection corresponds to a different vehicle moving at different speeds, the similarity between detections is low. However, the detections show clear interrelated spatial and temporal patterns. Stations near entrance gates show fewer detections on weekends than on workdays. Also, the hourly distribution of events agrees well with the work schedule. We are developing machine learning algorithms such as artificial neural networks to automatically distinguish traffic-related signals from noise. The use of machine learning will allow for near real-time processing of the seismoacoustic data and quick and accurate detection of vehicles. With field data from a functioning facility, we will be able to test our algorithms with real-life scenarios.

Near-regional to Local Event Location Using Infrasound Arrival Times From Single Sensors

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Infrasound arrays have been traditionally used for acoustic event location due to their ability to accurately determine direction of arrival. Global networks of infrasound arrays reduce the need to incorporate single stations for large events; however, small events typically produce signals that are not observable at global distances. Accurate location efforts rely on observations across smaller regional or temporary deployments. While infrasound arrays are standard in acoustic event location, their large aperture and prohibitive costs limit the availability of arrays in regional or temporary deployments. A single infrasound sensor is comparatively easier and cheaper to deploy, making them the preferred choice for temporary deployments. In this study, we demonstrate the ability to accurately locate local and near-regional acoustic events using infrasound sensor arrival times and infrasound arrival times recorded on seismic stations, in a probabilistic location framework using simplistic forward models. We also produce a model uncertainty function for a simplistic infrasound travel time model that is consistent with a catalog of seismoacoustic events. Our results indicate that single-sensor infrasound arrival times can provide accurate estimates of event location in the absence of array-based observations. Furthermore, we combine infrasound and seismic observations to explore the benefit of seismoacoustic event location algorithms. Finally, we compare arrival-time based locations with amplitude-based location approaches.

Nonlinear Infrasound Propagation Simulation by Hydrodynamic Models

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Infrasound (low-frequency sound below 20 Hz) is a key technology used to monitor energetic events in the atmosphere. Energetic man-made or natural events (e.g., chemical/nuclear explosions, rockets, and earthquakes) create large pressure disturbances which propagate as infrasound in the atmosphere. It is well known that the stratification of Earth's atmosphere plays an important role in transmitting the infrasound signals. For examples, the strong wind and temperature changes in the stratosphere trap infrasonic energy efficiently and transmit them for long distances without significant loss of energy. Unlike infrasound propagation in the middle and lower atmospheres, the characteristics of infrasound in the upper atmosphere has been less studied. As the atmospheric density in the upper atmosphere is extremely low and thereby intrinsic attenuation is prominent, infrasound in the upper atmosphere is often assumed negligible. However, the increasing volume of high-quality data and the improved coverage of global infrasound network allow for identifying infrasound signals traveling in the upper atmospheres. In spite of increasing number of energetic sources and detection capability, the study of upper atmospheric infrasound has been limited by a tool to model signal propagation. The classical linear acoustic theory does not work for non-linear infrasound propagation in the low-density upper atmospheres, and non-linearized fluid physics is required. In this study, we investigate the applicability of widely used hydrodynamic models to the nonlinear infrasound. GEODYN is a hydrodynamic simulation code used for nonlinear deformation of material and blast wave propagation by explosions in the air. We apply GEODYN for infrasound propagation in the conditions of high-altitude atmosphere and evaluate its accuracy by the comparison with experiment data.

Seismic Records of Human Induced Avalanche Signals at Taos Ski Valley

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Snow avalanches are a dangerous natural hazard that have been responsible for severe damage to infrastructure and many fatal accidents in mountainous areas around the world. Most of these fatalities result from a type of avalanche called a slab avalanche, which occurs when a cohesive slab of snow releases down slope due to the failure of a plane of weaker snow below. Using the added stress of an explosion, it is often possible to release slab avalanches in a controlled setting when the risk to humans is low. This is one of the preferred methods to mitigate avalanche hazard at many ski areas. These artificially released avalanches offer a unique opportunity to study the seismic signature of avalanches in a controlled setting. To study this further, we installed an intermediate period seismometer (flat to velocity from 108 Hz to 120 s period) at the base of Kachina Peak in the Taos Ski Valley (TSV) of New Mexico during the 2021 winter season. Using this data, along with explosion logs provided by TSV staff, we analyze the seismic and acoustic signatures, as recorded on our seismometer, of artificially released slab avalanches. Through particle motion analysis and the delay time between the seismic and acoustic arrival, we can locate the blasts that triggered each avalanche within TSV. Finally, in this work we discuss some of the noise sources from our installation as well as some of the complications of monitoring avalanches without infrasound or other relevant observations (e.g., multiple triggers or ambiguous locations).

Seismo-acoustic Observations From the 26 September 2022 Nord Stream Events

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In this study, seismic and infrasound signals from two seismic events coincident with media reported leaks from the Nord Stream gas pipelines in the western Baltic Sea are analysed. Seismic signals from the events in September 2022 were recorded on local and regional distance seismic networks, and arrival times are used to estimate precise epicentres for both events. Seismic signals from the first event are characteristic of a shallow source, and observed modulations in the spectra, which are assumed to be caused by reverberations in the water column, suggest both events occurred near to the seafloor. Signals from the two events are also compared with those recorded for other nearby historic seismic disturbances and using estimates of the local seismic magnitudes, estimates of the trinitrotoluene (TNT) equivalent charge weight for each event were obtained. Following both events, a long duration coda in the seismic data is observed which is too long to be from a single explosive source. Infrasound signals recorded at two International Monitoring System infrasound stations are associated with the events. The observed infrasound signals are also longer duration than would be expected from a single explosive source and show similarities with those observed from underwater volcano eruptions and gas pipeline explosions.

Understanding the Relationships Between Seismic Parameters and Landslide Characteristics From the Exotic Seismic Events Catalog

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The relationship between the behaviors of landslides and how they relate to the resulting seismic signals is still partially unknown, which poses challenges in monitoring and early-warning efforts. This knowledge gap can be attributed to difficulties in directly measuring landslide parameters and a lack, until recently, of systematic cataloging these parameters and seismic characteristics for the wide variety of landslide styles that can occur. Identifying relationships between seismic signals and physical properties is therefore crucial to better understanding mass-wasting events. To investigate these relationships, we select mass movement events from the Exotic Seismic Events Catalog (ESEC) – a collection of seismogenic landslides that includes properties like runout distance, drop height, and volume. The ESEC, available on IRIS's product depository or as a SQLite database on USGS ScienceBase, includes more than 240 events that span several continents, providing us with a large dataset for comparison. Unlike previous studies, which focus primarily on one event type and/or one region, we explore parameter relationships for a wider range of failure mechanisms, including avalanches, falls, and flows, and for many regions. We analyze seismic signals in the long-period (LP) range (20-60 sec) and the high-frequency (HF) range (1-5 Hz). To better understand the dynamics of the forces exerted by the flows and their particle impacts, we estimate the force history of large, rapid, events through the inversion of LP signals and compute smoothed HF envelopes using a Hilbert transform. We then derive peak amplitudes, peak forces, and signal duration, along with physical properties from imagery or published values. A comparison of these parameters shows that events with similar failure styles produce similar trends in seismic and physical characteristics. With this new information, estimating event size and runout distance of events from their seismic signals can be improved.

Using Dynamic Time Warping to Assist Conventional Waveform Cross-correlation

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Waveform cross-correlation is an exceptionally sensitive phase-matched filtering technique that can be harnessed for nuclear explosion monitoring to detect repeating similar seismic events, and to estimate their relative locations and magnitudes by comparison with carefully chosen template waveforms. The method becomes even more powerful when applied to multi-channel geophysical data, i.e., 3-component or array. However, there are outstanding challenges with correlation detectors, most notably a direct dependence on the completeness of the waveform template library that is used to match event signatures in an incoming continuous seismic data stream. In most cases template libraries are limited and slight differences in source location and/or type between template and target events could lead to the non-detection of a signal of interest.

We investigate the value of dynamic time warping as an additional analysis step to make waveform correlation more robust. Dynamic time warping (DTW) analyzes the differences and similarities between two time series and attempts to "unwarp" one time series relative to another by finding the minimum distance between them in a recursive manner, hence DTW can compensate for minor differences between a pair of template and target waveforms to get at the underlying overall similarity. We apply DTW to see if the method will allow us to expand the correlation capability of template libraries and to compensate for their limited sampling. We explore what conditions (e.g., source type, station distance, frequency bands) and/or algorithms generate stronger correlation scores. Several state-of-the-art DTW algorithms are used, and we highlight the successes and limitations of them when applied to synthetic earthquake and observed explosion seismic datasets.

Earth's Structure From the Crust to the Core

Oral Session • Tuesday 18 April • 08:00 AM Pacific

Conveners: Jeroen Ritsema, University of Michigan (jritsema@umich.edu); Vera Schulte-Pelkum, University of Colorado (vera.schulte-pelkum@colorado.edu); Keith Koper, University of Utah (kkoper@gmail.com)

Teleseismic P Wave Travel Times on Dense Nodal Networks Across the Kilauea East Rift Zone Reveal Two High-Speed Intrusive Cores

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Some of the most prominent features of Hawaiian shield volcanoes are the rift zones, which are also highly related to the volcanic hazards on the islands. One of the longest eruptions of Kilauea observed in the 20th century was the eruption of P'u'o'o along its East Rift zone. In addition, it has been observed that the large-scale rift zone eruption could lead to subsequent summit caldera collapse. Therefore, a better understanding of the rift zone structure could help understand the evolution of the volcanoes as well as mitigate future volcanic hazards.In this study, we used the data recorded by two linear dense nodal arrays across the lower East Rift zone of Kilauea and measured teleseismic P wave travel time delays. The travel time delays show a prominent negative relative travel time anomaly (indicating a faster wave speed) slightly to the south of the rift axis on the surface and asymmetrical with respect to the rift axis. The negative relative travel time anomaly measured on the relatively higher topography decisively requires fast speed materials to exist beneath the surface. Additionally, a less prominent negative travel time anomaly was found slightly to the north of the current rift axis on the surface. The existence of two local fast speed anomalies matches the lava flow map, where two separate series of vents existed in the lower East Rift zone, one north of the rift axis (last being active in 1840) and the other south of the rift axis (last being active in 2018).

Crustal Structure of the Caucasus

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The Greater Caucasus is a segment of the Alpine-Himalayan mountain belt that has undergone rapid uplift in the past 5 million years. The Caucasus is a unique place to understand the early stages of mountain building. Until recently, this region has had a lack of reliable digital data that has required extending existing geophysical monitoring systems. Relatively low-resolution seismic velocity models of this region show different lateral variability. The area has been largely unexplored regarding the detailed uppermost mantle and crustal seismic structure.

Seismic network resolution in the Caucasus countries has improved during the past several years. National networks deployed new seismic stations and established collaboration in exchanging online waveform data. Recently, the seismic networks in the region improved tremendously in the framework of the joint regional project "The Uplift and Seismic Structure of the Greater Caucasus," supported by the USA Department of Energy, IRIS PASSCAL and Science and Technology Center in Ukraine (STCU). Scientific teams from Armenia, Azerbaijan, Georgia, and the USA (Michigan State University, Oregon State University, and the University of Missouri) jointly deployed 53 seismic stations. Our seismic array has two components: (1) a grid of stations spanning the entire Caucasus and (2) two seismic transects consisting of stations spaced at distances of less than 10 km that cross the Greater Caucasus.

Our study addresses fundamental questions about the nature of continental deformation in this poorly understood region. Using data from new seismic stations in Georgia, we used receiver functions to estimate Moho depth and crustal properties. Teleseismic events between 30° and 90° with a magnitude greater than 5.5 were used for receiver functions at all stations to study lateral changes in the crustal thickness of the study area.

High-Resolution Crustal Attenuation Model in Southeastern Tibetan Plateau and Its Implications for Regional Tectonic Deformation

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The ongoing continental collision between the Indian and Eurasian plates since ~ 55 Ma led to the uplift of the Tibetan Plateau, which shortens and thickens in the north-south direction and expands towards its southeast and northeast margins (Holt et al., 1991; Zhang et al., 2004). In southeastern Tibet, the growth and deformation mechanism of the plateau has become the focus of attention. Some classical models have been proposed to explain the dynamic mechanism of the tectonic evolution of the Tibetan Plateau, such as the "rigid-block extrusion" model (Molnar and Tapponnier, 1975), the "mid-lower crustal channel flow" model (Royden et al., 1997), and the combination model of these two end-member models proposed in recent years (Liu et al., 2014; Bao et al., 2015; Qiao et al., 2018; He et al., 2021), etc. How to select these models and determine the tectonic deformation mode of the southeast margin of the Tibetan Plateau remains controversial.

The quality factor Q of seismic wave attenuation is more sensitive to temperature, partial melting and fluid content of the underground media than seismic wave velocity (Amalokwu et al., 2014; Winkler & Nur, 1982), thereby can be a useful indicator of potential crustal material escape. In this study, we use the seismic Pg-wave attenuation tomography method to construct the high-resolution broadband Q_{Pg} model for the crust in the southeastern Tibet and provide new constraints. Our result reveals two independent weak zones in the crust of the southeast margin of the Tibetan Plateau. The strong attenuation in Western Sichuan block and Songpan-Ganzi block may serve as the mid-lower crustal flow channel, with partial melting or aqueous fluids. The crustal ductile flow was blocked by the Emeishan Large Igneous Province and did not enter the foreland Yangtze Craton. The relatively weak zone under the Xiaojiang fault is likely related to the heating effect of the asthenospheric upwelling. This research was funded by the National Natural Science Foundation of China (U2139206, 41974061, 41974054) and the Special Fund of China Seismic Experimental Site (2019CSES0103).

A High-Resolution Phase Velocity Inversion for the Crustal Structure of the Southeastern US Using a Double-Sided Hankel Transform

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Understanding the Alleghenian orogeny and its influence on the tectonic evolution of Laurentia depends on understanding the structural relationship between the Suwannee and its adjacent terranes. Our study focuses on creating high-resolution phase velocity estimates of the entire southeastern US region with less non-uniqueness than that of current models and with more accurate locations and orientations of terranes to constrain passive margin formation.

Vertical component seismograms are used to model Empirical Green's functions (EGF) to measure Rayleigh waves via cross-coherence computation for all possible station pairs from approximately 300 broadband seismic stations deployed during the EarthScope project. Because the noise source distribution is not uniform from all directions, the EGF is corrected for all noise sources along the Great Circle Path (GCP) between the virtual source and receiver pair. This has been done with the help of Double Optimized Multiple Signal Comparison (DOPMUSIC), where the significant number of noise sources for all possible frequency bands along the GCP is used to estimate the appropriate EGF.

DOPMUSIC produces Rayleigh waves with significantly higher SNR for all frequency bands than the classical Double Beamforming (DBF) approach. The estimated EGF is used to calculate phase velocity dispersion curves with the help of spatially-variable Hankel transform functions. Classical phase velocity estimation approaches lack uniqueness because of cycle-skipping while matching the phase. The classical Frequency-Bessel transform often contaminates the phase velocity estimates by spatial aliasing and bi-directional velocity scans. And in effect, several crossed dispersion curves were observed in the spectrogram. We use the Hankel function instead of the Bessel function on the causal and acausal part of the EGF separately, which addresses this problem. Phase velocity maps are then used to estimate 1-D shear wave velocity profiles for the entire region.

[PJ1]Need to insert a comment here about what is missing from, or wrong about, current models or ideas about the passive margin formation.

New Images of the Radially Anisotropic Uppermost Mantle Beneath the Continental US

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Tomographic models of radial anisotropy can help understand the relationship between stress and deformation in the upper mantle, and have been used in the past to study mantle convection and flow in the asthenosphere. Beneath the U.S, the current generation of models of radial anisotropy show strong disagreement with each other. Incorporating Love wave phase velocities in the construction of these models offers a path forward to reconcile them, but Love wave phase velocity measurements can suffer from systematic bias and scatter due to contamination by overtone interference.In this study, we develop and successfully apply a simple method to identify and eliminate contaminated Love wave measurements. This approach reduces the detrimental impact of overtone interference through reducing a bias to higher phase velocity measurements and reducing scatter in measurements. We present the first earthquake-derived Love wave phase velocity maps for USArray, at periods with sensitivity in the crust and uppermost mantle. We show that radial anisotropy in parts of the crust and most of the lithospheric mantle is necessary to reconcile these maps with Rayleigh wave phase velocities. . We also show initial results from a new 3-D radially anisotropic model of the U.S.. Finally, our investigations highlight strong geographic and period-dependent variations in the likelihood of obtaining high-quality, uncontaminated Love wave measurements. High-quality measurements are more likely at European stations and less likely at stations in the Pacific, western US, and Australia, as a result of regional variations in the path-averaged group velocities.Overall, this contribution presents a solution to a long-standing challenge in measuring Love wave phase velocities across seismic arrays, and it highlights new paths forward to validate hypotheses for the nature and evolution of the lithosphere of the continental U.S.

Upper-Lithospheric Structure of Northeastern Venezuela From Joint Inversion of Surface-Wave Dispersion and Receiver Functions

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We use 1.5 years of continuous recordings from an amphibious seismic network deployment in the region of northeastern South America and the southeastern Caribbean to study the crustal and uppermost mantle structure through a joint inversion of surface-wave dispersion curves determined from ambient seismic noise and receiver functions. The availability of both ocean bottom seismometers (OBSs) and land stations makes this experiment ideal to determine the best processing methods to extract reliable empirical Green's functions (EGFs) and construct a 3D shear velocity model. Results show EGFs with high signal-to-noise ratio for land–land, land–OBS and OBS–OBS paths from a variety of stacking methods. Using the EGF estimates, we measure phase and group velocity dispersion curves for Rayleigh and Love waves. We complement these observations with receiver functions, which allow us to perform an H-k analysis to obtain Moho depth estimates across the study area. The measured dispersion curves and receiver functions are used in a Bayesian joint inversion to retrieve a series of 1D shear-wave velocity models, which are then interpolated to build a 3D model of the region. Our results display clear contrasts in the oceanic region across the border of the San Sebastian–El Pilar strike-slip fault system as well as a high-velocity region that corresponds well with the continental craton of southeastern Venezuela. We resolve known geological features in our new model, including the Espino Graben and the Guiana Shield provinces, and provide new information about their crustal structures. Furthermore, we image the difference in the crust beneath the Maturín and Guárico sub-basins.

Anisotropic and Anelastic Global Adjoint Tomography

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3D numerical simulations are essential to take the full complexity of wave propagation into account in seismic tomography. However, to further improve the resolution of tomographic models, we also need to better address the physics of the Earth's mantle in inversions through appropriate parameterizations. The first-generation global adjoint tomographic models are elastic and transversely isotropic in the upper mantle and constructed using traveltimes of waveforms only. There is strong evidence that Earth's upper mantle is azimuthally anisotropic, and there is no consensus on the current mantle attenuation models, which affect not only amplitudes but also the phase of waveforms due to physical dispersion. To this end, starting from GLAD-M25, we first constructed an azimuthally anisotropic global adjoint model of the upper mantle where we inverted both azimuthal and radial anisotropy simultaneously. Our model is the result of 25 conjugate-gradient iterations where we used minor and major-arc surface waves down to 35 s from 300 earthquakes during its construction. We started iterations with multitaper traveltime measurements and switched to the exponentiated phase misfit after 12 iterations to improve the resolution in the radial direction. Large-scale features are overall in good agreement with previous studies and plate motions. Moreover, we observe continental-scale resolution in our global model in regions with good data coverage. Meanwhile, we move towards a global full-waveform model by also assimilating amplitudes of waveforms in inversions and simultaneously inverting for elastic and anelastic parameters. We perform a set of 3D global synthetic FWI with a global source-receiver distribution to assess the trade-off between elastic and anelastic parameters and the expected resolution in a global anelastic adjoint model. These tests also guide us in choosing suitable measurements and parameterization for real-data applications. We perform our simulations on TACC's Frontera system, and we will present our results with future directions to further improve global mantle models.

Radial Reference Models: Core Structure and Spin Transition Effects

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The current set of reference models for the radial variation of Earth structure have been in use for several decades and provide a good representation of many aspects of the seismic wavefield. Nevertheless, strong constraints from the differential times between pairs of *SmKS* phases indicate the need to modify the P wavespeed profile in the upper part of the outer core. To incorporate such a change and maintain the representation of the full suite of seismic phases compensatory adjustments must be made, dominantly in the mantle. Using multi-objective optimisation, a new preferred radial model *ek137* has been generated that provides a good representation of the travel times of all core phases, whilst retaining a good representation of mantle phases.In the iron bearing minerals of the lower mantle, there is the potential for a transition from the high-spin state to the low-spin state, though there is, as yet, no definite consensus on behaviour. The relative behaviour of the shear and bulk modulus as a function of pressure for the *ak135* and *ek137* models is suggestive of a residual effect of a 3-D averaged spin transition in the ferropericlase component of the lower mantle. The character of the spin transition is commonly compared against reference models (particularly *PREM*) but needs to be compared with the defining data.

Revisit Smsks Differential Traveltime Data and the Inferred Stratification at Earth's Outermost Outer Core

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Recent seismic studies using SmSKS waves showed that the top a few hundred kilometers of Earth's core possess a P-wave velocity slightly lower than the PREM model, suggesting that stratification may exist within the outermost core. SmKS is a core phase being reflected *m-1* times from the lower side of the core-mantle boundary (CMB) and can be observed at epicentral distances of 120°-180°. Differential arrival times between SmKS pairs, such as S3KS and SKKS, S4KS and S3KS are usually employed in determining the P-wave velocity structure in the top part of the outer core since these pairs have very similar traveling ray paths in the mantle. Since there is a π/2 phase shift between two consecutive SmKS arrivals due to the internal caustic surface for underside reflections, measuring the differential times between the two arrivals using waveform cross-correlation requires performing a Hilbert transform of the first arrival before the regular cross-correlation operation. *Wang and Niu* (2019) found that postcritical refractions and reflections at the CMB of SmKS could lead to phase shifts of the arrivals, causing anomalous differential traveltimes that are not associated with velocity structure of the outermost outer core. In this study, we analyzed SmKS waves recorded by a large dense broadband array in southern China from deep earthquakes occurring in southern America. We found after correcting the postcritical reflection/refraction induced phase shifts, the differential SmSKS data do not support for the presence of a low velocity layer at the top of the outer core.

The UPFLOW Experiment: Peeking from the Sea Floor to the Deep Mantle with an ~1,500 km Aperture Array of 49 Ocean Bottom Seismometers in the Mid-Atlantic

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Constraining upward mantle flow is crucial to understand global mantle flow and directly link the Earth's interior with the surface. However, plume-like mantle upwellings that connect the deepest mantle to the surface are poorly understood. The goal of the UPFLOW project (https://upflow-eu.github.io) is to develop new high-resolution seismic imaging methods along with new data collection, and to use them to greatly advance our understanding of upward mantle flow. We carried out a large amphibian experiment in the Azores-Madeira-Canaries region, which is a unique natural laboratory with multiple mantle upwellings that are poorly understood. UPFLOW deployed 50 and recovered 49 ocean bottom seismometers (OBSs) in a ~1,000x2,000 km2 area in the study region starting in July 2021 for ~13 months, with an average station spacing of ~150-200 km. These data will be combined with observations from over 30 seismic land stations in nearby islands. The experiment included institutions from five different countries: Portugal (IPMA, IDL, Univ. of Lisbon, ISEL), Ireland (DIAS), UK (UCL), Spain (ROA) and Germany (Potsdam University, GFZ, GEOMAR, AWI). 32 OBSs were loaned from the DEPAS international pool of instruments maintained by the Alfred Wegener Institute (Bremerhaven), Germany, while other institutions borrowed additional instruments (7 from DIAS, 4 from IDL, 3 from ROA, 4 from GEOMAR). Most of the instruments have three-component wideband seismic sensors and hydrophones, but three different designs of OBS frames were used. Initial data analysis shows high-quality data, notably a substantial decrease in noise levels in the vertical component long-period data (T>~30s). We show illustrative recordings of teleseismic events, a local seismic swarm, and long-period seismic signals as well as of non-seismic signals such as whales vocalisations and ships' noise. We analyse the data performance as a function of the three models of OBS, recorder and seismometer types.

Imaging Deep Mantle Plumbing Beneath La Réunion and Comores Hotspots: Vertical Plume Conduits and Horizontal Ponding Zones

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Whether the two large low shear velocity provinces (LLSVP) at the base of Earth's mantle are compact structures extending thousands of kilometers upwards, or bundles of distinct mantle plumes, is the subject of debate. Full waveform shear wave tomography of the deep mantle beneath the Indian Ocean highlights the presence of several separate broad low-velocity conduits anchored at the core-mantle boundary in the eastern part of the African LLSVP, most precisely beneath La Réunion and Comores hotspots. The deep plumbing system beneath these hotspots may also include alternating vertical conduits and horizontal ponding zones, from 1000 km depth to the top of the asthenosphere, reminiscent of dykes and sills in crustal volcanic systems, albeit at the whole mantle scale. Our study was conducted using ocean-bottom and land-based seismic stations. We are currently investigating the current state of global tomographic model quality and data availability for a regional tomographic study in the Pacific Ocean around French Polynesia, where several hotspots are situated, in order to investigate their relation to any underlying LLSVP, and to evaluate the likely model improvement gained from incorporating hydroacoustic data from the over fifty mobile MERMAID instruments deployed in the region since 2018 as part of the South Pacific Plume Imaging and Modeling (SPPIM) project conducted under the auspices of the EarthScope-Oceans consortium.

A Seismic Investigation of Lithospheric Seismic Structure Beneath the Shillong Plateau and Adjoining Regions in N-E India by Jointly Fitting of Receiver Functions and Dispersion Curves

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The northeastern Indian region is characterized by a complex lithospheric structure that developed as a result of collision between the Indian and Eurasian tectonic plates, in the north, and to subduction beneath the Burmese arc, in the east. To constrain this structure we jointly model Ps receiver functions, Sp receiver functions, and Rayleigh wave group velocity dispersion curves by performing a broad search for acceptable models via Very Fast Simulated Annealing (VFSA). Seismic Vp and Vs profiles are estimated from teleseismic earthquake data recorded by nine broadband seismic stations. We identify three distinct tectonic domains: the Shillong plateau, Brahmaputra valley, and the Indo-Burma convergence zone (IBCZ). Our results reveal that the region's thinnest crust lies beneath the Shillong plateau, where crustal thickness increases slightly from the plateau's eastern edge to its center and reaches a maximum at the western edge of the plateau. Crustal Vp/Vs ratios range between 1.69-1.75 for the Shillong plateau, consistent with a felsic composition. Deeper Moho depths beneath the Brahmaputra valley, adjacent to the northern front of the Shillong plateau, may be due to the flexure of the Indian lithosphere subducting beneath Asia. Low-velocity zones are indicated at ~5-10 km depth beneath the Brahmaputra valley, which may have been developed by NE-SW trending compressional stresses from the collision at the Himalayan arc and subduction at the Burmese arc. The crust is thickest in Kohima, beneath the Naga thrust in the IBCZ, where a high-velocity zone is observed for both Vp and Vs at a depth of 25-40 km. This anomaly may be associated with a high-velocity slab, trending N-NE to S-SW, comprising the subducting Indian lithosphere in the IBCZ. Uncertainties of our Vp and Vs models for all the nine broadband stations are estimated with two statistical tools: Posterior Probability Density Functions and Parameter Correlation Matrices.

Effects of Partial Melt in the Uppermost Mantle on SK(K)S Splitting: Global Wavefield Simulations and Potential Applications

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Observations of seismic anisotropy can be caused by lattice-preferred orientation (LPO) of intrinsically anisotropic minerals such as olivine, or shape-preferred orientation (SPO) of elastically contrasting materials as in the presence of partial melt. A detailed understanding of anisotropy based on the fast polarization direction, *φ*, and the estimated delay time, *dt*, of shear-wave splitting (SWS) measurements, provides opportunities to infer constraints on subsurface deformation. However, the limited depth resolution of SK(K)S core-phases, used in investigations of the upper mantle, typically prevents unambiguous assignments on the origin of anisotropy. Even simple SWS patterns may potentially reflect scenarios in which multiple mechanisms (i.e., LPO vs. SPO) or olivine fabric types (e.g., A-, C-, or E-type) contribute to the observed splitting signal. If partial melt is present in the uppermost mantle, it may affect this signal via two different mechanisms: first, if melt inclusions are aligned through deformation, then SPO may contribute to anisotropy, and second, the partitioning of water into the melt may change the dominant olivine fabric in the surrounding matrix. In this study, we investigate whether splitting parameters can provide enlightening indications on the presence of partial melt. We adapt our model geometries to be applicable to the High Lava Plains in the Cascadia backarc where there is good evidence for the presence of melt in the uppermost mantle. AxiSEM3D is used to compute synthetic seismograms (for both axisymmetric and fully 3D global wavefield simulations) to be able to evaluate effects on SWS measurements for a variety of scenarios, considering different melt configurations (fractions/geometries) and olivine fabric types. Related SWS parameters are obtained by using SplitRacer to measure splitting on the synthetic seismograms over a range of frequencies (up to 0.25 Hz).

Post-Seismic Deformation Following a Deep (~560-km) Earthquake Reveals Weak Base of the Upper Mantle

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Mantle rheology is one of the least constrained properties despite its importance in mantle dynamics. In this study, we introduce a new approach to understand the viscosity structure by examining the Earth's response to deep earthquakes occurring near the bottom of the upper mantle. We utilize seismically constrained earthquake source properties and combine numerical modeling of viscoelastic deformation of upper mantle and the GPS observation of post-seismic deformation from deep earthquakes.

Major challenge in utilizing the post-seismic deformation from deep earthquakes, however, is on the observation side. So far, most GPS observations have been limited to shallow earthquakes since the amplitude of the surface deformation from deep events is relatively small. Here, we take advantage of data processing techniques such as independent component analysis to extract post-seismic signals from deep earthquakes. We examine the GPS data of one of the largest deep earthquakes ever recorded, 2018 Mw 8.2 Fiji earthquake which occurred at ~560-km depth. We detect a large scale post-seismic deformation that has been taking place for about two years. The overall directionality and amplitude of the deformation strongly suggest the presence of rheologically weak structure (with viscosity of 10^{17}-10^{18} Pa·s) on top of the lower mantle. Such a weak zone could explain slab flattening and orphaning observed in numerous subduction zones, which are otherwise challenging to explain in the whole-mantle convection regime. The low-viscosity layer may result from superplasticity induced by the post-spinel transition, weak $CaSiO_3$ perovskite, high water content, or dehydration melting.

The Mantle Transition Zone Seismic Discontinuities Beneath NW South America From P-Wave Receiver Function Analysis

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Two seismic discontinuities delimit the mantle transition zone (MTZ) at 410 km and 660 km. These seismic discontinuities were imaged under the northwestern corner of South America using the receiver function technique and a seismological record of up to 30 years collected by the National Seismological Network of Colombia. Significant variations and spatially systematic in the discontinuity depths were observed. The mean depths for the MTZ are 412±5.3 km and 671±5.9 km, with a mean thickness of 258±6.5 km. This last value doesn't differ too much from the global average. The significant depth variation and the thicker MTZ in some areas cause a low correlation between the depths of these discontinuities. We hypothesize that this thickness irregularity in the MTZ is due to the interaction between the Nazca and Caribbean tectonic plates during the subduction process beneath the South American lithosphere – Mantle system. On the other hand, the MTZ thinning beneath the Nazca plate possibly is due to a regional thermal disturbance or local

plume under the Malpelo ridge. These observations and seismic tomography images also support hypotheses regarding lateral variations in the thermal structure linked with the difference in age and composition of the Nazca and Caribbean tectonic plates in these depths.

Earth's Structure From the Crust to the Core [Poster]

Poster Session • Tuesday 18 April

Conveners: Jeroen Ritsema, University of Michigan (jritsema@umich.edu); Vera Schulte-Pelkum, University of Colorado (vera.schulte-pelkum@colorado.edu); Keith Koper, University of Utah (kkoper@gmail.com)

Crust and Upper Mantle Velocity Structure Beneath the Chhotanagpur Plateau, India Using Waveform Modeling of Shear-Coupled Pl Waves and Other Phases

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We perform waveform modeling of shear coupled-PL waveforms and S-to-P converted phases to estimate the shear and compressional wave velocity structure of the crust and uppermost mantle beneath the Chhotanagpur plateau and adjacent regions in India. We use broadband waveforms from teleseismic earthquakes with magnitudes between 5.5 and 8.0, focal depths ≥ 300 km, and epicentral distances between 300 and 700. Data are extracted from seismic stations located near the cities of Dhanbad (DHN), Bokaro (BOKR), Petarwar (PTWR), Khunti (KNTI), and Sahibganj (SBG). A modified form of the reflectivity method generates synthetic seismograms for the range of frequencies 0.002 Hz to 0.25 Hz, and the calculation of responses (essentially matrix multiplications) is distributed over 32 nodes of a High-Performance Computing (HPC) cluster, which reduces the computation time sufficiently to allow a global optimization to be performed via Very Fast Simulated Annealing. The crustal thickness of the study area varies between ~40.5 km and ~45.6 km. The thickest and thinnest crust are found in the NE and SW of the study area, beneath seismic stations SBG and KNTI, respectively. The thick crust observed at station SBG may be due to flexure associated with the subduction of the Indian lithosphere beneath the Himalayan mountain range. Also, a low-velocity zone is observed in the upper crust at station SBG, which we attribute to sediment deposition of Ganga-Koshi formation. The higher Poisson's ratios for seismic stations SBG (~0.29), DHN (~0.29), and BOKR (~0.30) indicate the possible presence of partial melt in the mafic lower crust. Statistical tools such as the Posterior Probability Density function and Parameter Correlation Matrices are used to estimate uncertainties associated with model parameters and to quantify trade-offs between model parameters in the modeling scheme.

Deep Crustal Imaging in Binchuan, China Based on a Wavefield Decomposition Analysis Using Wavelets on the Dense Array Datasets

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Ultra dense array data (spacing <100 m) has been demonstrated to be effective in imaging shallow subsurface structure. However, their rather small apertures (usually <10 km) limit the potential to image the crustal structure at greater depth, partly due to the recorded wavefields are significantly modulated by strong heterogeneities near surface. Here we develop a method to decompose the background teleseismic wavefields and local scattered wavefields using wavelets. A soft thresholding method is exploited for noise reduction and the background and local wavefields are separated out by applying a template matching analysis. We first conduct synthetic tests and find promising results, and then apply the technique on two linear dense arrays across the Chenghai fault in Binchuan, Yunnan, southwestern China. The wave partitioning result illustrates a coherent background wavefield, which is used for receiver function calculation. Through the common-conversion-points (CCP) stacking on two linear arrays, we obtain a clear Moho interface at 52 km depth and another noticeable velocity discontinuity around 30-34 km depth in Binchuan area. The latter is interpreted as the bottom layer of middle crust, in agreement with a large-scale tomographic imaging of deep crustal structures in Yunnan region. Here we demonstrate that the wavefield decomposition technique can effectively separate the local and background wavefields, enabling utilization of small-aperture temporary arrays to image crustal structure.

Lateral Variations of Crustal Lg-Wave Attenuation in the Scandinavia Peninsula and Its Vicinity

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The Scandinavian Peninsula region includes the Baltic shield and a series of passive continental margins, which are featured by abrupt changes in crustal thickness (Ziegler, 1986). A potential point of subduction initiation is likely located in the passive continental margins existed weak zone. Seismic Lg wave is sensitive to the sudden change of the waveguide structure, thermal anomaly, and weak zone in the crust (Bouchon, 1982). The Lg attenuation structure can provide constraints on the location of potential subduction initiation. Then, we construct a broadband Lg attenuation model between 0.05 and 20.0 Hz by conducting the Lg wave Q tomography (Zhao et al., 2010) in and around the Scandinavian Peninsula, with resolutions of reaching 1° or higher in the regions with dense ray path coverage. A total of 37,735 vertical-component broadband digital seismograms was used to create a dataset which is larger and more updated than those previously used in this region (Demuth et al., 2019). The dataset is composed of seismograms from 449 earthquakes recorded by 863 stations, mostly from the IRIS and GEOFON Seismic Network between 1992 and 2021. Prominent lateral variations of Q_{Lg} values at various frequencies and the consistent between Q_{Lg} distributions and the regional geological blocks were observed. The Baltic Shield, a large stable crust, is characterized by weak attenuation. The relatively low Q values in the North Sea Basin presented strong attenuation, presumably because the covered sediments and the developed graben structure hindered the propagation of the Lg wave. And strong Lg attenuation was observed in the passive continental margins, where the crust is weakening caused by underground high-temperature anomalies, changes in crust thickness, and overlying thick sediments. Therefore, it is speculated that the potential subduction initiation zone in the future may be located near the Lofoten-Vesterålen Margin with the strongest attenuation. This research was supported by the National Natural Science Foundation of China (41974061, 41974054, 41630210, and U2139206).

Lithospheric Structure of the Sabine Uplift From Joint Modeling of Receiver Functions and P Autocorrelations

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Joint modeling of receiver functions and teleseismic autocorrelations is an effective tool for modeling crustal structure, and is particularly useful in regions without regional seismicity and in the deep basins. P receiver functions contain energy converted from P-type to S-type at abrupt impedance contrasts, such as a sediment-basement contact and Moho, while vertical autocorrelations contain P wave reverberations from the same interfaces. Modeling both together provides better constraints on crustal structure than do receiver functions alone, since P wave reverberation delay times are sensitive to interface depth and Vp, while Ps delay times are sensitive to interface depth and Vp/Vs.

In this study we perform joint modeling to determine crustal structure in the vicinity of the Sabine Uplift, a feature at the Texas-Louisiana Border that has been shown to have a deeper Moho than the Ouachita Mountains to the north and the Gulf of Mexico to the south. It has been interpreted to be either an accreted Gondwanan terrane or island arc that collided with the North American craton during the Ouachita Orogeny. Further, the Sabine "Island", located to the south of the Uplift, is characterized by anomalously low velocities and low densities in lower crust or upper mantle.

P receiver functions in the region show at least two clear interfaces, likely the sediment-basement contact and Moho, while the vertical autocorrelations typically show the sediment-basement contact. Waveform modeling of the vertical autocorrelations and P receiver functions in the area indicates basin depths of ~2-8 km depth and Moho depths of ~30-42 km. P receiver functions computed from stations in the southern portion of the region show at least one additional interface, which could mark the lower bound of a rift pillow that has been proposed as a result of previous gravity modeling.

Mapping the Mantle Transition Zone Using the Coda Correlation Wavefield

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Hours-long seismograms recorded after major earthquakes include body waves reflected multiple times in Earth. These weak reflections can be detected by cross correlation and stacking. Coda correlation has been found to be a powerful probe for studying Earth's layered structure as well as Mars and Moon. Similar to previous work, we find a plethora of core-reflected and core-refracted phases in cross-correlations of vertical-component GSN waveforms. However, our preliminary analysis suggests that reflections from the 410-km and 660-km discontinuities in the mantle transition zone are much weaker than the core phases.

We further investigate whether coda correlation is an effective technique for studying the mantle transition zone. Using the South California Network, we have found the coda correlation signal of Pv410p in a narrow inter-station distance range. We are using spectral-element-method synthetics to test the influence of the 3-D crust and mantle. We will test various dense continental-scale networks, explore the influence of earthquake depth, location, and mechanism on the quality of the cross-correlations. Furthermore, we will compare 410-km and 660-km discontinuity depths to the depths constrained by SS and PP precursors and receiver functions.

On the Detection of Sharp Upper Mantle Discontinuities across North America: Silencing Echoes in the Crust with Sparse Non-linear Radon Filters

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Global maps of upper mantle discontinuities are typically produced using the receiver functions (RF) technique – source-deconvolved seismograms that target seismic structures directly underneath a seismic array. Although the compressional-to-shear receiver function (Ps-RF) technique has been widely successful for crustal imaging, it has seen limited use in continental-scale lithospheric imaging due to signal distortion caused by overprinting of crustal reverberations. For this reason, the shear-to-compressional receiver function (Sp-RF) is usually preferred; even though it produces images with lower frequencies and sparser data sampling. In this study, we obtain sharp images of mantle discontinuities by applying a selective sparse non-linear Radon filter to eliminate crustal reverberations from the Ps-RF. The key idea emphasizes stable decomposition of noisy data-domain RF images into their underlying wavefield contributions in the radon domain by imposing sparsity-promoting constraints. Initial tests using synthetic and data examples from stations CN-ULM and II-RAYN show that sharper and cleaner images of the mantle discontinuities can be obtained without compromising on image resolution. We have compiled waveform data for earthquakes with magnitude >5.5 and epicentral distance between 30º and 90º recorded at TA and all major regional seismic networks in the contiguous US. The proposed method is currently being applied to all ~630,000 events, where we hope to provide improved constraints on the composition, hydration, or change in anisotropic signature that best characterizes seismic discontinuities beneath the contiguous US.

Seismic Autocorrelation to Explore Subglacial Crustal Structure

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Recent advances in autocorrelation of teleseismic waves enable a new approach to study subglacial geologic structure in Greenland and Antarctica, capable of producing new estimates of crustal thickness and the first crustal P-wave velocity estimates using the timing of Pmp arrivals. Ice-rock interfaces at the bases of ice sheets generate high-amplitude ice multiples that mask subtler concurrent arrivals that are useful for studying crustal structure, such as the Pms phase typically identified in receiver function analysis. These multiples have hindered previous receiver function studies of subglacial crustal structure, forcing them to use more uncertain methods, such as identifying crustal multiple arrivals. We autocorrelated over twenty years of teleseismic earthquake records from stations in Greenland and Antarctica and developed a suite of forward models to compare our results to. We demonstrate that autocorrelation can resolve the Pmp phase through ice sheets at certain stations and use the arrival timing of this phase to directly estimate crustal thickness and P-wave velocity at select sites in Greenland and Antarctica. We additionally find that the Pmp phase is absent in data collected at some stations, implying either unexplained amplitude losses in these Moho arrivals or a diffuse crust-mantle boundary.

Seismic Waves Attenuation in Georgia

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Georgia is situated in the Caucasus. It is one of the most seismically active regions in the Alpine-Himalayan collision belt. The analysis of the data of historical and instrumental periods shows that this is the region of moderate seismicity. The strong earthquakes with magnitude up to 7 and macroseismic intensity 9 (MSK scale) occurred here. The recurrence period of such an event is of order 10^ 3 -10^4 years. My Phd study project is very important and valuable as it will adopt ground motion attenuation models for different parameters PGA, peak PGV and SA. These models are one of the most important stages in seismic hazard assessment, which in turn is the most important prerequisite for seismically resistant constructions and engineering projects. Recently, there has been an increase in construction and various types of engineering projects in Georgia, and therefore, in view of the implementation of projects in accordance with European and American standards, it is necessary to build full-fledged seismic hazard maps, an important part of which is the use of correct models of ground motion attenuation directly evaluated for the region from which the maps are developed. This study will be uniquely unique because the latest seismic data will be used together with the data of the 90s, which have accumulated in the last ten years by NSMC and its funding by the Department of Energy, United States of America. At the same time 12 newest seismic station data will be used in the study, which will make the study unique because for the first time in the Caucasus region Posthole seismic station has been installed in Georgia (12 in total), which has ability to record seismic waves over a wide frequency range (120 seconds to 150Hz). We will use data from the network of strong motion accelerographs in the period of 90s installed in Georgia and around this territory with the help of Swiss Seismic Service and other organizations. The use of this data is very important for those considering the fact that it is recorded in Georgia by the mentioned stations Significant earthquakes of the instrumental period.

SItomo – a New Matlab Toolbox for SKS Splitting Intensity Tomography and Application to the Dense SWATH-D Seismic Array in the European Alps

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The tomographic inversion of shear wave splitting data for upper mantle anisotropy has been a longstanding challenge for classical analysis techniques. This is due to the ray-based approximation of classical approaches and the near-vertical incidence of core-mantle converted phases that are often used. Recent developments involve the calculation of finite frequency sensitivity kernels for SKS splitting intensity observations, which allows us to take into account the laterally broadened sensitivity for the anisotropic structure with depth. A requirement of this tomographic technique is a dense station spacing, which results in overlapping sensitivity kernels at depth. This is satisfied by a growing number of temporary seismic deployments, which motivates the desire for an imaging of anisotropic complexities with depth.Here, we introduce a toolbox for the MATLAB environment which facilitates the application of finite-frequency splitting intensity tomography (Mondal and Long 2019) to arbitrary 2D and 3D dense seismic arrays. Our implementation includes: 1) A forward calculation of splitting intensities and sensitivity kernels for a complex anisotropic model space. 2) The code takes into consideration the dominant period, allowing for multiple-frequency analysis, as well as a non-vertical incidence of the incoming wave. 3) The inversion can be based on a classical gradient descent or on a gradient-informed stochastic reversible jump algorithm, allowing for a data-driven parametrization of the model space. 4) An import of splitting intensities from waveforms processed in SplitRacer allows a fast pre-processing of large data sets due to its fully automatic design (Link et al. 2021).

We apply this inversion procedure to the SWATH-D network, which densely covers the transition of the Central to the Eastern Alps (Heit et al. 2017). Previous studies showed evidence for an abrupt lateral change of layered seismic anisotropy that had been attributed to an opening for a channeled asthenospheric flow. Here, we are able to confirm the previous observations while providing additional constraints on the anisotropic distribution.

Towards Using Mermaid Waveforms in Seismic Tomography

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Sparse data coverage at the global scale is one of the main challenges for improving the resolution of seismic images, specifically underneath the oceans. MERMAIDs (Mobile Earthquake Recording in Marine Areas by Independent Divers) provide new opportunities to sample the oceans in a relatively cost-effective and practical way. Our goal is to minimize the oceanic multiples in MERMAID waveforms to facilitate cross-correlation traveltime measurements and more accurate onset time readings of primarily the first arrival P waveforms. To this end, we design an Adaptive Dereverberation and Deghosting (ADD) filter and explore to what extent we can remove oceanic multiples from MERMAID waveforms using 2D spectral-element simulations. We mitigate complications in the waveforms caused by variations in bathymetry and reflection coefficients at the ocean bottom by a grid search tailored to the filter. The ADD filter successfully minimizes a finite number of multiples and redatums synthetic MERMAID waveforms to the ocean bottom for flat bathymetry. We observe that for cases with varying reflection coefficients, varying wave traveltimes, and focusing, which may arise from ocean bathymetry, the ADD filter may introduce some minor artifacts which become negligible at longer periods. After applying the ADD filter, synthetic MERMAID waveforms match those recorded at the ocean bottom well in phase, while the amplitude information may be distorted by the filter. Our synthetic tests suggest that the ADD filter is promising for removing the imprint of the ocean from MERMAID waveforms for cross-correlation traveltime measurements for seismic tomography. We will present our synthetic experiment results and discuss how to extend the ADD filter to real-data applications and incorporate MERMAID waveforms in linearized and full-waveform inversions.

Unraveling the Iceland Plume Track Through Greenland's Mantle Transition Zone

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Over the last ~100 Ma, Greenland passed over the present-day Iceland hotspot. However, the path of the plume track across Greenland is debated and obscured by the Greenland ice sheet. The passage of Greenland over the Iceland hotspot provides an opportunity to investigate how mantle transition zone structure recovers from hotspot interaction over time. We analyze information from converted Ps phases to infer the characteristics of the mantle transition zone below Greenland using data from broadband stations, including the first analyses of recent deployments of seismometers on the Greenland ice sheet. We calculate receiver functions in a 2-100 s period band using time domain deconvolution, after separating the P and SV components using a free-surface transform where free-surface velocities were obtained from P and S waveforms. High-quality receiver functions are identified and are migrated to depth using a recent 3-D tomographic model (Lei et al., 2020). Depth-migrated receiver functions are stacked in 30° back-azimuthal bins at each station and the observed depths of the positive phases corresponding to the 410 and 660 km discontinuities are used to calculate transition zone thicknesses. The thickness measured for a given bin is assigned to all mid-transition zone piercing points for that bin. Thicknesses are smoothed laterally with a 1° radius spherical cap to generate a map of transition zone thicknesses. We find a corridor of thin mantle transition zone across Greenland and Iceland, consistent with some models of the Iceland plume track and the distribution of coastal paleogene basalt provinces. We also observe areas of thick transition zone beneath mid-latitude eastern Greenland, possibly related to remnant subducted lithosphere in the transition zone, and an additional thin transition zone region in northeast Greenland.

Updated SALSA3D Tomographic Velocity Models for Improved Travel-Time Prediction and Uncertainty

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Monitoring the Earth for nuclear explosions depends on seismic data to detect, locate and characterize suspected nuclear tests. Motivated by the need to locate suspected explosions as accurately and precisely as possible, our team at Sandia National Laboratories and Los Alamos National Laboratory developed a specialized tomographic model of the compressional wave slowness in the Earth's mantle, SALSA3D (SAndia and LoS Alamos 3D; Ballard et al., 2016). While the aim of conventional tomographic modeling is to better understand the structure and dynamic history of the Earth's mantle, the primary focus of SALSA3D is on the accuracy and precision of travel time predictions for P and Pn ray paths through the model with quantifiable uncertainty. We obtain path-dependent uncertainty estimates for travel-time predictions by computing the full 3D model covariance matrix and then integrating slowness variance and covariance along ray paths from source to receiver. While this uncertainty method requires significant additional computational resources to develop and store when compared to simple distance dependent uncertainty estimates, the result is a more complete prediction capability that can be incorporated into event location estimates using this model. In this contribution, we present updated SALSA3D P and S-wave slowness models. The updated models utilize an extensive dataset with stronger quality control measures, which allows for improved resolution compared to previous iterations of SALSA3D. We observe a significant decrease in the root-mean-square (RMS) residual of the predicted travel times, indicating the new models produce improved travel-time estimates that will result in better location estimates and robustly characterized uncertainties.

Earthquake Early Warning Optimization and Efficacy

Oral Session • Thursday 20 April • 02:00 PM Pacific

Conveners: Alison L. Bird, Natural Resources Canada, Sidney (alison.bird@nrcan-rncan.gc.ca); Claire Perry, Natural Resources Canada (claire.perry@NRCan-RNCan.gc.ca); Sara K. McBride, U.S. Geological Survey (skmcbride@usgs.gov); Danielle Sumy, Incorporated Research Institutions for Seismology (danielle.sumy@iris.edu)

False and Missed Alerts: A Performance Analysis of a Community-Engaged Earthquake Early Warning System

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False and missed alerts are two key concerns regarding Earthquake Early Warning (EEW) Systems. Every year, earthquakes strike New Zealand, making it one of the most earthquake-prone countries on the planet. Thousands of quakes occur each year, and around 150 earthquakes are felt. Citizen seismology, which refers to research partnerships between seismologists and non-scientist volunteers, is a developing field. In this study, citizen seismology encourages the public to participate in gathering ground motion data for EEW. Community volunteers host low-cost Raspberry Shake ground motion sensors in their homes. The volunteers have the flexibility to install the sensors at their own discretion; the sensor's location in their homes and installation methods are not pre-defined. On 22 September 2022, a moderate M5.2 earthquake occurred in the Cook Strait region of New Zealand, which caused moderate levels of shaking in the lower part of the North Island, mainly in the greater Wellington region. Fortunately, the experimental community-engaged Earthquake Early Warning System (EEWS) was operating during this earthquake. Preliminary analysis of the ground motion data collected during the earthquake event demonstrates that EEW is achievable with a citizen seismology-based approach. However, the reliability and accuracy of the EEWS must be evaluated in depth to understand whether this network is capable of generating accurate warnings. Therefore, this study analyses the false and missed alerts of the implemented EEWS during a 48-hour time window of the mentioned earthquake using four different P-wave detection algorithms. Results show that a wavelet transformation-based P-wave picker is the most suitable algorithm for the community-engaged EEWS in detecting an earthquake with

minimal false and missed alerts. By assessing the performance through false and missed alerts, this study discusses whether a citizen seismology-based approach is appropriate for an EEWS.

The Use of Early Earthquake Warning in Hopsitals in Mexico: Safeguarding Vulnerable People

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Since the introduction of the public early earthquake warning (EEW) in Mexico, only one study known to date has been carried out to inform the socio-technical interactions between the EEW and the most vulnerable users – schoolchildren. However, another large and extremely vulnerable group of population resides at public and private hospitals in Mexico City. It is unknown to what extent EEW supports the safeguarding of vulnerable populations and corresponding challenges. An emphasis on the cultural aspects of safety in disaster response maintains that populations and safety culture of institutions should be studied to assess the implications of behavior for preparing for and responding to events such as earthquakes. Using the qualitative methodology, this study 1) explores and documents existing protocols for EEW and earthquakes in Mexico City hospitals using in-depth interviews; 2) investigates the behavior of the staff and the population in hospitals in response to EEW and earthquake; 3) compares and contrasts the effectiveness of behaviors in relation to existing protocols. The hypothesis of this study is that EEW could trigger protective behavior that is not aligned with official advice and, therefore, may be detrimental to people's well-being. To explore this hypothesis, the interviews with hospital Disaster Risk Prevention Units and the information about the protocols will be analyzed through thematic analyzes. The results offer an insight into the differences in risk perception, protocols, preparation, response, and response effects between individual groups receiving EEW and those who do not across Mexico City.

Characterizing Earthquake Early Warning's Efficacy

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Earthquake Early Warning (EEW) will undoubtedly lead to success stories, yet some letdowns will occur due to alert limitations or inaccuracies. Though strategies vary, magnitude and location are typically the ingredients needed for determining alert regions, so evaluating their accuracy, timeliness, and capacity to predict shaking is essential. Empirical analyses can bear out EEW's technical success, and seismologists are working diligently to test EEW alerting. However, EEW is also a human endeavor— converting seismological information into alerts meant to elicit human and technological reactions. So how do we formulate a testable hypothesis on the success of EEW from the societal perspective, and how can we collect the requisite observations? Technical evaluations should be transparent and informative, mapping populations who experience each level of shaking and tallying those who were successfully warned (or not). In addition to technical evaluations, we need approaches for objective data gathering to evaluate EEW's societal benefits. For one, the USGS has implemented a post-event EEW questionnaire as a follow-up to "Did You Feel It?". Respondents will contribute quantitative survey data about alert timeliness and functionality and actions taken—all as a function of reported intensity. In addition to general user-volunteered evaluations, we could benefit from sociotechnical evaluations after each event by surveying technical users, such as utilities and other registered alert recipients. Additionally, forensics aimed at understanding damage, injuries, or incidents avoided—or those aggravated by EEW—need to be documented and evaluated to understand the interplay of EEW technology and society fully. Finally, we aim to form an international collaborative community to follow up on each earthquake for which an EEW alert was (or should have been) issued so that we can learn as much as possible about the technological and human endeavor that is EEW.

Addressing Misconceptions Around Magnitude and Intensity to Inform Earthquake Early Warning Alerting Strategies

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Canada is currently in the development phase for a national earthquake early warning system (EEWS) that will operate in regions including British Columbia, and Ontario, Quebec, and New Brunswick. To ensure effectiveness, the public needs to understand the alert message when they receive it and immediately know what to do. Maintaining these goals is not limited to the system and its operations, but also with how the public interprets the alert.

Our group is researching the messaging about earthquakes to the public, trying to understand the history of messaging about earthquake magnitude and intensity, to make that messaging more effective in the future. To do this, we approach the problem from three directions:

· Historical (H)–Conceptual biography of earthquake magnitude and earthquake intensity

· Linguistics (L)–The language and especially metaphors used when talking about earthquakes, earthquake intensity, and magnitude, by the general public as well as by news and social media platforms

· Socio-cultural (SC)–The state of seismicity education in Canada, how that education has developed through time, and how it compares to the contexts of other seismically active regions around the world

This presentation will highlight our research to date:

· (H) Intensity has been at the heart of trying to better understand earthquakes because that has been the most concrete aspect. Local magnitude originally resulted from intensity as it was calculated from the shaking.

· (L) Different factors impact how the public perceives an alert, their experiences with and perceptions of both the phenomenon and the alerts. "Did you feel it?" data from the USGS is helping us understand the way people talk about earthquake magnitude and intensity.

· (SC) Activities to date: Preliminary analysis of Seismic Science Education/Communication; 2. Systematic evaluation of gaps and future information needs to build geoscience knowledge to EEW action capacity 3. Development and implementation of a Pan Canadian Bilingual E3 Survey and 4. Reporting E3 Survey Results.

Uses of the Myshake App in Earthquake Early Warning and Rapid Response

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MyShake is a free citizen science smartphone app which has been downloaded globally 2.3 million times. Most of the downloads originate in the western US, where MyShake has been serving as a delivery service for earthquake early warnings produced by ShakeAlert since October 2019. In addition to serving earthquake warnings and educational information, MyShake also collects data for research, including waveforms recorded on the accelerometers in-built in smartphones, real-time triggering and latency information, and crowdsourced experience reports. We present an overview of the array of MyShake's capabilities, including its effectiveness as a warning delivery service, its potential to contribute to the generation of early warnings using real-time STA/LTA triggers, and rapid response products that estimate shaking intensities and structural response.

Building out the Earthquake Early Warning sites in the Pacific Northwest Seismic Network - If you build it, you can improve it

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An Earthquake Early Warning (EEW) seismic network is a very beautiful and noble thing. It is also very complex involving locating hundreds of seismic sites for an area as large as the Pacific Northwest Seismic Network covers. Like most EEW systems, the creation of this network started with a base layer of existing analog and digital stations that were sited and installed to fulfill the tracking of earthquake and volcanic hazards in addition to special cases such as monitoring ground motion in and around a former nuclear site that is now a Superfund site. Expanding the network from 184 EEW-eligible stations in 2017 to currently 525 seismic stations that have sent data to ShakeAlert serv-

ers involved lots of moveable dots, hazard and population center identification, Google Earth, land ownership databases, door knocking, and more. This presentation will review the gradual change from creating station maps for the best estimate for even coverage of hazard areas to more nuanced approaches and techniques for identifying new seismic station locations and dealing with the remediation and/or relocation of underperforming sites. It is and always will be a task of continual optimization and improvement!

Optimizing Real-Time Gnss-Based Magnitude Estimation for Shakealert

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To improve alerting for M7+ earthquakes, we adapted a magnitude estimation algorithm ("GFAST", Crowell et al., SRL, 2016) based on real-time, GNSS-measured peak ground displacement (PGD) for use in the ShakeAlert EEW system for the U.S. West Coast. As implemented for ShakeAlert, GFAST runs in parallel with two seismic algorithms. The magnitude estimates from all three are combined in a weighted average (M_{AV}). What is the optimal logic for determining which magnitude estimates are included in M_{AV} each time source parameters are updated during an earthquake? Murray et al. (BSSA, in review) presented a framework and preliminary parameters to suppress inclusion of (or "throttle") GFAST magnitude estimates (M_{PGD}) that may be unreliable due to noise in the GNSS position estimates. Ahead of formal evaluation for inclusion in the production system, we are monitoring GFAST behavior on ShakeAlert servers that simulate the production environment under typical real-time conditions. This has highlighted aspects of the initial throttling criteria that warrant optimization. The initial criteria required 1) ≥3 GNSS stations to report PGD exceeding time-dependent threshold values determined empirically from analysis of GNSS position noise, and 2) M_{PGD} uncertainty ≤0.5 unit. We have since added two criteria: excluding position data with large uncertainties and only including M_{PGD} when M_{AV} already exceeds 6.0 using seismic data alone. We also re-estimated the PGD thresholds to obtain more conservative values that better eliminate suspect M_{PGD} and a finer temporal discretization to reduce abrupt changes in M_{PGD} throttling over time. In parallel we are exploring ways to reduce noise and steps in the GNSS position time series themselves and to better characterize their true uncertainties. Finally, we are considering adopting spatially variable PGD thresholds to account for geographic variation in station density, as well as refinements to the method for deriving M_{PGD} uncertainty.

Real-Time Gnss Point Positioning for Shakealert

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We have developed a real-time GNSS point positioning capability based on low-latency measurements from ~ 1000 Global Navigational Satellite System (GNSS) receivers to rapidly characterize large earthquakes and, where relevant, tsunami. For earthquake early warning applications such as ShakeAlert, the system can enhance traditional seismic monitoring by allowing moment release to be quantified as fault rupture unfolds. Position time series from all stations within the ShakeAlert footprint are continuously estimated within an earth center of mass-fixed reference frame and streamed as local north, east and vertical coordinates to ShakeAlert centers in Seattle WA and Berkeley and Pasadena, CA. Average positioning latency, which includes satellite observable acquisition, telemetry, and processing, averages about 0.5 seconds and average position variance within the ITRF reference frame of 4, 6 and 8 cm in the north, east and vertical components, respectively.

This system captured the 2019 Ridgecrest California M7.1 earthquake and determined its coseismic deformation of up to 70 cm on 12 nearby stations within 22 seconds of event nucleation. Those 22 seconds comprise the fault rupture time itself (roughly 5-10 sec), another ~5s for propagation delay between various regions of slip and GNSS stations, another 5-10s for dynamic displacements to dissipate such that coseismic offsets 'settle down,' plus another 1.4 seconds for telemetry and data analysis latency. Comparison of coseismic deformation estimated within 25 seconds to that determined with post-processing using several days of post-processing show that the real-time offsets were accurate to within 10% of the post-processed "true" offsets.

The GNSS-based high-M6 PGD magnitude at ~25 seconds could have nonetheless triggered or revised an alert before S-waves reached the LA Basin. This highlights how GNSS can improve earthquake early warning magnitude estimation for large events whose duration and extent of rupture precludes accurate assessment using only the first few seconds of P-wave amplitudes.

An Earthquake Early Warning System Validation Framework for Western Canada

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We present a framework for validating synthetic seismograms for use in earthquake early warning (EEW) systems, that are at the forefront of seismological and seismic hazard research. The Cascadia Subduction Zone (CSZ) is generally seismically-quiet yet has historically hosted large (>M8) events, and seismologists estimate a 7-15% chance of a margin-wide rupture in the next 50 years. Developing an EEW algorithm is crucial in minimizing fatalities and loss resulting from an imminent event. The algorithms used in most EEW systems require seismic data with which to train them. Although the paucity of seismicity along the CSZ is a limiting factor in training algorithms, synthetic seismic and geodetic data can be used as a supplement. However, a framework has yet to be published validating synthetic data for such applications.

We use a set of semi-stochastic forward modeling codes to generate 112 CSZ, as well as two crustal Leech River Valley Fault Zone (LRVFZ) rupture scenarios and associated waveforms. The CSZ scenario events range from 6.8 < M < 9.5, and the LRVFZ scenario events are an M6 and M7. The waveforms are generated for 29 collocated GNSS and accelerometer stations located on Vancouver Island, 157 accelerometer stations located along Washington and Oregon, and 5 offshore accelerometers. To ensure the synthetic data are representative of true earthquake scenarios, we develop a validation framework consisting of three main steps. (1) We compare high-frequency peak ground acceleration, peak ground velocity, and Modified Mercalli Intensity; (2) low-frequency peak ground displacement; and (3) P-wave displacement amplitude (Pd) with well-validated models. We also evaluate whether the scenario P-waves would trigger an STA/LTA algorithm, which is key in determining the onset of an earthquake before the more destructive waves arrive. Through the validation process, we find the synthetic seismic data to be representative of true earthquake scenarios and a valuable component in the training of EEW algorithms in western Canada.

Combining Earthquake Early Warning Solutions From Different Algorithms: Application to Switzerland

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It is increasingly common for seismic networks to operate multiple independent automatic algorithms to characterise earthquakes in real-time. In particular, multiple algorithms are an advantage when operating an earthquake early warning (EEW) system, allowing for redundancy and increasing tolerance to algorithm errors. Today, 'decision modules' that select the preferred solutions are rather simple and use ad hoc rules - an efficient real-time method is lacking. The Swiss Seismological Service (SED) currently tests the Virtual Seismologist (VS) and the Finite-Fault Rupture Detector (FinDer) (Massin et al., 2022). We have explored how to combine ongoing solution updates from these algorithms, inspired by the approach outlined in Minson et al. (2017). First, we use the event characterisation (origin time, hypocenter and magnitude) to predict, at each station in our network, the ground motion envelopes that match the duration of data already observed. We provide an absolute measure of how well the event origin matches the observations by the goodness-of-fit between the observed and predicted envelopes. This method provides a measure which can be used to determine when a preferred solution reaches an appropriate confidence level to send an alert, or indeed to compare two (or more) different event characterisations directly. We demonstrate that this approach can also be used to suppress false alarms commonly seen at seismic networks, improving over using traditional quality criteria based on e.g. location pick RMS or azimuthal gap. Initial tests using the 10 largest earthquakes in Switzerland between 2013 and 2020 and events that caused

false alarms (quarry blasts, teleseismic earthquakes, etc.) demonstrate that this approach can effectively identify event characterisations with small errors in location and magnitude, and can clearly identify and discard false origins or incorrect magnitudes. The next step will be to implement the algorithm in a real-time workflow.

Earthquake Early Warning Optimization and Efficacy [Poster]

Poster Session • Thursday 20 April

Conveners: Alison L. Bird, Natural Resources Canada, Sidney (alison.bird@nrcan-rncan.gc.ca); Claire Perry, Natural Resources Canada (claire.perry@NRCan-RNCan.gc.ca); Sara K. McBride, U.S. Geological Survey (skmcbride@usgs.gov); Danielle Sumy, Incorporated Research Institutions for Seismology (danielle.sumy@iris.edu)

Alaska Earthquake Early Warning Scenarios and Warning Time Estimates

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Alaskans face a pervasive seismic hazard due to numerous fault systems, such as the Aleutian subduction zone, the Queen Charlotte-Fairweather fault system, and crustal faults like the Denali fault. These hazards leave many communities in Alaska vulnerable to strong shaking caused by large earthquakes. An Alaska earthquake early warning (EEW) system has the potential to reduce emergency response times and give Alaskans time to take protective actions. Despite this, Alaska does not presently have EEW capabilities. Alaska's size, diverse population, and highly varied tectonic environment pose scientific and social questions distinct from current EEW development in the United States. We present a range of deterministic earthquake scenarios designed to examine how different source characteristics, such as magnitude, depth, location, and fault system, impact the performance of EEW in Alaska. For each scenario, we use travel-time estimates and the distribution of the existing seismic network in Alaska to model detection, alert, and warning times. We compare warning times to peak ground motions – obtained using ShakeMap 4 – to determine which ground motion intensities can receive warnings. Our results suggest that timely warnings for shallow earthquakes are reliable for ground motion intensities up to MMI V, with ideal scenarios receiving warnings up to MMI VII. We also find that deep earthquakes along the subducting slab have higher warning times for the same ground motion intensities when compared to shallow earthquakes.

Earthquake Early Warning Instrumentation and Efficient Workflows

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To optimize earthquake early warning (EEW) systems, much can be learned from existing and industry proven EEW solutions and how they can be efficiently deployed with high quality ground motions seismic stations capable of delivering the highest fidelity and low latency data sets to the processing data centers' detection algorithms. Specifically, public safety EEW systems require strict service level agreements (SLA) with regards to overall uptime, prompt arrival of high quality data, and issuance of accurate and timely warnings. This can only be achieved via the proper definition and selection of sensors, dataloggers, power systems, and communication systems. Also, when planning EEW Networks, it is important to consider the end-to-end workflow, from system definition and roll-out, through to network operation, maintenance and ongoing validation to ensure the system continues to satisfy its mandate. Deployment of an EEW system can represent a significant challenge to monitoring agencies, but leveraging proven implementations and technology partners can greatly reduce the associated risk and implementation timeline.

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Earthquake Science Communication of the 6.4 M Event Through Various Dissemination Products Used at the Puerto Rico Seismic Network

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The Puerto Rico Seismic Network (PRSN) is recognized as the alternate Tsunami Focal Point by the Puerto Rico Rico Emergency Management Bureau (PREMB). One of its goals is to distribute earthquake and Tsunami information to the local government, Emergency Management offices (Puerto Rico Emergency Management Bureau (PREMB), Virgin Islands Territory Emergency Management Agency (USVI-Vitema), Department of Disaster Management (British Virgin Islands-DDM), National Weather Service, Dominican Republic-ONAMET, University Seismological Institute Dominican Republic-ISU, and the general public. The Puerto Rico Seismic Network seismic area of responsibility (AOR) includes the Virgin Islands, British Virgin Islands and Eastern Dominican Republic. There are various dissemination products used to send information to these distinct offices. The dissemination products include (Broadcast server in which is the principal sending method, RSS, SMS, PRSN webpage, catalogues, Social Media (Twitter/Facebook), Regroup, Phone Calls, Fax, and Press). In addition, in case PRSN is confronted with a hurricane it has an internet and satellite broadcast system in which is the Dartcom/XRIT Ingester that works with the Weather Message Software and receives information from the NOAA Weather Wire data stream. The information received is observed in the Weather Message Client, within the Weather Message Client; Tsunami and Earthquake information statements and bulletins can be observed. The Agency that transmits Tsunami information statements and bulletins through the Weather Message Client is the PTWC. One of the earthquakes that has caused a major impact within Puerto Rico was the 6.4 M event that was on January 7, 2020. This event caused a massive blackout in which the majority of communities within the south region of Puerto experienced. Even though, these challenges were faced the geophysical analysts on shift and PRSN staff worked long hours and dedicated a lot of effort to ensure all agencies and public were informed. Lessons learned throughout this event have been to keep working with a lot of dedication to have a better efficient communication.

Empirical Calibration of Site Amplification From Residual Analysis of Earthquake Ground Motion Spectra and Station Magnitudes in Eastern Canada

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In this study, we find that local site amplification of short-period seismic waves are large sources of variability in the mean station magnitude residuals and ground motion intensity estimates needed for accurate earthquake monitoring and hazard mitigation. The adoption of ground motion models (GMMs) that account for source, path and site variability are important to consider for accurate Earthquake Early Warning (EEW) alerting. For periods in the range 0.02-10 seconds, we find that instrumentally observed ground motion intensity parameters are amplified by as much as 8-10 at some seismic stations located in glaciated regions of eastern Canada. Glaciation left many high seismic velocity, low attenuation shield rock sites exposed but where glacial sediments overlay the rock, high impedance contrast conditions exist. Such sharp impedance contrasts result in resonant effects that amplify short-period seismic energy, which has implications for EEW alerting systems in zones of high population density and critical infrastructure in eastern Canada. Using instrumentally observed New Generation Attenuation East (NGA-East) ground motions, we develop a log-linear relationship between seismic station site amplification and station magnitude residual (Mw). In addition, horizontal-to-vertical spectral ratio (HVSR) from microtremor are used to determine fundamental site period at the same sites. The comparison of HVSR site period to that obtained using NGAE-GMM earthquake spectral ratios provides proxy relationships between station-based magnitude, amplification and site period that should be implemented in EEW alerting systems in eastern Canada for improved accuracy of the predicted shaking.

Engagement and Outreach to Ensure the Success of Canada's Earthquake Early Warning System

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Natural Resources Canada (NRCan) is developing a national Earthquake Early Warning (EEW) system for regions of moderate to high earthquake risk in Canada. The EEW sensor network will be focussed along the west coast of British Columbia, in eastern Ontario, and in southern Quebec. Canada's EEW system will facilitate mitigation of earthquake impacts through advance notification of strong ground motion, allowing for timely and appropriate response actions by emergency measures organizations, critical infrastructure (CI) operators, other industrial facilities, and the public. For the EEW system to be effective, however, a culture of awareness is necessary to ensure appropriate protective actions are taken when alerts are received. This will be achieved through a substantial, coordinated public education campaign. NRCan is also hosting workshops and other outreach activities with CI operators to ensure they are aware of the benefits of installing systems which will automatically translate EEW alerts into protective actions, such as opening doors, sounding alarms, closing valves, stopping hazardous machinery, and halting trains. Similarly, NRCan is encouraging technical providers in Canada to develop such automated systems for the country's various CI sectors.

NRCan is working with federal and provincial public safety organizations, private and international collaborative partners, and Non-Governmental Organizations, to ensure authoritative, consistent, accessible EEW messaging is available to the public and technical users. Additionally, NRCan contracted an Indigenous Communications Assistant to develop educational materials and engagement activities specifically for First Nations' communities. With the ability of humans and automated systems to take safe actions before the arrival of potentially harmful shaking, the national EEW system will contribute to Canada's efforts to meet the recommendations within the United Nations Sendai Framework for Disaster Risk Reduction.

Evaluating the Impact of Location Errors on Magnitude Estimates Through Epic

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Earthquake early warning (EEW) programs like ShakeAlert, can send timely alerts to regions prior to damaging shaking. These alerts allow people to take protective action such as to drop, cover, and hold on, and mitigate their seismic risk. EPIC, a network-based point source algorithm used in ShakeAlert, determines the location and magnitude of earthquakes using data from the first few seconds after P-wave arrival at local to regional stations. While EPIC has reliably provided estimates of locations and magnitudes for many recent earthquakes, some poorly constrained events exist particularly at the edges of the ShakeAlert reporting region. Because EPIC relies on station-epicenter scaling laws to aid in calculating the magnitude, poorly located earthquakes can also lead to an increased error in magnitude estimates. In this presentation, we identify the degree that recent high location error events have affected the resultant event magnitude and what effect these events have on EPIC's overall magnitude uncertainty. Using a retrospective catalog of recent events, we also show how recently developed algorithms that improve EPIC's location estimates for edge of network events have improved related magnitude errors. Improvements in both location and magnitude estimates limit the likelihood of a missed event, or conversely an overestimate leading to an erroneous error.

Evaluating the Performance of Long Short-Term Memory Neural Network in Predicting Peak Ground Acceleration of Earthquakes Using Shrinking P-Wave Data

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Institutional use cases of Earthquake Early Warning Systems (EEWs) estimates of Peak Ground Acceleration (PGA) using P-wave data include automated high-speed transportation systems that can stop, abort airplane landings, prevent additional cars from riding on bridges and tunnels, initiate shutdown of sensitive industrial infrastructure like gas pipelines before peak ground motion arrives, preventing cascading failures. Traditional EEWS systems rely on the evaluation of 3 seconds(s) of P-wave data to make predictions about PGA. However, this paper evaluates the performance of varying durations of P-wave data on predicting PGA using a Long Short-Term Memory (LSTM) Recurrent Neural Network.

The LSTM model was trained, tuned, and evaluated on nineteen (19) moderate to large earthquake events collected in Japan by the National Research Institute for Earth Science and Disaster Prevention (NIED). The methodology involves three independent experiments using 4 seconds, 3 seconds, and 2 seconds of seismic data recorded after the arrival of P-waves to predict PGA. After evaluating the model's performance on unseen accelerograms, the experiments using 4 seconds, 3 seconds, and 2 seconds of P-wave window data achieved average Test Root Mean Square Error (RMSE) of 0.559, 0.500, and 0.497, respectively. Surprisingly, the experiment using 2-second P-wave data achieves average test RMSE, which is 0.6% less than that of the 3-second P-wave experiment. We conclude that LSTM models are as effective in using accelerograms of the first 2 seconds after the arrival of P-wave to predict PGA as 3 seconds. The result of this study has positive implications for the timely prediction of PGA in existing EEWs and the improvement of existing mathematical models that predict PGA.

Expected Contribution Metrics for Earthquake Early Warning Network Telemetry

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Earthquake early warning (EEW) requires reliable, low-latency data delivery. Limits on funding require engineers and network sponsors to consider which investments in telemetry and stations are most effective in terms of mission and cost.In previous work we presented a method to estimate annualized contributions of individual stations based on return times of strong shaking at the station drawn from hazard curves developed by the USGS National Seismic Hazard Mapping Project (NSHMP). Return times (years) can be interpreted as the reciprocal of the expected participation rate (1/yr) at a given ground motion, i.e., how often the station is expected to experience that ground motion amplitude.For the analysis we use peak ground acceleration (PGA). Hazard curves are available on a 0.05x0.05 degree grid for the western U.S. For an added station, the station-expected contribution is the product of the annual rate, the area improved by the station, and the alert-time reduction because of the new station, with physically meaningful units of km^2-s/yr. While simple to calculate for individual stations, this approach cannot be directly applied to telemetry because a telemetry node can be shared among stations with different seismic hazard rates. To generalize the expected contribution for a telemetry change, we discretize the area affected by the change, and calculate the return time for each discrete cell. The result is an improved and consistent estimate that applies both to individual stations and to collections gathered to a telemetry component or system. We illustrate the approach with stations and telemetry hubs in the Southern California Seismic Network (SCSN) that contribute to the ShakeAlert EEW system. Results provide relative ranking among components and systems, which can be used to guide investments in system hardening and redundancy.

Geocoding Applications for Social Science to Improve Earthquake Early Warning Systems

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Geocoding is a spatial analysis technique that uses address information (e.g., street address, intersection, census tract, zip code, etc.) to determine geographical coordinates (latitude and longitude). In recent decades, geocoding has gone beyond its primary use for census and demographic information to novel applications in disaster risk reduction, even to earthquake early warning. The ShakeAlert® earthquake early warning system, operational on the West Coast of the United States, has begun public alert testing in California, Oregon, and Washington. Communication, education, and outreach efforts with the over 50 million diverse people who live in these states has rapidly increased. In tandem, surveys, interviews, and other techniques have aimed to collect data from these individuals to best understand what people know about the system, sources of misconceptions, and how to improve access to alerts for people with disabilities or limited-English proficiency, as examples. Geocoding these data can improve our overall understanding of the system, including whether the areal alerting polygon holds after alert distribution,

whether individuals take protective actions such as 'Drop, Cover, and Hold On', and the demographics of the communities that the system is reaching or unintentionally missing. Here I demonstrate the usefulness of geocoding techniques to earthquake early warning through its application to two case studies: one on survey responses gathered from tests of the ShakeAlert system in 2019, and the other on how geocoding applies to earthquake video footage used to study individual and group behavior during earthquakes. Geocoding and its application to earthquake early warning systems combines physical and social science data together to build a stronger understanding of how these human-centered systems are working, whether alerting polygons hold during an earthquake, and may have future applications to a more robust understanding of seismic intensity, especially in areas with sparse seismic networks.

National Public Earthquake Early Warning Systems Emerging Across Central America.

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Within the next 2 years, operational public EEW will emerge across Central America. In this region, with high earthquake hazard, a vulnerable building stock, and rapidly increasing population density, an EEW system can mitigate some of the casualties from the frequent subduction and shallow crustal earthquakes. The ATTAC (Alerta Temprana de Terremotos en América Central) project includes seismic agencies in Guatemala (INSIVUMEH), El Salvador (MARN), Nicaragua (INETER), and Costa Rica (OVSICORI-UNA) together with SED at ETH Zurich in an effort to build national public EEW systems. Each EEW system operates on a high-quality permanent seismic network with the ETHZ SeisComP EEW (ESE) system that ncludes the Virtual Seismologist and FinDer EEW algorithms. 70 new low-latency EEW-ready accelerographs have been deployed across the region. In order to track the network and to monitor EEW configuration and results, performance-tracking tools and procedures have been introduced. A dissemination module allows to select the best EEW solution, and to provide targeted alerts to the public through the various dissemination channels. Currently, alerts to limited user numbers are delivered via a mobile App and the Japanese-developed EWBS system based on digital TV EWBS, each of which can be expected to scale to the population. The Mobile app is the most promising. Basic data analysis demonstrated that at least 74% percent of the app users can receive a notification in less or equal to 5 seconds. We analyze the current performances regarding accuracy and speed (ranging from 10-15s for shallow on-shore seismicity, and between 20-25s for offshore or deep events), we demonstrate successful EEW for the recent felt earthquakes, and we show how we intend to extend EEW to public users across the region. Improving network practice and software management remains a priority because false alerts are typically related to configuration and metadata errors.

Performance of a Real-Time Machine Learning Classifier in the Epic Earthquake Early Warning Algorithm

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ShakeAlert is the US West Coast Earthquake Early Warning (EEW) algorithm, now delivering alerts of impending shaking from earthquakes to users throughout California, Oregon, and Washington. The Earthquake Point-source Integrated Code (EPIC) (formerly ElarmS) algorithm is one of two algorithms currently running in the production ShakeAlert EEW System. EPIC is fast, usually the first algorithm to alert, and can create accurate point-source estimates of earthquake magnitudes and locations using a minimum of 1 sec of data from one station, and 0.5 sec of data from three additional stations.

We have implemented the Meier et al., 2019 Machine Learning (ML) classifier into the EPIC algorithm with the goal of reducing the number of false triggers coming into the system. This reduction of spurious triggers could prevent erroneous alerts and also allows EPIC to create alerts using fewer than the currently required 4 stations due to increased confidence that the signals are from earthquakes. This modified version of EPIC allows for the creation of 2-station alerts using triggers that pass the ML classifier. For those 2-station alerts, we have also added a PGA/PGV amplitude threshold for those first two triggers following the methodology of the PLUM algorithm. Here we present the replay and real-time results of the latest version of EPIC with the ML classifier implementation

Redundant Telemetry, System Monitoring, and Planning Tools for a Highly Resilient and Secure Regional Seismic Network (RSN)

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The Caltech/USGS Southern California Seismic Network (SCSN) is a modern digital ground motion seismic network. It develops and maintains data acquisition and delivery systems for rapid earthquake information products like earthquake origins, magnitude, and ShakeMap as well as for Earthquake Early Warning (ShakeAlert).
Here we present recent and ongoing innovations in telemetry, system monitoring, and planning tools that keep the network running efficiently and provide timely high-quality streaming data.

Our goal is to improve telemetry by making it more resilient and secure. Most of SCSN sites deliver data continuously to the cloud (AWS) and terrestrial servers located on the Caltech campus in Pasadena. This allows SCSN to keep processing data during extreme events. We also try to diversify the telemetry at each site to be less dependent on one type of hardware and service providers by using cell modems, SS radios of 900 and 700 Hz, regular satellite and Starlink, direct internet connections, microwave, and 4.9GHz public safety connections. We continue to improve the telemetry path diversity, minimize data transfer latency, and increase available bandwidth. We are in the process of connecting the SCSN sites to the California State Microwave Tower backbone in collaboration with CalOES PSC. We have also established VPN connections to most of our sites to keep the data encrypted.

We developed tools to monitor the system state of health, including regular measurements of data transport latency and telemetry link bandwidth from each datalogger to the data center. Using these results, we prioritize low-performing sites for improvements based on their importance for ShakeAlert. For newly installed sites, we track if they meet our latency and bandwidth targets.

For more than 390 seismic stations currently installed, we are building tools to evaluate the value of their contribution to ShakeAlert, real-time earthquake detection and data archiving. To identify which stations would have the biggest impact if they were improved? The answer is critical for planning station maintenance and new station installations.

Toward Implementing Earthquake Early Warning in Resource-Limited Regions: Comparing Magnitudes Predicted by Traditional Regressions and by Convolutional Neural Networks

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Strong earthquakes present major hazards to millions of people and the built environment worldwide. Earthquake early warning (EEW) systems have the potential to provide strong shaking warnings and thus allow proactive measures to be taken to lower the associated risks. However, current EEW models suffer from tradeoffs between timeliness and prediction accuracy and can generate false alerts. Also, the model development procedures are not transparent enough for duplication by low-tech communities. Thus, additional work is needed to make robust EEW systems that are readily reproducible. As part of a larger project to develop EEW systems from scratch for limited-resource communities exposed to high seismic hazards, this research

focuses on magnitude prediction. We evaluate the accuracies of earthquake magnitude predictions from the traditional linear regression approach and from a machine learning model using three-component recordings of global earthquakes in the Stanford Earthquake Dataset. The magnitudes of the earthquakes used ranged from 3.5 to 7.9. The linear regression model we evaluated estimates earthquake magnitudes from peak P-phase displacements. We used Convolutional Neural Networks (CNN), which can capture trends in the data that the traditional linear regression method cannot tap into, for feature selection. The CNN takes 10 s time series, consisting of 3 s of pre-P noise, 4 s of signal starting from the first P-wave arrival, and padded with zeros for 3s to construct windows of uniform length. These features are combined with the peak vertical acceleration and are fed to a series of dense layers for magnitude predictions. Preliminary results show that the current CNN model does not outperform the linear regression approach. However, the CNN model training and optimization is ongoing. At a later phase, we plan to use the extracted features in a Transformer to improve the model's performance. The results of the final CNN model performance will be presented.

Keywords: earthquake early warning, feature selection, machine learning, neural networks

Update on the Progress of California Strong Motion Instrumentation Program (CSMIP) Toward Real Time Data Acquisition

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The CSMIP network of over 1360 seismic stations has been a predominately triggered system where segments of strong motion data are only sent into the CSMIP server after shaking at a station exceeds a set threshold. Once triggered, the recorders connect to the server and send in the data. With the start of CSMIP's involvement in the California Earthquake Early Warning System (CEEWS), the contributing CSMIP stations send real time streaming data to the ShakeAlert servers. During the last few years, number of CSMIP stations that would send streaming data to contribute in the CEEWS project has increased. Additionally, the CSMIP is currently modernizing the seismic equipment (recorders and communication) at all stations which will allow for real time streaming. The CSMIP with collaboration of the Instrumental Software Technologies, Inc. (ISTI) has established a real time data system in the cloud. This system collects earthquake data at 100 samples per second in real time for rapid response to earthquake. However, CSMIP will continue recording and disseminating triggered data at 200 samples per second.

This poster will present the status of the CSMIP real time data system and the plans for future expansion and real time data flow.

Earthquake Preparation Across Scales: Reconciling Geophysical Observations With Laboratory and Theory

Oral Session • Thursday 20 April • 08:00 AM Pacific

Conveners: Piero Poli, Università di Padova (piero.poli@unipd.it); Patricia Martinez-Garzon, GFZ Potsdam (patricia@gfz-potsdam.de); Gregory McLaskey, Cornell University (gcm8@cornell.edu)

What Controls the Characteristics of Compressive Failure and Accelerated Seismic Release?

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Externally stressed brittle rocks fail once the stress is sufficiently high. This failure is typically preceded by a pronounced increase in the total energy of acoustic emission (AE) events, the so-called accelerated seismic release. Yet, other characteristics of approaching the failure point such as the presence or absence of variations in the AE size distribution and, similarly, whether the failure point can be interpreted as a critical point differs across experiments. Here, we show that large-scale stress heterogeneities induced by a notch --- which have already been shown to lead to significant aftershock activity during loading --- fundamentally change the characteristics of the failure point in triaxial compression experiments under a constant displacement rate on Westerly granite samples. Specifically, we observe accelerated seismic release without a critical point and no change in power-law exponent epsilon of the AE size distribution. This is in contrast to intact samples, which exhibit a significant decrease in epsilon before failure. Our findings imply that the presence or absence of large-scale heterogeneities play a significant role in our ability to predict compressive failure in rock.

Complex Multi-Scale Preparatory Processes of Large Stick-Slip Events in Laboratory Experiments

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Earthquake forecasting relies on identification of distinctive patterns of precursory parameters that might precede large earthquakes. Laboratory stick-slip experiments provide an analog of the seismic cycle with dynamic slip and Acoustic Emissions (AE) characterizing brittle failure events before, during and after large lab earthquakes in controlled conditions. Recent laboratory studies showed that the ML/AI techniques may open new avenues towards laboratory earthquake prediction on smooth faults. However, not enough work with deep learning techniques has been yet done on rough and heterogeneous faults.

In this study laboratory stick-slip experiments were performed in triaxial pressure vessel on Westerly Granite samples at constant displacement rate on rough pre-fractured fault. The experiments produced complex slip patterns including fast and slow, large and small slips of the fault surface, and confined slips producing AE data bursts without externally measurable slip. Preparatory and nucleation processes were tracked with an ensemble of 16 features characterizing damage and stress evolution, localization and cluster processes, earthquake interactions, and local micromechanics and stress heterogeneity. At different experimental boundary conditions, we decompose observable complex spatio-temporal trends in features identifying effects of persistent fault roughness, a cross-play of local and global damage, and local stress evolution approaching system-size events. The observed trends highlight localization processes, and the nucleation of the system size events is masked or governed by interaction of different spatial scales during the preparatory process, which are also affected by the boundary conditions. The results provide a pool of reliable, physics-based characteristics that signify processes leading to system-size earthquakes, which could be used in development of ML/AI aided earthquake forecasting.

Towards Identifying Fault Heterogeneity Based on Nucleation of Large and Small Events: Insight From Simulations of Earthquake Sequences on Rate-and-State Faults

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Understanding the relation between heterogeneity on frictional interfaces and the resulting slip patterns is a challenging, highly nonlinear, and dynamic problem. Here, we aim to advance this topic by conducting numerical simulations of long-term slip histories on rate-and-state frictional interfaces with heterogeneous normal stress, the main consequence of rough interfaces, and/or heterogeneous rate-and-state friction properties. We consider heterogeneity that introduces instability lengthscales ("nucleation sizes") that vary by orders of magnitude. Systematic increase in normal-stress heterogeneity (NSH) induces an increasing complexity of the resulting earthquake sequences as well as a continuum of behaviors ranging from fault-spanning to foreshock-like events. In fault models with sufficient NSH, we observe both large and small events initiating from scales much smaller than the nucleation size estimates based on fault average properties. In such models, the initial seismic moment rates are similar for events of different eventual sizes; in other words, large events are just small events that run away. However, in models with uniform normal stress and the same significant nucleation-size variation achieved by varying the rate-and-state characteristic slip parameter rather than the normal stress, the nucleation processes of large events are similar to those on uniform interfaces. Small events still occur, but they have less tendency to grow into large events. Furthermore, the initial moment rate release for the large and small events is very different. Our study suggests that faults with different types of heterogeneity may have different seismological observables, such as different initial rate of moment release for large and small events, opening the possibility of constraining fault heterogeneity based on a range of seismic observations. Our current work focuses on investigating the differences in slip complexity of fully dynamic, quasi-dynamic, and 2D simulations of heterogeneous interfaces.

Precursory Deformation in the Lab – Effects of Roughness, Loading Rate and Effective Pressure

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Seismic and geodetic studies of large earthquakes at plate-bounding faults suggest potential preparation phases potentially extending for months before main shocks occur. Field observations show a varying deformation behaviour preceding failure including aseismic creep and foreshock activity. Seismic foreshocks and aseismic slip may or may not interact, low and decreasing seismic b-values may change in space and time or remain roughly constant. A spatial correlation between inter-seismically locked fault patches and co-seismic slip distribution has been suggested and is corroborated by experimental studies. Here we report on laboratory experiments performed at confining pressures of 30- 150 MPa on intact and faulted samples with different roughness, rock types (granite, sandstone, shale) and varying boundary conditions (loading rate, geometry, fault prestress and fluid pressure). Precursory deformation approaching failure is mainly affected by loading conditions (displacement-driven shear vs injection-driven shear), fault roughness, effective normal stress and load point velocity. For all faults, we observe that enhanced loading/injection rates promote unstable stick-slip events. Rough (heterogeneous) faults exhibit extended precursory slip and interplay of smallscale high frequency acoustic emission events and slow confined ruptures during runup to system-wide slip events. Smooth faults with polished surfaces typically display short preparatory slip that is mostly aseismic. Slip events occur abruptly and are initiated by few large acoustic events. Typical signatures derived from high-frequency monitoring of picoseismic events include space-time changes in b-values, spatial correlation of events (c-, d-values), changes in focal mechanism orientation patterns, seismic moment release and partitioning between seismic and aseismic deformation. Localization of deformation in slip patches during the precursory deformation phase affects subsequent rupture and slip.

The Seismological Signature of Earthquake Nucleation

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Frictional theory and laboratory experiments indicate that earthquakes initiate gradually over a finite fault region, with a dimension related to local elasto-frictional properties. Estimating this nucleation dimension on natural faults could therefore provide constraints on in-situ frictional properties and stress state; however, direct observation of the nucleation phase has proved challenging, also because the effect of nucleation on far-field seismological observables was not quantified.Here I introduce a source model for earthquake nucleation and discuss the resulting scaling relations between source properties (far-field pulse duration, seismic moment, stress drop). I derive an equation of motion based on fracture mechanics for a circular rupture obeying rate-state friction and a simpler model with constant stress drop and fracture energy. The latter provides a good approximation to the rate-state model, and leads to analytical expressions for far-field displacement pulses and spectra. The onset of ground motion is characterized by exponential growth with characteristic timescale $t_0=R_0/v_f$, with R_0 the nucleation dimension and v_f a limit rupture velocity. Therefore, normalized displacements have a constant duration, proportional to the nucleation length rather than the source dimension. For ray paths normal to the fault, the exponential growth results in a Boatwright spectrum with corner frequency $\omega_c=1/t_0$. For other orientations, the spectrum has an additional sinc(.) term with a corner frequency related to the travel time delay across the asperity. Seismic moments scale as $M_0 \sim R(R-R_0)R_0$, where R is the size of asperity, becoming vanishingly small as R approaches R_0. Therefore, stress drops estimated from M_0 and f_c are smaller than the nominal stress drop, and they increase with magnitude up to a constant value, consistent with some seismological studies. The constant earthquake duration is also in agreement with reported microseismicity: for $0 < M_W < 2$ events studied by Lin et al (2016) in Taiwan, the observed durations imply a nucleation length between 45-80m.

The Complexity of Earthquake Generation in Nature: Beyond Cascade and Pre-Slip

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Detection and analysis of earthquake precursory processes is a challenging topic that have concerned geoscientist from different disciplines over almost a century. The classical view on how earthquakes nucleate evolved for decades around two widely accepted models where the mainshock is promoted by either the stress change from previous earthquakes or the occurrence of an aseismic transient. The improvements in earthquake monitoring, integration of geodetic techniques to capture slow deformation, and the incorporation of artificial intelligence for seismic data processing recently allowed a more complete picture on how earthquake sequences evolve before the occurrence of the mainshock. Here, we review and compare the available analyses describing observations on precursory processes of 32 earthquake sequences covering a magnitude range M_W [3.2, 9.1]. We combine and present both seismological and geodetic analysis and discuss the patterns that emerge collectively, with a special emphasis on relating the observations with the physical processes driving the evolution of earthquake sequences. Our analysis highlights various structural, tectonic and boundary conditions that play a role in the dynamics of the earthquake sequences, as well as various physical processes that may be acting superimposed. From it, we propose the idea of earthquake nucleation as a complex imbricated process, involving several temporal and spatial scales.

Waveform Similarity and Differential Travel Times Illuminate a Spatial Coalescence of Foreshock Activity Prior to Fast Laboratory Earthquakes

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Earthquake nucleation is a key problem in earthquake science with rich implications for earthquake early warning systems, earthquake forecasting, and understanding foreshock properties. Foreshocks are often viewed as a byproduct of the nucleation phase, and thus, understanding properties of foreshocks and the factors that control their spatiotemporal behavior is key for determining how earthquakes get started and their connection to the impending mainshock. We report on a suite of well-controlled laboratory friction experiments instrumented with an array of acoustic emission (AE) transducers. We systematically modulated the stiffness of the loading apparatus in tandem with the fault zone normal stress to produce a spectrum of slow and fast slip behaviors. AE data were measured in parallel with fault zone properties, allowing for a more robust understanding of the casual processes driving foreshock activity. We measured waveform similarity and pair-wise differential travel-times using AE templates and tracked their spatiotemporal evolution throughout the seismic cycle. During slow stick-slip, the fault creeps continuously throughout the seismic cycle and differential travel-times and waveform similarity remain constant. In contrast, during fast laboratory earthquakes, the fault remains locked throughout most of the seismic cycle and begins to unlock and accelerate once the fault reaches ~ 80% of its peak frictional strength. Once the fault begins to unlock and creep, the data show a sharp increase in waveform similarity and a rapid decrease in differential travel times, indicating that the foreshocks are starting to coalesce in space and time immediately before failure. These observations point to key differences in the nucleation process of slow and fast lab earthquakes and suggest that the spatiotemporal evolution of laboratory foreshocks is linked to fault slip velocity. Our data indicate that high waveform similarity and low differential travel-times are a fingerprint of fault creep and could be useful tools for tacking precursory processes before tectonic earthquakes.

Spatio-Temporal Localization of Seismicity in Relation to Large Earthquakes

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Progressive localization of deformation may signify a regional preparation process leading to large earthquakes [Ben-Zion & Zaliapin, GJI, 2020; Kato & Ben-Zion, Nat Rev Earth Environ. 2021]. The localization framework describes the evolution from distributed failures in a rock volume to localized system-size events. Ben-Zion & Zaliapin (2020) documented robust cycles of localization and de-localization of background earthquakes with M > 2 in Southern California that precede the M7 earthquakes within 2-4 years. This

analysis has been done on regional scale, without posterior selection of the examined areas (e.g., around epicenters of large events). Similar results are observed before M7.8 earthquakes in Alaska using background seismicity with M > 4, and in laboratory acoustic emission experiments. In this work we examine spatial characteristics of the localization process, identifying subregions that are responsible for the observed localization and delocalization. The analysis focuses on relative (with respect to other areas) changes in the background intensity. On sub decadal temporal scale, the observed relative seismic activity tends to concentrate on and switch between several subsets of the regional fault network. Within 2-10 years prior to a large event, there is relative activation in a large volume that not necessarily include the impending epicenter. This is followed by a prominent deactivation 2-3 years prior to a large event, reminiscent of the "Mogi donut", potentially reflecting a transition to aseismic or small events. Some regions may experience multiple activation episodes before a large earthquake. The results emphasize the importance of examining small-magnitude events and joint analyses of seismic and geodetic data.

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The Evolving Tidal Sensitivity of the Seismicity Rate in the Decade Before the M7.1 Ridgecrest, California 2019 Earthquake

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Solid Earth and ocean tides cause the oscillatory deformation of the crust and, thus, modulate stress on faults. Such stress modulation should be accompanied by the modulation of seismicity rates but, due to the small amplitudes of tidal stresses, the modulation is usually weak. If detectable, the sensitivity of seismicity rates to the tides is a valuable tool to probe fault state. We analyzed a decade of microseismicity in the Ridgecrest, CA area in the decade preceding the M7.1 2019-07-06 earthquake to study the tidal sensitivity of the seismicity rate and its temporal evolution. We applied a fully automated workflow combining machine learning detectors and template matching to the continuous waveforms to build a rich, high-resolution earthquake catalog. We used this catalog to investigate the modulation of seismicity rates by the tidal Coulomb stress and volumetric strain. Our study shows that seismicity is ubiquitously modulated by the tides and that the area along the M7.1 earthquake rupture shows increasing sensitivity prior to the rupture, starting in 2017.

Testing Earthquake Nucleation Length Scale in North-Central Oklahoma With Pawnee Aftershocks

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The interpretation of precursory seismicity can depend on a critical nucleation length scale that has been documented in laboratory experiments but is largely unconstrained in the seismogenic crust. To probe the nucleation length scale and associated earthquake nucleation processes at 2–7 km depths in Oklahoma, we studied seismic activity occurring prior to nine M 2.5–3.0 earthquakes that are aftershocks of the 3 September 2016 M 5.8 Pawnee, Oklahoma, earthquake. We analyzed seismicity occurring prior to these larger aftershocks and estimated the static stress changes associated with each event of each sequence based on precise earthquake relocations and magnitude estimates. If the earthquakes are spaced close enough to prior events, they could be plausibly triggered through standard stress transfer, and this might be evidence for a small nucleation length scale. On the other hand, if the events are spaced very far apart relative to their size, then static stress transfer is an unlikely triggering mechanism and some other process, such as widespread aseismic slip, would be required to collectively trigger the seismicity. Five of the nine large aftershocks studied did exhibit foreshock sequences, and we found all five of them were plausibly triggered via static stress transfer from nearby earthquakes occurring hours to seconds earlier, consistent with the cascade nucleation model and a small nucleation length scale (≤ 1 m) in this region. The smallest earthquakes we could quantitatively study were M −1.5 events, which likely have 1–2 m rupture dimensions. The existence of these small events also supports a small nucleation length scale ≤ 1 m, consistent with laboratory experiments on flat, smooth, bare rock samples. The other four of the nine large aftershocks studied did not have detectable seismicity within a 2 km radius of their hypocenters in the preceding 16 hour time windows. While this does not constrain nucleation length, it indicates strong variability of fault properties even within our 15 km study region in north-central Oklahoma.

Earthquake Source Parameters: Theory, Observations and Interpretations

Oral Session • Tuesday 18 April • 08:00 AM Pacific

Conveners: Vaclav Vavrycuk, Institute of Geophysics of the Czech Academy of Sciences (vv@ig.cas.cz); Pavla Hrubcova, Institute of Geophysics of the Czech Academy of Sciences (pavla@ig.cas.cz); Grzegorz Kwiatek, GFZ Potsdam (grzegorz.kwiatek@gfz-potsdam.de); Satoshi Ide, The University of Tokyo (ide@eps.s.u-tokyo.ac.jp); German A. Prieto, Universidad Nacional de Colombia (gaprietogo@unal.edu.co)

Leveraging the Iran Regional Moment Tensor Database to Estimate Parameter Uncertainties in 1D and 3D Earth Models

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The Arabia-Eurasia plate convergence is accommodated in a wide deforming zone spanning most of Iran resulting in frequent moderate-to-large earthquakes. We used in-country data to build a regional moment tensor database that includes over 2,000 events from 2004 to 2022 ranging in size from Mw 3.4 to 7.8. The magnitude of completeness is near Mw 4.2 since 2013 when broadband data from the Iranian Seismological Center became available in addition to data from the Iranian National Seismic Network. We used a single 1-D velocity model for all events adjusting the modeling frequency band based on event size and event-station distances when inverting 3-component data for the deviatoric moment tensor. To better understand and constrain source parameter uncertainties and the effects of unmodeled 3D structural effects, we are now re-analyzing selected events using the MTUQ (moment tensor uncertainty quantification) software, which performs a grid search over the full parameter space - double couple, deviatoric, or full moment tensor - for 1D and 3D velocity models. The computationally expensive calculation of 3D synthetics and fine-scale grid searches are performed on an HPC facility at USF. Initial results indicate that double couple and deviatoric grid searches usually agree well with earlier inversion results, while full moment tensor searches using surface waves only may result in significant, spurious non-deviatoric contributions. The use of appropriate 3D models significantly improves waveform fits and seems to reduce the non-double couple source contributions. Grid searches also reveal that a wide range of source parameters often results in misfits relatively close to a best-fit solution. This is particularly true for long-period analyses or datasets with limited azimuthal coverage and/or data with a low signal-to-noise ratio.

Time-Domain Determination of Regional Wave Propagation Characteristics and Earthquake Source Spectra: Application to the Ridgecrest, California Earthquakes

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Earthquake catalogs are growing exponentially in size thanks to the development of advanced detection and location methods. However, most deep catalogs contain only rudimentary information that quantifies the source, such as a Local Magnitude. We have developed a straightforward method that can measure the seismic moment and corner frequency from simple measurements of the seismogram. We analyze the spectral content of *S* waves using time-domain measurements of the horizontal shear wave maximum displacement amplitude, passed through a set of one-octave band-pass filters between

0.25-32 Hz. Following the development of Richter's 1935 Local Magnitude scale, we derive a functional form of maximum amplitude versus distance for each frequency band and use it to estimate wave attenuation as a function of frequency and distance. Using events in the Ridgecrest, California earthquake sequence, we derive frequency dependent attenuation curves for epicentral distances between 10 and 120 km. Attenuation is a strong function of frequency, inversely proportional to frequency, at a specific epicentral distance. The path averaged Q also increases at all frequencies (attenuation decreasing) with increasing epicentral distance. At 50 km distance Q(1-2 Hz) ~100 and Q(16-32 Hz) ~300, while at 100 km Q(1-2 Hz) ~ 200 and Q(16-32 Hz) ~500. If the maximum amplitude *S* wave samples increasingly greater depths in the crust with increasing distance, then Q increases significantly with depth. We use these empirical attenuation curves to correct the time-domain peak amplitudes to a reference distance of 10 km to recover the source spectrum. We find that the spectral shape is consistent with the Brune model, with a well-defined plateau at low frequency and a decay at high frequency inversely proportional to frequency squared. This time-domain method provides a reliable and efficient way to accurately measure earthquake source parameters.

Use of the Second Seismic Moments to Estimate Source Parameters and Rupture Directivity of Moderate Earthquakes in Central Italy

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Although directivity effect is usually associated with high magnitude earthquakes, it can also be relevant in moderate and small events. This effect results in azimuthal and spectral variations in ground motion that can be used to estimate the orientation of the fault plane or a prevailing rupture propagation. The associated spectral variations can strongly amplify the ground motion at locations that are in the forward-direction of the rupture propagation, so that even moderate magnitude earthquakes can cause severe unexpected damages. Knowledge of rupture directivity is therefore important for understanding seismic hazard and in the design of safe and resilient structures. However, determining directivity and source parameters for small to moderate magnitude earthquakes remains a challenge.

A common method for estimating the directivity is based on measuring the duration of the source pulse (the apparent source time function) at each location and then modelling it with a line source. Some approaches rely on the deconvolution of waveforms by an empirical Green's function to overcome the problems associated with the presence of path and site effects. A promising approach for estimating the rupture directivity effect and the associated source properties is based on the calculation of the second seismic moments. In this study we apply a method based on the calculation of the second seismic moments to estimate the rupture process and source parameters of moderate earthquakes that occurred in central Italy in 2016 using waveforms recorded by the RAN (Acceletrometic National Network) and the RSN (Seismic National Network) italian networks. We first used synthetic apparent source time functions computed from a geometric source model obtained from a real event to test the robustness of the method. Then, we applied the second-seismic moments method on moderate earthquakes occurred in Central Italy in 2016 trying two different deconvolution processes: one in the time domain and the other one in the frequency domain. The results are discussed and the strengths and weakness of the two approaches are highlighted.

Duration and Dynamic Stress Drop During the Initial Rupture "Breakaway" Stage of Ridgecrest Earthquakes

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The initial slope of P wave velocity seismograms often starts with a relatively low rate for a short time before growing quickly with an approximately ramp-like shape (Iio, 1992; Ellsworth and Beroza, 1995, Meier et al., 2016). The latter stage was named the "breakaway" stage by some authors. We adopt the self-similar dynamic circular growth model (Kostrov, 1964; Boatwright, 1980) and use P wave records at hypocentral distances less than 50 km to constrain the duration and dynamic "breakaway" stress drop for Mw>3.9 Ridgecrest earthquakes. The "breakaway" phases that we examined are generally well recorded by multiple local seismic stations, allowing us to assess the measurement uncertainties. All of the selected earthquakes have reliable moment tensor solutions (Wang and Zhan, 2020), which are used to estimate the P-wave radiation pattern. We calculate the P-wave response using a 1D Southern Sierra model and a station-dependent near-surface velocity structure. The latter is constrained using the P wave polarization information (Ni et al., 2014; Park and Ishii, 2018) and empirical relations derived from laboratory observations (e.g., Boore, 2016). We find breakaway durations for 3.9<Mw<5.5 Ridgecrest earthquakes are about 0.1 s, 5-30% of the total rupture duration. The "breakaway" stress drop is nearly independent of magnitude and the "breakaway" duration, but it is positively correlated with Brune's stress drop of the entire rupture. The measures are proportional to $(V_R/V_s)^{-3}$ where V_R and V_s are rupture velocity and S wave speed. Assuming V_R/V_s=0.7, the geometric mean of the "breakaway" stress drop is 21 MPa with a factor of 1.8 uncertainty. This mean changes from 112 MPa to 10 MPa when V_R/V_s increases from 0.4 to 0.9. It is 4.5-51 times the mean Brune's stress drop (~2.2 MPa) of these earthquakes. The estimates of "breakaway" stress drop statistically significantly increase with source depth at a rate of 1.9 MPa/km. A conceptual rupture model is proposed to explain the big difference between the "breakaway" stress drop and Brune's stress drop.

Early Parameters of Seismograms: What Influences Them and Are They Useful in Understanding Earthquake Determinism?

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It is reasonably simple to determine the magnitude of an earthquake after it has happened. However, it is unclear to what extent an earthquake's final magnitude is 'known' before rupture ends. We are interested in whether features of the initial stages of an earthquake can make accurate predictions about the earthquake's final size: whether earthquakes are deterministic. This is not a new question, and several approaches have been taken in the past. For example, Olson and Allen (2005) found a relationship between the final magnitude and predominant period of the first 4 seconds of earthquakes. However, the results remain controversial, partly because they and subsequent researchers analyzed only moderate numbers of earthquakes, and examined long windows of time relative to the durations of most earthquakes. The increase in data availability and quality over the last 15+ years now allows us to re-investigate this issue in a more statistically robust way.

We examine the beginning of ~8000 earthquakes from around the world. We quantify the predominant period, average period, integral of velocity squared (IV2) and peak ground displacement (PGD) in time windows ranging from 0.3 to 4 s, and investigate their relationships with magnitude. We find the strongest relationships with PGD and IV2. Whilst these relationships are strongest in the longest windows, they do persist as we look at increasingly shorter windows. For other parameters such as predominant period, we see a relatively constant correlation coefficient as we increase the calculation window duration, but see a decreasing correlation as we increase the minimum magnitude of the dataset, regardless of calculation window length. We then propose physical mechanisms for these observations.

Challenges in Quantifying Small Earthquakes

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If properly done, systematic determination of regional moment tensors, RMT, has the potential of yielding a catalog of parameters that will be useful for studies of regional stress, ground motion, probabilistic seismic hazard and local magnitude calibration. The catalog is only useful if the procedure and data sets are documented. Lessons learned from manually processing more than 4000 regional moment tensors with Mw > 3 show that the confidence in a particular solution depends not only on waveform fit in a specified frequency band, but also on the regional velocity model used, compatibility with previous solutions in a region, e.g., regional context, and agreement with observed P-wave first motions. For archival purposes a solution must be accompanied by sufficient metadata so that the results can be duplicated. This recommendation applies not only to RMT but to other approaches to determining moment tensors. Illustrations of problems and differences will be presented for selected events to highlight the care required to produce a defendable catalog.

On the Limitations of Spectral Source Parameter Estimation for Minor and Microearthquakes

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In order to improve the understanding of earthquake source physics and for ground motion modeling in seismic hazard assessment, a reliable estimation of earthquake source parameters is necessary. Due to the increase in the number of stations (including borehole ones), methods traditionally used for investigating the source parameters of earthquakes with M>=3, such as spectral fitting or spectral ratio approaches, are nowadays also extensively applied to smaller magnitude events. However, significant limitations of the usable frequency range spanned by the spectra arise when working with recordings of such minor and micro earthquakes. Low signal-to-noise ratio limits the usage of low frequencies, while the typical sampling rates of seismological networks and the high-frequency attenuation can be limiting factors in the upper end of the usable spectra. In addition, earthquake source parameters determined from ground motion spectra are known to exhibit potentially serious trade-offs, in particular the corner frequency and high-frequency attenuation. In this study, we investigate the impact of the background wave propagation model on the source parameter trade-offs as well as its effect on the feasibility of obtaining useful source parameters by means of spectral fitting for minor and micro events. The analysis takes advantage of ad-hoc simulated synthetic seismograms with well-defined underlying background propagation where increasing complications in the crustal structure are considered (intrinsic & scattering attenuation). The results show that with given realistic background models and usable frequency bands, the source parameter estimation for minor and micro events can be significantly biased and, not surprisingly, this bias is mainly affecting the estimation of the corner frequency. The results indicate that the source parameters from minor and micro earthquakes should always be viewed with great caution when physically interpreted.

Effects of Failure Parameterization on Pre- and Co-Seismic Earthquake Rupture

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Different physical processes accommodating fault failure during an earthquake rupture affect how the shear stress along the fault evolves with fault slip – the failure parameterization used in earthquake models. We investigate different failure parameterizations (failure laws) to determine how the shapes of the laws and their parameters affect earthquake nucleation and the coseismic phase of the earthquake rupture. We use the 2D finite element method and perform quasi-static simulations to study the implications of these different parameterizations for the slip amount, slip rate, and timing of the earthquake nucleation phase. We use dynamic simulations to address the specifics of rupture propagation during the coseismic phase. Failure laws studied include slip-weakening friction, exponential cohesive zone law, parabolic cohesive zone law, and several poly-linear failure laws. We use fracture energy and other common failure law parameters for quantitative comparison. From the quasi-static models and the initial phase of the dynamic models we find that different failure laws play a significant role in the duration of the earthquake nucleation phase, the amount of accumulated preseismic slip and the lateral slip propagation. The later stages of the dynamic rupture models show Lorentz contraction of the process zone, which results in almost indistinguishable dynamic ruptures with almost identical far field observables: source-time functions and spectra. This result confirms the validity of the small-scale yield approximation (i.e., process zone details can be ignored and the rupture propagation is governed by the fracture energy magnitude) for sufficiently fast ruptures.

Yielding and Fracture in the Nucleation of Frictional Fault Slip

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Although friction is reduced in textbooks to a simple friction coefficient, reality is much more complex than it seems. The transition from static to dynamic friction that lies behind seismic activity happens through a nucleation process involving the yielding and fracture of contact asperities along natural faults. However, little is known as to what the dominant underlying process is or what the implications are for nucleation dynamics and the onset of frictional instability. In this work, we show that fault heterogeneity, modeled through the correlation length and the amplitude of frictional strength, plays a key role in determining the driving force behind the nucleation of slip. In particular, we found that a transition from yielding to fracture is triggered above a certain level of heterogeneity, which is responsible for the generation of foreshock events, and that the magnitude of such events increases with the correlation length and decreases with the amplitude of the frictional strength profile. Moreover, high levels of heterogeneity are shown to favor stability and delay the onset of dynamic friction. Overall, our results demonstrate how fault heterogeneity influences the nucleation of frictional slip by determining whether yielding or fracture dominate the process. This bridges the gap between the two most common criteria for nucleation, which apply only to the yielding or the fracture phase, exclusively.

Four Granites in the Lab: Acoustic Emission During the Uniaxial Loading

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Laboratory loading experiments on rock samples are proxies of earthquakes in nature, and acoustic emission (AE) is an eye into the rock to view its fracturing. Obviously the texture and grain size are the crucial parameters ruling the properties of a rock. We analyzed four different granites in the uniaxial loading to observe the way of their fracturing in terms of (i) the time sequence of the AE initiation and its clustering in time and space, and (ii) of the retrieval of the mode of the fracturing. The shear-tensile crack (STC) source model is advantageously used as a robust inversion tool. Concerning (i), from the seismicity distribution in space and time we evaluated the correlation integrals, and from them the fractal dimensions in space and time. While the temporal fractal dimension seems to be independent of the granite type, the spatial fractal dimension decreases slightly on the line from the fine-grain granite to that one with the largest grain size. It means that in the latter case the AE foci are clustered more than in the former one. Within the study (ii), we performed a detailed analysis of the errors of the retrieved mechanisms in terms of constructing the confidence regions related both to (a) the geometry/orientation of the mechanism and (b) its decomposition into shear vs. non-shear components. In this way we sorted the seismicity into shear events (S), shear-tensile (ST) and tensile events (T) and analyzed their occurrence and orientation changes in the course of the experiment. A simplistic prior idea about prevalence of shear fracturing in materials with grains of large size seems to be not supported.

Review of the Seismicity of Mars

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The InSight mission collected an astounding seismic dataset from Mars during more than four years (1450 sols) of operation until it was retired on 21 December 2022. The Marsquake Service detected more than 1300 events of seismic origin. The largest marsquake (S1222a, M=4.6) was recorded recently on May 4, 2022. Two other significant events (S1000a and S1094b) have been confirmed as distant impacts, with magnitudes of M4.0 and 4.2 and crater diameters of 130 and 150 m respectively. Here, we present the current understanding of the Martian seismicity and the different types of events we have observed on Mars.The Low Frequency (LF) family of events include energy predominantly below 1 Hz. They are similar to teleseismic events on Earth, with clear P and S waves. The epicenter is known for about half of the LF events, owing to the difficulty of determining back-azimuth. Seismicity occurs at only a few spots around Mars and no tectonic events were located within 25°

of InSight. A large number of LF events are located 26–30° from the station, associated with the volcanic Cerberus Fossae region. Two events lie beyond the core shadow and have PP and SS phases - S0976a in the Valles Marineris region 146° away from InSight, and the S1000a impact. LF events have the largest magnitudes. The High-frequency (HF) family of events exhibit energy predominantly at and above the 2.4 Hz local subsurface resonance. HF events generally have magnitudes below M2.5 and originate from a distance range of 25–30°, from a region around the central Cerberus Fossae. Likely these are shallow events associated with volcanic dykes. HF events have a clear seasonal trend that is not yet understood. A small number of HF events are characterized by higher frequency content, up to 20–30 Hz with a notable amplification on the horizontal components at very high frequency, and are termed Very High Frequency (VF) events. The amplification is plausibly explained by the local subsurface structure. These events are observed only close to the lander. The closest VF events include a distinctive acoustic signal, and remote imaging confirms they are impacts.

The 2017 Pohang, Korea, Earthquake and its Largest Aftershocks: Stress Drop and Source Complexity Suggestive of Fluid-faulting Interaction

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The Pohang earthquake (Mw 5.5), which occurred in the southeastern part of the Korean Peninsula on November 15, 2017, has been reported as one of the biggest earthquakes associated with fluid injection activities. For the Pohang earthquake and its seven largest aftershocks, we determined the source spectra and source time functions using the empirical Green's function spectral ratio approach, and computed corner frequencies and stress drops. The stress drops vary from 17 to 39 MPa, which corresponds well with the previously observed values along the Korean Peninsula when considering the Madariaga model used. We obtained a two-pulse moment rate function and bimodal spectrum for the Pohang mainshock along with plausible rupture directive effects. The aftershocks located off the main fault generated larger stress drops than those on the main fault plane, likely indicating the rupturing of new or strongly coupled/healed fault segments. The observed source spectra for the aftershocks are simpler and well explained by a circular rupture approximation. These findings indicate that the mainshock may have been caused by a complex rupture process, such as a near-simultaneous activation of differently oriented fault segments. Fault-valve mechanism along the previously unmapped fault system that intersects the causative fault would increase the coulomb static stresses reducing effective normal stresses. This could cause aftershock migrations on both sides of the intersecting faults and high stress drop events at the edge of the main fault. Our result is one of the clearest examples of fluid-faulting interaction, which is expected to be involved in migrating earthquakes, and also important in seismicity triggered/induced by hydraulic stimulation in modern enhanced geothermal systems.

Shallow Serpentinization Promoted the Up-dip High-Frequency Seismic Wave Radiation During the 2021 Mw8.1 Kermadec Megathrust Earthquake

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It has been widely observed that large megathrust earthquakes are featured by frequency-dependent rupture with high-frequency (HF) seismic waves primarily radiated from the down-dip portion of the coseismic slip, which has been attributed to the mechanic heterogeneity at the lower boundary of the locking zone. In contrast to this common belief, here we report that during the 2021 Mw 8.1 Kermadec megathrust earthquake, the HF energy was mostly radiated from the up-dip portion of the coseismic slip. We resolve the kinematic rupture process and HF radiation of the mainshock with a finite fault inversion method and a travel-time calibrated back-projection technique, respectively, where the travel time calibration was obtained by relocated aftershocks and historic events. The resolved mainshock rupture is characterized by a single slip patch located at the depth of 20-45 km, elongated ~100km parallel to the trench. The HF sources are distributed along the up-dip edge of the coseismic slip, within a belt that also contains refined seismicity, as well as the mainshock epicenter and the triggered HF sources of the Mw7.4 foreshock. Strong stress heterogeneity in this belt at the depth of 15-20 km is mostly likely caused by the beginning of serpentinization in the overriding oceanic mantle wedge. The abnormal event suggests re-evaluation of earthquake hazards in conventionally considered aseismic area.

New Empirical Source Scaling Laws for Crustal Earthquakes Incorporating the Fault Dip Angle and Seismogenic Thickness Effects

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We developed new global source scaling laws for crustal earthquakes that include the effect of the fault dip angle and bottom depth of the seismogenic zone. The bottom-depth effect consists of a regional term and a normalized hypocenter depth term. In contrast to the commonly used scaling relations between moment magnitude (M), fault length (L), width (W), and area, we relate M to the aspect ratio (L/W) and to the fault area simultaneously to control the main behavior that the aspect ratio increases once the rupture width reaches the fault width limit. A global data set of finite-fault from multiple references, such as the Earthquake Source Model Database (SRCMOD) and several extra Taiwan events, was compiled for use in developing the source scaling relation for crustal earthquakes in this study. The scaling differences are physically related to the fault geometry but do not appear to depend on the rake angle. The scaling for the dataset can be captured very well by the proposed aspect-ratio scaling law with geometry-related effects, such as the magnitude-dependent dip and the bottom depth of the seismogenic zone. We used a bilinear relation to model the magnitude-area scaling law, and it generally behaved similarly to the scaling in previous area-M studies. Finally, the corresponding L and W scaling relations obtained by converting the area and aspect ratio to L and W showed good agreement with the previous regional scaling laws on average but provide better fault-specific application due to the inclusion of fault-specific dip angles and seismogenic depths.

Slow Earthquake Scaling Revisited

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The scaling law for slow earthquakes, which is a linear relationship between seismic moment and duration, was proposed 15 years ago and initiated a debate on the difference in physical processes governing slow vs. fast (ordinary) earthquakes. Based on new observations across a wide period range, we show that linear scaling of slow earthquakes remains valid, but as a well-defined upper bound on moment rate of ~ 10^{13} Nm/s. The large gap in moment-rate between the scaling of slow and fast earthquakes remains unfilled. Slow earthquakes occur near the detectability threshold, such that we are unable to detect deformation events with lower moment rates. Observed trends within slow earthquake categories support the idea that this unobservable field is populated with events of lower moment rate. This suggests a change in perspective that the proposed scaling should be considered a bound, or speed limit, on slow earthquakes. We propose that slow earthquakes represent diffusional propagation, and that the bound on moment rate reflects an upper limit on the speed of diffusional process. Ordinary earthquakes, in contrast, occur as a coupled process between seismic wave propagation and fracture. Thus, even though both phenomena occur as shear slip the difference of scaling reflects a difference in the physical process controlling propagation.

The Devastating 2022 M6.2 Afghanistan Earthquake: Challenges, Processes and Implications

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On June 21th, a Mw6.2 earthquake struck the Afghan-Pakistan-border-region, an area dominated by partitioned deformation related to the India-Asia collision. Despite its moderate size, 1150 deaths were reported, making the event the deadliest earthquake of 2022 so far. We investigate the event's rupture processes, aiming to understand what made it that fatal. Our InSAR-constrained slip model and regional moment-tensor inversion reveal a sinistral rupture

with maximum slip of 1.8 m at 5 km depth on a N20°E striking, sub-vertical fault. Field observations confirm fault location and slip-sense. Based on our analysis and a global comparison, we suggest that not only external factors (e.g. time of the event and building stock) but also fault-specific factors made the event excessively destructive. Surface rupture was favored by the local rock anisotropy (foliation), coinciding with the fault strike. The distribution of Peak Ground Velocity was governed by the sub-vertical fault. The maximum slip was large compared to other events globally and might have resulted in peak-frequencies coinciding with the resonance-frequency of the local one-story buildings. More generally, our study demonstrates the devastating impact of moderate earthquakes, being small enough to be accommodated by many tectonic structures but large enough to cause significant damage.

2021 and 2022 North Coast California Earthquake Sequences and Fault Complexity in the Vicinity of the Mendocino Triple Junction

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North of 40N and west of 122W lies the Mendocino Triple Junction (MTJ), one of California's tectonically most active and complex regions. Damaging earthquakes can occur on the San Andreas and Mendocino faults, within the Gorda and North American plates, and on the Cascadia subduction interface. Recent earthquake sequences in the MTJ region, starting on 2021-12-20 (2021) and 2022-12-20 (2022), highlight the complex interactions of regional faulting. In the catalog, the 2021 foreshock/mainshock (FS/MS) pair, separated by ~10 s in time and 30 km in distance, have catalog magnitudes of 5.7 and 6.2. Detailed analysis indicates they are more likely to be a doublet, both with M~6.1, with the onshore MS triggered by the S-waves of the FS which occurred to its W on the Mendocino Fault. Finite fault analysis shows the FS ruptured to the W, and the MS to the NW, away from the population centers. The 2022 MS (M6.4) occurred just offshore, to the NW of the 2021 MS and produced aftershocks within the Gorda Plate and beneath the False Cape Shear Zone. Its largest aftershock (AS, M5.4) took place ~40 km to the ESE of the main fault rupture. We present finite fault analysis of the 2022 MS which indicates that it ruptured NE, toward the towns in the area and causing damage, which was exacerbated by the 2022 AS. Over the past few years, the instrumentation in the region has been upgraded as part of the implementation of the earthquake early warning system. We explore the seismicity associated with these earthquakes, looking to better define the faults in the MTJ region, as well as their modes of rupture.

Bayesian Source Mechanism Inversion and Uncertainty Quantification With Dense Array Strong Motion Data for 2022 Luding Earthquake in China's Sichuan

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Sichuan in China has a high level of seismic activity due to the complex active fault zones nearby, resulting from the collision between the Indian Plate and Eurasian Plate. Understanding the source physics of past earthquakes in Sichuan is significant for ground motion prediction and seismic risk analysis for the future. In this study, we developed a Bayesian approach to infer the source mechanisms of earthquakes given first P polarities and S/P amplitude ratios, accounting for the velocity model misspecifications. The first P polarity is described by a probit model, while the S/P amplitude ratio is represented by a Gaussian model. This method was applied to the 09/05/2022 M6.8 Luding earthquake, the most devasting earthquake in Sichuan since 2017, using acceleration data from 510 local strong motion stations. The Bayesian inference was conducted to strong motion data bandpass filtered to different frequency ranges. Our results show a frequency dependent moment tensor distribution. Although the strong motion instruments are less sensitive compared to the broadband data, the good coverage of strong motion stations in the region with epicenter distance less than 50 km provides good constraints for the moment tensor and reduces the uncertainties.

Insights Into Volcanic Rift-Tectonic Fault Interactions From Moment Tensor Analysis of the Seismicity Prior to the 2021 and 2022 Fagradalsfjall Eruptions in Iceland

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The two fissure eruptions at Fagradalsfjall volcano (located in the Reykjanes Peninsula in southwestern Iceland) in March 2021 and August 2022 were preceded by intense seismicity up to magnitude Mw 5.7. Thousands of events were reported by the Icelandic Meteorological Office (IMO), and many inhabitants in and around Reykjavík felt many intermediate and large-magnitude events. We retrieved the seismic moment tensor for around 100 events recorded before the 2021 and the 2022 eruptions inverting waveforms recorded by the IMO broadband seismic network. Although it is assumed that earthquakes in the Reykjanes Peninsula are due to strike-slip displacements of an array of sub-parallel N-S-trending faults in so-called bookshelf-type faulting, our moment tensors showed more diversity in the seismic sources in addition to N-S strike-slip faults. We performed a cross-correlation analysis of waveforms verifying that source parameter diversity agrees with different waveform clusters. Our goal is to understand the cause of those non-pure double-couple strike-slip mechanisms in the context of an imminent fissure eruption in a complex oblique rift system.

Observations of the 2017 Earthquake Swarm in SW Iceland Used for Mapping Stress Prior to the 2021 Fagradalsfjall Eruption

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The analysis of earthquake source parameters in divergent regions represents a challenge in understanding processes related to the origin and evolution of tectonic plate margins. The Reykjanes Peninsula in SW Iceland is a part of the Mid-Atlantic plate boundary. It forms its transtensional segment with several volcanic and faulting systems. We focus on the 2017 seismicity that occurred in the central part of Reykjanes at the place of Fagradalsfjall volcano prior to its eruption on March 19, 2021. We invert well-determined focal mechanisms of the 2017 seismicity recorded by broadband stations of local network. We analyse this seismicity and provide mapping of tectonic stress in space and time. Our results disclose heterogeneous stress field manifested by mix of shear, tensile and compressive fracturing. Although the fracturing was diverse, directions of the principal stress axes were stable and consistent with the processes at the transtensional divergent plate boundary. The prominent stress direction was in the azimuth of 120°±8°, which represents the overall extension related to rifting in the Reykjanes Peninsula. The activity initiated on the transform fault segment with predominantly shear strike-slip events. The non-shear fractures occurred later being associated with normal dip-slips and corresponding to the opening of volcanic fissures trending in the azimuth of 30-35°, perpendicular to the extension. The dip-slips were mainly located above an aseismic dike detected in the centre of the 2017 swarm. This dike represents a zone of crustal weakening during a preparatory phase of future 2021 Fagradalsfjall volcanic eruption located at the same place. Moreover, we detected local variation of stress when the stress axes abruptly interchanged their directions in the individual stress domains. These stress changes are interpreted in a consequence of plate spreading and upcoming fluid flow during a preparatory phase of a rifting episode.

Earthquake Source Parameters: Theory, Observations and Interpretations [Poster]

Poster Session • Tuesday 18 April

Conveners: Vaclav Vavrycuk, Institute of Geophysics of the Czech Academy of Sciences (vv@ig.cas.cz); Pavla Hrubcova, Institute of Geophysics of the Czech Academy of Sciences (pavla@ig.cas.cz); Grzegorz Kwiatek, GFZ Potsdam (grzegorz.kwiatek@gfz-potsdam.de); Satoshi Ide, The University of Tokyo (ide@eps.s.u-tokyo.ac.jp); German A. Prieto, Universidad Nacional de Colombia (gaprietogo@unal.edu.co)

A Relative Moment Tensor Inversion Scheme for Local Earthquakes: Application to San Juan Cluster

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The relative abundance of small earthquakes renders them potentially useful tools in improved understanding of regional seismotectonics; however, determination of moment tensors (MTs) for such events recorded on regional networks is complicated by low signal-to-noise ratios, sparse station sampling and complex wave propagation at short periods. We build upon previous work in designing a multiple-event, simultaneous moment tensor inversion scheme for small earthquakes that employs constraints from P-wave polarities and relative amplitudes of direct P and S-waves recorded at common stations. The scheme exploits the principal component decomposition of clustered-event waveforms to derive high-fidelity measures of the aforementioned quantities. I will demonstrate the approach on a seismic cluster near San Juan Island, ~70 km south of Vancouver.

Adjoint Earthquake Source Inversion Method Using P-Wave Spectra and Focal Mechanism Solutions

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Comprehensive and accurate characterization of small earthquake sources helps illuminate fine-scale fault structure and understand earthquake physics. In the past decades, seismologists developed methods for estimating small earthquake focal mechanism, stress drop, and rupture directivity, which constrains the radiation pattern and rupture dynamics of small earthquakes, respectively. However, focal mechanism solutions provide two nodal planes instead of one; stress drop estimations usually stack spectra from all stations without considering the rupture directivity effect; and rupture directivity estimations usually ignore vertical directivities due to limited station coverage. These limitations prevent effective interpretations of the obtained source properties and the comparisons between small- and large-magnitude earthquake source properties. Therefore, we propose an adjoint source inversion method combining focal mechanism solutions and P-wave spectra to solve these problems. We first solve the apparent P-wave corner frequencies of the target event and its neighboring Empirical Green's Function (EGF) events at each individual station using the source spectra ratio between the target event and its EGF events. We then combine the solved apparent P-wave corner frequencies at all stations and all possible fault plane orientations from the focal mechanism solution to find the best-fitting fault plane orientation, and 3D rupture directivity that can minimize the differences among the corrected P-wave corner frequencies from all stations after removing the rupture directivity effect. The obtained corrected P-wave corner frequencies at all stations are further stacked and used to estimate the stress drop, radiated seismic energy and apparent stress. We validate our method using events in the Parkfield area. The results illustrate unprecedented, detailed spatiotemporal variation of high-quality small earthquake properties, including fault orientation, 3D rupture directivity, and stress drop, which provides a great opportunity to study fault geometry, kinematics, and dynamics.

An Improved Estimation of Stress Drop and its Application on Induced Earthquakes in the Weiyuan Shale Gas Field in China

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The hydraulic fracturing activities in the Weiyuan Shale Gas Field of Sichuan Province, southwestern China, have triggered an increasing amount of earthquake activities in the past 8 years compared to the silent historical record, accompanied by a deadly ML4.9 earthquake in 2019 and multiple ML4.0+ earthquakes afterward. How these earthquakes are related to injection activities is still under debate. Earthquake stress drops have been found to vary spatially and temporally from anthropogenic activities, therefore in this study we aim at estimating the stress drops in the Weiyuan region to reveal the triggering mechanisms of the large earthquakes and inspect the seismic hazard from shale gas exploration.

We include 28,000 earthquakes from Feb. 2019 (after the ML4.9 earthquake) to Aug. 2020. Most are located at shale layer depths (2-4km over space). We propose an improved spectral-decomposition-based approach to estimate their stress drops: the method does not assume stress drop dependence earthquake scale, and significantly mitigate stress drop underestimation. The median stress drop of the Weiyuan earthquakes is 3.08MPa, and stress drops show strong spatial heterogeneity. Based on Mohr-Coulomb failure law, we calculate pore pressures of five ML>4 earthquake from their stress drop values. The results indicate that the Molin fault ruptured by the deadly ML4.9 is near hydrostatic; in the nearby injection zone, other faults of ML>4 earthquakes show over-pressure. These estimates agree with observations that the ML4.9 are missing aftershocks while others do not. Our results show that stress drop can help understand the mechanisms of large induced earthquakes.

Brune Stress Drop, b-Value, and Modeling Through Finite Element Models (FEM) of Earthquakes that Occurred close to the 30 October 2016, Mw 6.3 Norcia Earthquake

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Previous investigations on the relationship between b-value and Brune stress drop often lead to opposite conclusions, going from a clear dependence of b-value on stress regime to a complete independence among b-value, fault mechanism and stress drop, suggesting that this issue deserves further investigation. The interaction between large events and aftershocks is also studied through finite element models (FEM): aftershocks of major earthquakes are considered to occur in response to stress variations caused by the main shock. The finite element method is useful to build a complex crustal model and provides a more comprehensive relationship between stress drop, stress regime and b-value. From the analysis of the earthquakes occurred close to the 30th October 2016, Mw 6.3 Norcia earthquake, we found that: (i) b-values estimated in the epicentral zone are greater than the estimated reference b-value for the same area; (ii) the correlation analysis between the main rupture propagation direction and the seismicity migration direction indicates that the maximum number of events with positive correlations are observed in the Norcia area, with 100% against 91% of the events located in the area affected by the Amatrice-Visso-Norcia 2016-2017 seismic sequence; (iii) for 82% (9 of 11) of the events that occurred in the Norcia area, 1 to 9 aftershocks of magnitude greater than 3.5 occurred along the main rupture propagation direction; (iv) the events located in the Norcia area show a stronger dependence of stress drop on seismic moment. These results suggest that in the Norcia area the correlation between the main direction of the rupture propagation and the direction of migration of the seismicity implies a possible increase of the degree of fracturing. The consequent decrease of stress drop correlates with the b-value observed in the area.

Characterization of the 2020 Mw 5.7 Magna, Utah Seismic Sequence Full Wavefield Decay

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On March 18, 2020, an M5.7 earthquake occurred in Magna, Utah; the event struck a populated, urban area which raised the concerns of aftershocks. An

aftershock forecast was provided by the USGS and the University of Utah Seismic Network (UUSS) using the earthquake catalogue. This study was conducted to observe and analyze the full wavefield of the aftershock sequence to see if it followed an Omori-Utsu Law-like trend. The RMS ground motion displacements were derived using the SeismoRMS python code of (Lecocq, et al., 2020) from Power Spectral Densities recorded by the UUSS stations located around the epicenter. An Omori-Utsu Law-like noise decay was observed at frequency bands of 4.0-14.0Hz and 4.0-20.0Hz at the stations located within 40km from the epicenter, as well as at a station located 113km away. The observations presented here indicate that the full wavefield may be used as a Omori-Utsu proxy at local seismic stations, but may have limitations due to the impacts of cultural noise as well as local geologic structures that influence the propagation of the seismic wavefield. The data collected in this study will be combined with data from other locales to see if the observable trend is endemic across all significant earthquake events irrespective of magnitude or tectonic setting. Ultimately the goal is to develop constitutive equations that may potentially provide an avenue for the development aftershock forecasts that do not rely on earthquake catalogue completeness or a network of seismic stations.

Characterization of the Southwestern Puerto Rico Seismic Sequence Full Wavefield Decay

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The 2020 Southwestern Puerto Rico Seismic Sequence (SWPRSS) started on December 28, 2019,with foreshocks that led to the magnitude 6.4 event on January 7, 2020. Thousands ofaftershocks followed, but many of these were not recorded in official catalogs in real time due tooperational or network geometry constraints. This research aims to characterize the full wavefield-decay produced by the 2020 SWPRSS by calculating the RMS ground motion displacements of thepower spectral densities using the SeismoRMS code of (Lecocq et al., 2020) for Puerto RicoSeismic Network and USGS seismic stations on the Island. The ground displacements for stationsin SW Puerto Rico exhibit an Omori-Utsu-like behavior. Here we aim to establish a set of boundaryconditions, including epicentral distance, channel type, and frequency to observe the full wavefielddecay. The displacements show stronger Omori-Utsu-like behavior in the stations closest to theepicenter, but it is still observable in stations that are over 100 km from the epicenter. The Omori-Utsu-like behavior is observable regardless of channel type (BH?, HH?, and EH?) and is observableon both broadband and short-period instruments. The signal is observable in frequency bands4.0–14.0 Hz, 4.0–20.0 Hz, 1.0–20.0 Hz, but it is best shown in the band range of 4.0 Hz–14.0 Hz.The signal is not observable in the frequency band 0.1–1.0 Hz which is expected as a signalproduced by local aftershocks should be constrained to frequencies above this band. If this signalis Omori-Utsu-like, related to aftershocks, and endemic across other aftershock sequences, itcould lead to a new method that would decouple aftershock forecasts from the earthquakecatalog. Further developments of this study have been carried out for the 2019 Ridgecrest,California and 2020 Magna, Utah earthquake sequences in order to confirm the endemic nature ofthis behavior, and have held similar results.

Estimating Faulting Mechanisms From Single-Station Seismic Data

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Earthquakes in sparsely instrumented regions or small earthquakes might be recorded above noise levels at no more than one seismic station. Moreover, small earthquakes do not generate surface waves. Hence it is desirable for the purpose of estimating faulting mechanisms, to use information from body waves recorded at a single station. Polarity and amplitude information for P, SV, and SH waves can more precisely pinpoint the orientation of a shear dislocation faulting mechanism. However, Earth structure that affects body wave amplitudes is often not precisely known and affects theoretical estimates of the amplitudes. To avoid such uncertainties associated with absolute amplitudes, we use relative body wave amplitudes, as well as polarities, to estimate faulting mechanisms. Traditional single-station methods for estimating faulting mechanisms that rely on relative amplitude measurements use amplitude ratios as their data. However, these ratios become unstable when an amplitude in a denominator is small.

Instead, we define the data (body wave amplitude and polarity) as vectors in a 3D space, which continuously represents amplitude combinations for different take-off angles from the focal sphere. Given the take-off angle of the observed amplitudes we perform a grid search over all possible faulting mechanism orientations and select the mechanism that most closely reproduces the observed relative body wave amplitudes. In order to represent the uncertainty in this estimate, we also select a range of mechanisms that produce relative amplitudes and polarities close to the observed ones and assign a weight that is calculated based on noise levels in the seismograms and the geometry of the modeled vectors. In this presentation we demonstrate application of our approach to single-station data from several different types of earthquakes, partially benchmarked against faulting mechanisms derived with established methods. We will demonstrate the method's performance, including optimal conditions for and limitations of the method.

Estimating Magnitudes of the 1868 and 1877 Earthquakes Using Tsunami Records

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As is the case in most of the western coast of South America, southern Peru and northern Chile have been exposed to several great earthquakes and catastrophic tsunamis. Two of the largest events that affected these coasts took place in the latter part of the XIX century: the August 13, 1868, and the May 9, 1877 (local time), earthquakes. Their magnitudes have been estimated between 8.5 and 9, rupturing contiguous segments several hundred km each.

Both events accommodated the convergence between Nazca and South American plates producing large seafloor and coastal elevation changes. These changes generated significant tsunamis that affected, not only the coasts close to the rupture regions -with reported local run-ups reaching values of the order of 20 m- but also were observed along most of the coastlines of the Pacific Ocean basin. Local reporting times of tsunami arrivals in relation to the time of occurrence of both earthquakes have been used to estimate their rupture areas by using inverse ray tracing.

In addition, both trans-pacific tsunamis were recorded at the tide gauge located in Fort Point, in San Francisco Bay, California. Here, we report on the characteristics of these records and compare them to recent records of tsunamis produced by the largest earthquakes in the region. We report as well on the numerical simulations of both tsunamis on this tide gauge.

Extension of Aseismic Slip Propagation Theory to Slow Earthquake Migration

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Natural faults host various types of migrating slow earthquake phenomena, with migration speeds much lower than seismic wave speeds and different moment-duration scaling from regular earthquakes. To advance the obtained quantitative understanding of the migration process and long duration of slow earthquakes, I study a chain reaction model in a population of brittle asperities based on a rate- and state-dependent friction on a 3-D subduction plate boundary. Simulation results show that the migration speed is quantitatively related to frictional properties by an analytical relation derived here. By assuming that local pore water in front of the migration drives rapid tremor reversal and is so local as to hold a constant stress drop, the application of the analytical solution to observational results suggests that (i) the temporal changes of observed migration speeds for the rapid tremor reversal could be explained by about 70% reduction of the effective normal stress; (ii) effective normal stress for the deeper extension of the seismogenic segment in the western part of Shikoku is about 1.5 times greater than that in the central part. Applying rupture time delay between slow earthquake asperities for a duration longer than regular earthquake, I also conclude that (iii) the characteristic slip distance of rate-and-state friction for low-frequency earthquakes is roughly between 30 μm and 30 mm; (iv) the stress and strength drops of very low-frequency earthquakes is much smaller than 1 MPa. I also discuss the different time delays between Tonankai and Nankai earthquakes for previous events. Reference:

Ariyoshi, K. (2022). Extension of aseismic slip propagation theory to slow earthquake migration. *Journal of Geophysical Research: Solid Earth*, 127, e2021JB023800. https://doi.org/10.1029/2021JB023800

FocMecDR: A Cross-Correlation-Based Double-Ratio Earthquake Focal Mechanism Inversion Algorithm

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Focal mechanisms of earthquakes play significant roles in earthquake seismology. Waveform-based methods work well for relatively large earthquakes (e.g., M>3) but may fail for small ones. As a result, first-motion polarities and P/S amplitude ratios have been widely adopted to invert focal mechanisms for small events. Whereas the identification of polarities is challenging, for example, phases with low signal-to-noise ratios and slow-starting arrivals. On the other hand, P/S amplitude ratios usually vary by a factor of 2 or more, which requires empirical station correction for individual stations. Recent work shows that polarities and P/S amplitude ratios can be inverted for a cluster of earthquakes using cross-correlation and matrix inversion (e.g., Shelly et al., 2016; Shelly et al., 2022), providing inputs for the traditional focal mechanism inversion software (e.g., HASH). Though this method significantly improves the accuracy of the focal mechanism solutions and the number of solvable events, but it still has the drawbacks of traditional methods, for instance, station corrections are required.

In this work, I propose a cross-correlated-based double-ratio earthquake focal mechanism inversion algorithm to automatically invert relative focal mechanisms for clustered earthquakes. Like the concept of double-difference in earthquake location, here I use an earthquake with known focal mechanism as a reference and invert focal mechanisms for the nearby target events through minimizing the difference between the ratio of P/S ratio for the observed data and theoretical values, which can be computed given a pair of focal mechanisms, as well as matching their relative polarities, which can be inferred from the normalized CC coefficient (from -1 to 1) with a cut-off threshold. The assumption is that the Green's functions for the clustered events are the same (slight arrival differences can be handled by time shift via CC) and the differences of P/S ratios are attributed to the focal mechanism change. Field benchmark in the Ridgecrest region shows promising results for accurate relative focal mechanism inversion.

Global Evaluation of Large Strike-Slip Ruptures Using a Bayesian Estimation of Stress Glut Second Moments

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Earthquake ruptures are complex processes that may vary with the structure and tectonics of the region in which they occur. Characterizing this potential variability may yield fundamental insights into how fault zones control how earthquakes happen. We investigate this by determining second moments of the stress glut for a global dataset of large strike-slip earthquakes. Our approach uses a Bayesian inverse formulation with teleseismic body and surface waves, which yields a low-dimensional probabilistic description of rupture properties including spatial extent, directivity, and duration. This technique is useful for comparing events, because it makes only minor geometric constraints, avoids bias due to rupture velocity parameterization, and yields a full ensemble of possible solutions given the uncertainties of the data. We apply this framework to all great strike-slip earthquakes of the past three decades, and we use the resultant second moments to compare source quantities like directivity ratio, rectilinearity, stress drop, and depth extent. We also use these second moments to resolve nodal plane ambiguity for oceanic intraplate earthquakes. We find that most strike-slip earthquakes have a large component of unilateral directivity, oceanic intraplate earthquakes usually rupture much deeper than other strike-slip earthquakes, and the strikes of oceanic intraplate earthquakes usually do not align with encompassing fossil fracture zones.

MTUQ: A High-Performance Python Package for Moment Tensor Estimation and Uncertainty Quantification

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Understanding the underlying source mechanisms of earthquakes, volcanic eruptions, nuclear explosions, and other seismogenic geological events is fundamental to seismology. Characterizing the source parameters might entail evaluating its location, onset time, moment tensor (fault orientation, source type, magnitude), and source-time function. Evaluating these coupled parameters requires quantification of uncertainties to provide meaningful interpretation. Here, we present the latest developments of MTUQ, an open-source python package for Moment Tensor estimation and Uncertainty Quantification in 1D and 3D Earth models. MTUQ uses mpi4py for distributed parallelism, and its parallel grid-search routines have been tested on HPC systems for efficient exploration of the parameter space. Synthetic seismograms are obtained on the fly from precomputed 1D green's function databases (FK, Axisem/Instaseis) or 3D green's functions computed with SPECFEM3D. We use waveform-based misfit and allow for custom misfit functions to evaluate the best-fitting source parameters. MTUQ also benefits from advanced sampling and inversion methods (Hamiltonian Monte Carlo and Covariance Matrix Adaptation-Evolution Strategies) to improve time efficiency and enable tackling ambitious problems that consider joint inversion of larger parameter sets, such as multiple moment tensors (or forces), hypocenters, and source-time function. We showcase recent applications of the code, including the result of a study of the Hunga-Tonga volcanic eruption of January 2022 and an overview of the first workshop—online and free—dedicated to the code.

Not So Planar Faults – On the Impact of Faulting Complexity and Type on Earthquake Rupture Dynamics

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The increasing quality and completeness of global moment tensor solutions allow to advance our comprehension of seismicity delving into the connection between earthquake occurrence, tectonics, and faulting. Since, at least theoretically, each seismic event can be described using a time-dependent moment tensor averaging over different spatial orientations of various fault patches; then, if the rupture is roughly nonplanar, shear sliding may not be appropriate to modelling the whole seismic event. This implies a drop of the double-couple components. Therefore, we focus our attention on the different compositions of the moment tensors of moderate and large seismic events of global and regional catalogues as a function of the tectonic setting looking for the effect predicted by theory. We have found that thrusts host earthquakes with more elevated double-couple percentages with respect to strike-slip and normal faults. The compensated-linear-vector-dipole component decreases as the size of earthquakes increases in reverse faulting, while this trend is weaker or absent in other classes of seismicity. We have also noticed that the double-couple component positively correlates with the b-value and it is negatively related to the corner magnitude of the frequency-size distribution, which is compatible with a systematic magnitude underestimation in low double-couple earthquakes. Our results suggest that, at least for large seismic events featured by suspiciously high non-double-couple components (above 30%, e.g., 30/10/2016 Mw 6.5 Norcia and 13/11/2016 Mw 7.8 Kaikoura events) should be considered to better assess their size accurately also because of possible impact on seismic forecasting.

Regional Alaska Earthquake Moment Tensors Inverted Using 3D Green's Functions

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Moment tensors are a fundamental seismological product that benefit our understanding of the active tectonic processes on Earth. Global moment tensor solutions are automatically calculated by several entities (GCMT, USGS) for earthquakes above Mw 5, and they rely on relatively long-period waves for the processing. At regional and local scales, smaller-magnitude (Mw 4-5) moment tensor solutions are routinely estimated using high frequency Green's functions calculated from 1D velocity models. Both global and regional moment tensor solutions contain greater uncertainties because of inaccuracies in the 1D velocity models relative to real (three-dimensional) Earth structure. Here we calculate receiver-side Green's functions in a 3D velocity model using the software package SPECFEM3D_GLOBE, and we use the resulting database to invert for the moment tensor solutions of 70 regional earthquakes in Alaska using the Python-based package MTUQ. These earthquakes were carefully chosen with the intent of using them in a later tomographic study, in which the quality of the moment tensor solution influences the quality of the resulting tomographic model.

Robust Explosion Screening Based on Moment Tensor Angular Distance

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We extend moment tensor screening methods to account for variation in waveform misfit not just around the maximum likelihood solution, but over all moment tensor space. By integrating over the entire likelihood surface, we show how to obtain 1D marginal angular distance distributions that emphasize source-type information important for explosion monitoring, remain reliable at low magnitudes, and allow for robust screening and uncertainty analysis. By comparing ground truth explosions and nearby earthquakes, we demonstrate that the new method provides reliable source-type screening even in challenging scenarios involving low signal-to-noise ratios, cycle skipping, and explosion-dipole tradeoffs.

Seismic Moment Tensors Evaluation of Earthquakes in Central Zagros (Iran)

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Due to the influence of crustal structure on wave propagation, seismic waves contain substantial information about the Earth's crust, and their analysis contributes significantly to a better understanding of the Earth's interior. Calculating the moment tensor based on seismic data is one of the physical methods for classifying and physically interpreting seismic sources. An earthquake moment tensor is a complete representation of interval forces on a point source which represents its fault geometry and size using moment tensor components and scalar moment, respectively. Specifically, each tensor component represents the dynamic effect in a particular direction, which can be calculated by decomposing the moment tensor. By doing so, we can analyze the earthquake source mechanism. This study used the Global Centroid Moment Tensor (GCMT) catalog to calculate seismic moment tensors of events with M≥5 in Central Zagros (CZ), Iran, based on seismic data (e.g., strike, dip, and rake angles). We decomposed each diagonalized tensor into two parts: Isotropic (ISO) and Deviatoric (M'). To evaluate the contribution of each component to the seismic source, we further decomposed M' into a best Double Couple (DC) and Compensated Linear Vector Dipole (CLVD) components. Moreover, owing to the convergence of the Arabian and Eurasian plates that formed Zagros Mountain in the western part of Iran, we expected to find only DC faulting in this region. However, we found more than 50% of misfit between M' and a pure DC for some events, indicating that the CLVD faulting type was dominant. We found a good agreement between the locations of these events and the geology structures, including active anticlines, active salt domes, fault links, and fault tips which are the local effect of dominant CLVD in this area. Keywords: Moment Tensor, Central Zagros, Deviatoric Moment Tensor, Double Couple (DC), Compensated Linear Vector Dipole (CLVD).

Source Parameter Analysis Indicates Both Hydrous Phase Breakdown and Thermal Shear Runaway Drive Unusual Subduction Seismicity in Central Colombia

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Unusual earthquakes occur 60–200 km beneath Colombia where the young, warm Nazca slab subducts. These earthquakes in the Cauca cluster, between 3.5°-5.5° N and 77.0°-75.3° W, occur within and up to 50 km above the Nazca plate. The earthquakes above the plate represent an instance of long-lived supraslab seismicity. To understand how rupture varies with different pressure-temperature regimes of the subduction process, we estimate the stress drop and energy efficiency for 472 earthquakes (magnitudes 1-4) in the slab and supraslab regions using P and S wave data from the Servicio Geológico Colombiano. We use a clustering approach, forming 10 Nazca slab and 3 supraslab subgroups, to reduce the tradeoff between source properties and along-path effects. Within a subgroup, each earthquake has an independent corner frequency but a common average along-path effect to each station. We jointly invert for these two parameters using simulated annealing. Initial results suggest that the supraslab region may have lower average stress-drops (0.2–12.7 MPa) and less spread in radiation efficiency (0.03–0.65) than the Nazca slab (stress drops of 0.2–77.4 MPa; radiation efficiencies of 0.01–1). Large errors limit resolution, so we test different models assumptions to check the robustness of observed trends.

High stress drop and low radiation efficiency suggest thermal shear runaway due to increased slip and increased heat generation, whereas low stress drop and moderate-to-high radiation efficiency indicate the breakdown of hydrous phases due to efficient slip across a hydrated rupture. While earthquakes in both regions have similar average efficiencies and stress-drops, the higher stress-drop and efficiency averages in the Nazca slab suggest that both thermal shear runaway and hydrous phase breakdown cause earthquakes in this region. In the supraslab region lower stress drops and efficiencies may indicate that most of these earthquakes are caused by the breakdown of hydrous phases.

Source Stress Drop for Continental Collision Zones: Deviation From "Textbook" Earthquake Models

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Continetal faults are known for more irregular distribution of slip compared to their subduction counterparts, as often exhibited in differenct source kinematics and the corresponding stress drop of earthquakes. Immature faulting, believed to be one of the main causes for this behavior, is a property of continental collision zones. In this context, we present the results of our study of earthquake slowness parameter, THETA, for the M_w>5.0 CMT events in Iran between 1990-2022 as a measure of stress drop. As the energy-to-moment ratio of ruptures, this quantity is obtained using only teleseismic body waves and is largely invariant of source mechanism. Statistical analysis of our dataset reveals an ~0.6 units increase in slowness values for the Iranian earthquakes, corresponding to four times higher stress drops in an active collision zone. We attribute the variations of SIGMA=0.3 logarithmic units in the calculated slowness to the seismotectonic zoning of Iran, revealing different slowness trends in various faulting regimes of the region. This conclusion is in agreement with the different rates of convergence along the deformation bands in the Iranian Plateau.

Emerging Developments in Operational Monitoring Systems and Products

Oral Session • Tuesday 18 April • 04:30 PM Pacific

Conveners: Michelle Guy, U.S. Geological Survey (mguy@usgs.gov); Kirstie Haynie, U.S. Geological Survey (khaynie@usgs.gov); Ellen Yu, Southern California Earthquake Data Center, California Institute of Technology (eyu@caltech.edu)

Utilizing the Cloud to Modernize Delivery of Earthquake Information and Products

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Following a federal government initiative to effectively adopt cloud resources in government agencies (https://cloud.cio.gov/strategy/), the U.S. Geological Survey's (USGS) Geological Hazards Science Center (GHSC) began migrating resources from on-premises servers to the cloud. Over the last three years, developers at the GHSC have worked to design infrastructure that increases the security, stability, and efficiency of our systems. Through this improved infrastructure, we ensure that earthquake information is delivered in a consistent and timely manner.

In this presentation, we examine three different cloud systems that provide vital information about seismic events: 1) the product distribution layer (PDL), 2) the Ground Failure Product, and 3) the Sequence Product.

PDL is a USGS platform that relays information about seismic events. The Ground Failure Product provides estimates of earthquake induced landslides and liquefaction. The Sequence Product is still under development and aims to provide information about how events are related by designating them as potential foreshocks, mainshocks, and aftershocks in an earthquake sequence. We will discuss how each of these systems posed a unique set of challenges that we considered when designing their individual cloud infrastructures. These challenges included but were not limited to designating resources to accommodate large numbers of requests following major earthquake events, run computationally expensive modelling code, and query large earthquake databases to dynamically generate up to date information. By examining these lessons learned, we hope that the wider seismic information community can be empowered to utilize the cloud for the delivery of earthquake information.

Integrated Seismic Program (ISP): A New Python GUI-based Software for Earthquake Seismology and Seismic Signal Processing

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Integrated seismic program (ISP) is a graphical user interface designed to facilitate and provide a user-friendly framework for performing diverse common and advanced tasks in seismological research. ISP is composed of six main modules for earthquake location, time–frequency analysis and advanced signal processing, implementation of array techniques to estimate the slowness vector, seismic moment tensor inversion, receiver function computation and ambient noise tomography. In addition, several support tools are available, allowing the user to create an event database, download data from International Federation of Digital Seismograph Networks services, connect to SeisComP3 databases, inspect the background noise and compute synthetic seismograms.ISP is written in Python3, supported by several open-source and/or publicly available tools. Its modular design allows for new features to be added in a collaborative development environment.Recently ISP has been upgraded to be able to manage earthquake detection, classification, location and estimation of focal parameters automatically. Results are shown in the Alboran Sea (western Mediterranean Sea) in an earthquake cluster.

Using the University of Utah Messaging Passing System to Help Realize Real-Time Machine-Learning Modules in Network Operations

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Machine learning (ML) and, in particular, deep-learning (DL) models have demonstrated their improved utility over traditional (near) real-time seismological methodologies during periods of enhanced seismicity. As such, University of Utah Seismograph Stations is eager to begin leveraging these tools so as to improve its monitoring capabilities. However, operationalizing ML models still faces significant challenges. These challenges include, but are not limited to, models that are underlain by substantially more complex software stacks and models with computational demands much greater than that of their traditional seismological algrorithm counterparts. Both problems can simultaneously be addressed by way of distributed computing. Regardless of whether the computational hardware exists in the cloud or on-premises, distributed computing challenges are ultimately solved by the movement of data. To that end, we will provide a status update on the University of Utah Message Passing System (UMPS) as a pathway to utilize ML models in an operational setting. Currently, UMPS provides low-overhead, secure mechanisms that allow computers connected via a network to communicate through broadcast and request-reply patterns. Of particular importance is that the request-reply mechanisms allow for not only many requestors but many repliers. Consequently, computationally demanding DL algorithms are now inherently scalable and will be able to keep pace with the ever-increasing rate of data acquisition. Additionally, we introduce a preliminary many-to-many communication strategy that enables interaction with remotely running daemon processes.

Using a Consistent Travel-time Framework to Compare Three-dimensional Seismic Velocity Models for Location Accuracy

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Location algorithms have relied on one-dimensional (1D) velocity models for fast, seismic event locations. The fast computational speed of these models made them the preferred type of velocity model for operational needs. 3D seismic velocity models are becoming readily available and usually provide more accurate event locations over 1D models. The computational requirements of 3D models tend to make their operational use prohibitive. Comparing location accuracy for 3D seismic velocity models tends to be problematic as each model is determined using different ray-tracing algorithms. Attempting to use a different algorithm than used to develop a model usually results in poor travel-time prediction. We have previously demonstrated and validated the ability to quickly create 3D travel-time correction surfaces using an open-source framework (PCalc+GeoTess, www.sandia.gov/salsa3d, www.sandia.gov/geotess) that stores spatially-varying data, including 3D travel-time data. This framework overcomes the ray-tracing algorithm hurdle because the lookup tables can be generated using the preferred ray-tracing algorithm. We have created first-P 3D travel-time correction surfaces for several publicly available 3D models (e.g., RSTT, SALSA3D, G3D, DETOX-P2, etc.). We demonstrate using these correction surfaces to compare models fairly and consistently for seismic location accuracy via a set of validation events and International Monitoring System (IMS) stations.

Rapid Delivery of Earthquake Catalog With Azure

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There is a critical need for emergency service providers to receive rapid earthquake information during an emerging earthquake sequence. To that end, we designed a cloud-based system to deliver an earthquake catalog and related products based on web services. In this presentation, we discuss how we implemented this system for the California Geological Survey (partially funded by the California Office of Emergency Services) using Microsoft's cloud computing platform Azure. System requirements were low latency, high availability, real-time data delivery, and security. The source of the data is the USGS Product Distribution Layer. The system's end users are emergency service providers and the public.

The cloud-based delivery system is deployed in Azure and uses a complement of services to accomplish a multitude of functionalities. Key services include Kubernetes, serverless functions, push notifications, content delivery networks, container registries, storage, databases, maps, and active directory. The back end system is responsible for all data collection, storage, and distribution. The front end is a single-page application that requests a one-week earthquake catalog and receives real-time updates via push notifications. The single-page application's use of reactive components and responsive web design efficiently present the data to a large audience of users and devices. Management tools facilitate system monitoring and updates as needed.

Emerging Developments in Operational Monitoring Systems and Products [Poster]

Poster Session • Tuesday 18 April

Conveners: Michelle Guy, U.S. Geological Survey (mguy@usgs.gov); Kirstie Haynie, U.S. Geological Survey (khaynie@usgs.gov); Ellen Yu, Southern California Earthquake Data Center, California Institute of Technology (eyu@caltech.edu)

Developing International Standards and Guidelines for Curating, Disseminating, and Validating Simulated Ground-Motion Data

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We are leading an effort to develop international standards and guidelines for curating, disseminating, and validating simulated ground-motion data. This effort is organized as a working group within the Consortium of Organizations for Strong Motion Observation Systems (COSMOS). In 2022 we held online workshops on 7-8 June and 20 October. The first workshop focused on curating and disseminating simulated ground-motion data. The second workshop focused on validating simulated ground-motions for engineering applications. About 100 people participated in each of the workshops with strong representation from North America, Europe, and western Asia. In the coming year, we intend to form a technical committee to draft the international guidelines and standards while continuing to engage stakeholders from across the globe through online and in-person meetings.

The key points from workshops include: (1) Numerous groups are generating simulated earthquake ground motions and making them openly available, however there is very little coordination among groups to provide consistent interfaces for searching and retrieving data; (2) Standardizing interfaces for metadata and data access should consider agile approaches that can adapt to changing capabilities and user needs while building upon existing efforts; (3) Participants advocated for a distributed architecture that would allow institutions to host and manage their own data while broadcasting their holdings to a combined catalog; (4) Validation of ground-motion simulations applies to the entire workflow for simulating earthquake ground-motions, including the rupture model, seismic velocity model, and seismic wave propagation software; (5) Metrics to evaluate the validation are application dependent; more research is needed to tie structural response characteristics to ground-motion characteristics; and (6) Validation results should provide a clear, transparent, quantitative assessment of the simulated ground motions.

Edge Continuous Waveform Buffer Enhanced Station Monitoring Using a Web Interface and Containerized Deployment

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The Edge Continuous Waveform Buffer (CWB) is a publicly available system used by the U.S. Geological Survey (USGS), which collects data from thousands of stations and channels from over a hundred networks worldwide. To achieve the goal of real time seismic monitoring it is essential to be aware of the current status of this data collection. The Edge has a Java graphical user interface (GUI) client that receives status updates and displays them in a tabular format. While this client GUI provides the necessary data, it requires local installation of the client GUI, the proper version of Java installed, and direct connection to the Edge. Additionally, this client uses dated technology and requires a specific integrated development environment (IDE) to handle the GUI maintenance. One goal of the new web interface was to overcome these limitations while also creating a platform that will allow future enhancements to be made as the technology it is built upon also advances. The new web interface was developed using Java Spring Boot for the service layer, and Angular for the web interface, two open-source frameworks with sizeable user base and support. The service layer is deployed into a Docker swarm container using Gitlab Continuous Integration Runners onto a system that has the necessary access to the Edge data providers. The result is an interface that provides multiple users the needed data more efficiently and only requires a web browser and no direct access to edge systems. Beyond providing the features of the previous GUI, the new codebase facilitates new functionality due to the many open-source libraries that are available. The first major addition, using Leaflet, is the ability to show on a map the locations and statuses of the stations the user is currently observing. Because the system is web based using a Docker container, deploying new features and fixes is greatly simplified versus having to distribute a Jar file to every user.

Modern Tools and Approaches to Earthquake Monitoring and Product Generation at the Southern California Seismic Network (SCSN)

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Earthquake monitoring systems used at regional seismic networks currently run software on local servers that process continuous seismic data in real-time and output earthquake products such as event origins, focal mechanisms, moment tensors, ShakeMaps, and waveforms. The Southern California Seismic Network (SCSN) is exploring ways to generate and distribute earthquake products with modern software technologies such as cloud-native services in Amazon Web Services (AWS), serverless computing, containers, and Infrastructure as Code (IaC). These technologies have potential to improve the timeliness of earthquake product delivery for end-users, as well as expedite testing and incorporating new scientific algorithms, software, and other infrastructure into operational earthquake monitoring. We discuss software infrastructure design choices, strategies for integration with existing monitoring systems, and cost considerations for cloud operation. We also explain how SCSN is using cloud-based tools and services for earthquake monitoring and product generation, such as AWS lambda functions for auto-scaling computation on large incoming data requests; IaC tools for setting up, configuring and tearing down computing resources; Docker containers for testing and executing software; and AWS Open Data for allowing public access to SCSN continuous waveform data archives.

Motus: The U.S. Geological Survey National Earthquake Information Center's New Earthquake Monitoring System

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The U.S. Geological Survey (USGS) National Earthquake Information Center's (NEIC) real-time global monitoring system, Hydra, supports the NEIC missions to detect earthquakes, estimate source parameters, and produce a reviewed earthquake bulletin. The NEIC has used Hydra for over fifteen years and continues to develop it to meet NEIC's evolving needs. Throughout this time, developers and researchers have made several significant algorithmic advancements to the Hydra system to improve its ability to characterize earthquakes, including the addition of new moment tensor techniques, waveform modeling for earthquake depth, machine learning to characterize seismic phases, and a local-to-global scale arrival time associator.

However, due to the age of the technologies that underpin Hydra, the system does not easily support rapid development and the ability to leverage new software technologies. This hinders the NEIC's capability to integrate new algorithms, make changes to analyst procedures, and support research into novel monitoring processes. Therefore, the NEIC has begun the processes of evolving the Hydra system into a new system, Motus, that will fundamentally advance our operational and developmental capabilities.

The Motus system is underpinned by a significant shift in the NEIC's system design framework towards a service-oriented architecture to allow for more rapid development, testing, and research. We will present our recent work to create web-based data services, modern user interfaces, containerized deployment environments, and Continuous Integration and Continuous Delivery (CICD) pipelines. We will also present new seismic analysis interfaces designed to allow analysts to quickly classify and publish high-quality automated solutions. Finally, we will discuss the challenges and lessons learned using our approach of evolving and updating an existing system with new features and new methods, while maintaining our existing 24/7 mission critical operations.

Near Real-Time Repeating Earthquake Monitoring System

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Repeating earthquakes are the result of asperities creeping along the plate interphase. Under stable conditions, repeating earthquakes show relatively constant recurrence times and quasi-identical waveforms. Nonetheless, recurrence time and waveform similarity of these events may vary over time likely due to temporal variations of the plate interface coupling, i.e., due to velocity changes of the interface creeping. Daily monitoring of RE may thus help to assess the interface current state in those terms. Here, we present a near real-time repeating earthquake monitoring system designed to continuously detect repeating earthquakes along the Mexican subduction zone to have updated insights of seismotectonic processes when initiating. Previous studies have shown that repeating earthquakes may act as an indicator for the nucleation of large earthquakes and may provide evidence for changes in the slip rates associated with stress transfer due to the interaction between slow slip events and moderate to large earthquakes (M>7.0).

Pysolate: A Python-Based Thresholding Tool to De-Noise or De-Signal Seismic Waveforms Based on the Continuous Wavelet Transform

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Removing noise from seismic data to increase signal-to-noise ratios is one of the most important efforts in seismology. An abundance of preprocessing methods have been applied to extract signals out of noisy data as increased noise in the microseismic band is a challenge to lowering regional monitoring thresholds. Improved accuracy of shorter period (<20 second) waveform simulations is only useful if clear short period signals can be extracted from noisy waveform records. The application of a filtering method that removes microseismic noise, thus isolating the seismic signal, will be key to better utilization of improved short-period waveform simulations. To this effort, following the Langston et al. (2019) CWT application, we developed a Python-based toolset that implements the CWT-based, non-linear thresholding operations to de-noise or de-signal seismic data. We test this application using the 2020 Mw 6.5 Monte Cristo Range earthquake sequence to assess automation and portability into a processing scheme. We find that the denoiser performance varies with event size and distance from the station. As expected, smaller events are best observed on the closer stations after denoising, and larger events can be denoised on stations further from the event. Preliminary results show that denoising many events using a single noise model will be helpful in aftershock sequences, where signals arrive in rapid succession and no clear noise window can be identified. Further analysis will help us understand how far stations can be for this process to produce useful signals. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-ABS-843563.

Exploiting Explosion Sources: Advancements in Seismic Source Physics

Oral Session • Wednesday 19 April • 02:00 PM Pacific

Conveners: Catherine M. Snelson, Los Alamos National Laboratory (snelsonc@lanl.gov); Jenna L. Faith, Los Alamos National Laboratory (jfaith@lanl.gov); William R. Walter, Lawrence Livermore National Laboratory (walter5@llnl.gov); Colin Pennington, Lawrence Livermore National Laboratory (pennington6@llnl.gov); Christian Stanciu, Sandia National Laboratories (astanci@sandia.gov); Elizabeth A. Silber, Sandia National Laboratories (esilbe@sandia.gov); Cleat P. Zeiler, Nevada National Security Site (zeilercp@nv.doe.gov)

Joint Regional Waveform, First Motion Polarity, and Surface Displacement Inversion Using a Layered Elastic Model With Topography for North Korean Nuclear Explosions

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On September 7th 2017, The Democratic People's Republic of North Korea carried out its latest and largest nuclear test (DPRK6) that registered Mw 5.2. Recent efforts have been made to increase understanding of this and previous nuclear tests using seismic waveform, and synthetic aperture radar (SAR) geodetic deformation data (e.g. Chiang et al. 2018, Myres et al. 2018, Wang et al. 2018). Additionally, in our previous work (Chi-Durán et al., 2021) we performed a joint regional waveform, first motion polarity, and surface displacement inversion demonstrating improved discrimination of the source-type of the event, obtained a revised moment tensor solution with reduced uncertainty in scalar moment, and constrained its location. In this work, we have applied the aforementioned joint inversion with a layered velocity model, informed on geologic structure interpretations of Pabian and Coblentz (2015) based on satellite imagery. We propose a 4-layered model, composed of a 50-m basalt layer (Vp = 1.73 km/s, Vs=1.0 km/s), 250-m stratified volcanic deposit layer (Vp=2.25 km/s, Vs=1.3 km/s), 700-m highly weathered granodiorite layer (Vp= 2.25 km/s , Vs= 1.3 km/s) over a half-space (Vp=5.35 km/s, Vs=3.09 km/s) which shares the velocity of the regional MDJ2 velocity model (Ford et al. 2009) which has proven effective in waveform inversion for the region. This model considers the range of reported values for the different lithologies and also weathering effects over the top layers. We find that the consideration of the layered velocity model improves the recovery of source depth. Furthermore, we tested this layered model with an earlier, smaller explosion (DPRK4) that occurred on January 6, 2016, inverting regional waveforms, first-motion polarity and line-of-sight (LOS) deformation from ALOS-2 InSAR data. In this case, the joint inversion is found to provide better discrimination of the source-type and better constrain the scalar seismic moment needed for downstream yield estimation.

An Overview of the Rock Valley Direct Comparison Project

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How do we identify the cause of seismic energy from the signals themselves? We currently have a variety of empirical methods to distinguish explosions from earthquakes, cavity collapses, and other types of events. Recent work using local distance (<200 km) data have revealed new challenges, however, and there remains uncertainty in our understanding of the underlying physics because so many different variables (e.g., propagation, depth, medium properties, source time function, mechanism) are in play. To evaluate source differences alone, we plan to compare, for the first time, a co-located chemical explosion to a shallow earthquake in the Rock Valley Direct Comparison (RV/DC) project.

The RV/DC takes advantage of the 1993 shallow earthquake sequence in Rock Valley on the Nevada National Security Site (the former Nevada Test Site). The largest event, M3.7, was followed by eleven M>2 events ranging in depth from 1-3 km. All are well constrained due to the deployment of tempo-

rary stations early in the sequence. We will conduct two chemical explosions at similar hypocenters to the earthquakes to understand the discrimination features between these types of events. We have systematically relocated the 1993 events, varying velocity models and codes, but using a common pick data set to choose the experiment borehole location. Three additional boreholes are planned and will be instrumented to obtain microseismicity data, sample fault properties, and record the chemical explosions. We are installing a dense surface seismoacoustic network, including re-occupying stations that recorded the 1993 earthquakes. A geologic framework for modeling and predicting synthetic both earthquake and explosion waveforms is being developed in advance of the actual explosions. We believe this exciting effort will reveal new insights into discriminating explosions from a background of earthquakes, as well as provide novel information about the physics of earthquakes themselves.

Prepared by LLNL under Contract DE-AC52-07NA27344. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Evaluating the Efficacy of Inverting Local-Scale, High Frequency Seismograms for Effective Source Mechanisms Using Various Source Assumptions

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Seismic source parameters are usually estimated by fitting the observed data to a series of force couples scaled by a symmetric tensor. This type of analysis is quite successful for analyzing low frequency regional (0.05 – 0.1 Hz) and teleseismic (0.01 - 0.1Hz) wavefields, however it requires simplifying assumptions about the source. Specifically, the source is assumed to be a point in time and space, and the (assumed) source time function (STF) is assumed to be identical for all components of the moment tensor. For local-scale data (particularly high frequency data produced by buried explosions) that assumption may not be appropriate because the initial energy release from the explosion may produce secondary sources of seismic energy (e.g. explosion-induced fracturing). In these cases, the conventional inversion effectively averages all the source types and mechanisms into a single representation of the source, which in some cases can produce nonsensical and/or grossly inaccurate estimates of the seismic source parameters. For this work, we investigate the efficacy and pitfalls of various waveform inversion techniques with the goal of resolving the source mechanism of a small, buried, chemical explosion. The seismic data are collected on a network with stations no more than 100m from the surface-projection of the source, where the source is ~40m meters deep. We find that the conventional inversion techniques fail to describe the data to an acceptable level of fit. However, using a more complex inversion, where the STF is neither assumed nor restricted to be similar for all tensor components, we can better fit the data. The resulting time-variable moment tensor can be interpreted as a time-varying source mechanism. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Implications of Local Wave Propagation Effects on the Performance of P/S Source Discriminants Using High-Frequency Simulations of a Chemical Explosion and Small Earthquake

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Analysis of seismic records of local earthquakes and a series of underground chemical explosions conducted during the Source Physics Experiment (SPE) at the Nevada National Security Site have shown that at local distances (<200 km) the effectiveness of the single-station P/S ratio source discriminant is inconsistent, and with high spatial variability. The main factors that are known to affect the spatial variations of P and S waves amplitude at local distances are the source radiation pattern and wave propagation effects. We used high-frequency (0-10Hz) simulations of recorded earthquakes and the SPE-5 underground chemical explosion to investigate the effects of source radiation pattern and propagation of seismic waves on the performance of the P/S source discriminant at local distances. In our simulations we used a local velocity model that was generated by combining the regional Geological Framework Model with small-scale correlated stochastic perturbations.Through waveform matching, we found that the deterministic high-frequency modeling requires velocity models that also include small-scale complexities of the shallow crust. The inclusion of correlated depth-dependent stochastic velocity perturbations in our model, greatly improved the quality of simulated source radiation and local waveforms, which resulted in better reproduction of the observed spatial variations of the P/S discriminant. We found that the performance of the P/S discriminant declines in areas where the shallow wave scattering effects deform the radiation pattern of source generated P and S waves. The overall variability in local P/S ratios at different locations was reduced when network averaging of P/S ratios was applied.

Shallow Soil Response to an Explosion With Geophones and Distributed Acoustic Sensing

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Soft sediments have been observed to respond non-linearly to large dynamic strains over a wide range of scales - from laboratory experiments at centimeter scales, to active source studies at local scales (i.e., m to km), and from measurements of ground shaking during large earthquakes at regional scales (i.e., km to hundreds of km). This study focuses on the near-field response of shallow soils to the shaking from a series of planned underground chemical explosion, which occurred at the Nevada National Security Site during the second phase of the Source Physics Experiment (SPE). We examine in detail the recordings of an explosion emplaced in weak rock which was detonated at a depth of ~300 m in the Dry Alluvium Geology (DAG) borehole with a TNT equivalent yield of 50, 997 kg (i.e., DAG-2). The explosion was densely recorded by approximately 460 geophones and 2200 Distributed Acoustic Sensing (DAS) channels within 2 km from ground zero. The frequency content of the signal recorded by both types of sensors is significantly modified by the explosion. To quantitatively characterize the temporal evolution of the shallow soil properties in the hours following the explosion, we develop a stretching method which uses the high-frequency (10-30 Hz) content of the Fourier amplitude spectra at each sensor. We observe a pronounced recovery phase following the ground shaking from DAG-2, which we interpret to be indicative of a healing process within the soils (e.g., slow dynamics). The sensors located close to ground zero (within 400 m) exhibit particularly strong modulations of several percent which then recover within 12 hours following a log-type recovery. We interpret the healing process of shallow soils to be associated with damage generated by the ground spall. Sensors located far from ground zero (>1.5 km), for which ground motion levels were moderate, show that the soil properties are not significantly affected by the explosion. Finally, co-located geophones and DAS channels display similar results, which validates the use of DAS to infer the non-linear behavior of shallow soils at local scale.

Seismic Source Characterization and Screening for Three Large Mining Events in Sweden, Northwest Russia, and the Eastern United States

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We estimate full moment tensors with their uncertainties for three large mining events in Kiruna (Sweden, 2020), northwest Russia (2022), and Tennessee (United States, 2021). Their magnitude estimates (ML) were respectively 4.5, 3.7 and 4.1, and all events were observed at open, regional seismic stations and by stations of the International Monitoring System (IMS).

The International Data Center (IDC), which attributes source screening parameters to seismic events, reported an MS/mb score of -2.03 for the event in Kiruna, and as a result the event could not be screened out as being of non-nuclear in origin. The Tennessee event did not get a score because of insufficient observations at IMS stations, and the NW Russia event was screened out as being of non-nuclear in origin.

These inconsistencies highlight challenges in screening criteria, which may be addressedwith moment tensors source types. Using waveform data from all possible IMS stations and openly available seismic stations, we estimate moment tensors with uncertainties for the mining events using the methodology described by e.g., Alvizuri et. al, 2018. The methodology has proven successful in characterizing and screening various other types of events, including explosions such as the 6 nuclear tests in North Korea, and collapses, including one 8 minutes after the 2017 nuclear test in North Korea. The results revealed mechanisms with positive isotropic parameters for the nuclear tests and negative isotropic for the collapse event.

Similarly for the mining events analyzed here, they reveal mechanisms with negative isotropic parameters with uncertainties localized towards the negative isotropic region of source-type space. The Kiruna event was also extensively analyzed by the local mining company, and their results show widespread surface subsidence, rockmass failure, and their analysis of microseismic events show negative isotropic source parameters.

Our results highlight the connection between different types of mechanisms and their source-type representation and suggest a robust metric for screening explosion type of events such as nuclear tests.

Seismic Characterization of the Explosive Subevents in the 2022 Hunga-Tonga Volcanic Eruption Using Joint Moment Tensor Inversion

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The Hunga-Tonga submarine volcanic eruption of January 15, 2022, was notable for its size and effects on the atmosphere, including the generation of sound waves. In this work, we are interested in the seismic signal from this event, which was recorded by global seismic stations and lasted approximately 20 minutes, with the largest subevents occurring over a 5-minute period starting at 04:15:17 UTC. Our previous study identified four subevents and a predominantly explosive source mechanism in the associated seismic activity. However, it relied on a hypothesis that each subevent had an identical source mechanism. In this study, we analyzed waveform data from regional surface waves filtered between 25 and 70 seconds and used a computational approach to estimate a set of parameters that best fit the data and allowed a different source mechanism and onset time to be estimated for each subevent. The analysis was conducted using the Covariance Matrix Adaptation Evolution Strategy (CMA-ES), which allowed us to design a scalable inversion scheme required to increase unknown parameters (28 in total). Our results indicate that all subevents had explosive source mechanisms, as indicated by all-positive eigenvalues of the subevent moment tensors. The combined magnitude of the four subevents ranged from 6.35 to 6.71 Mw, highlighting the difficulty of precisely defining the source magnitude with the set of available regional data. These findings suggest that the subevents were similar in nature and may aid in understanding the overall sequence of the eruption. Due to the stochastic nature of the CMA-ES algorithm, we validated our findings by producing ten independent parameter searches of the model space.

Examination of the Debate on the 12 May 2010 Low-Yield Nuclear Test

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On 12 May 2010, the North Korean official daily morning newspaper Rodong Sinmun reported that North Korea succeeded in nuclear fusion on the Day of the Sun. The claimed event was investigated by several radionuclide groups and seismology groups. The main results in the radionuclide studies include: 1) the radioisotope data confirm the existence of an event with estimated origin time ranging from 11 May to 13 May 2010; 2) the presence of barium-140 can be explained only by a sudden nuclear event; and 3) the radioxenon analysis suggests that it was a low yield nuclear fissile rather than a nuclear fusion. However, the seismological evidence for the existence of this event has been under debate. Schaff et al. (2012) denied the existence of the event. Zhang and Wen (2015) confirmed that they found the seismological evidence of this low-yield nuclear test based on the consistency of radionuclide results and seismic analysis, including the origin time, location, Pg/Lg spectral ratios of the event. Kim et al. (2017) confirmed the occurrence of the event reported by Zhang and Wen (2015) but disagreed on the location and the nature of the event. They located the event at > 4 km southwest of the 2009 nuclear test and suggested that the event has more earthquake-like features.

In this work, we re-exam the accuracy of location determination and event discrimination for the 2010 event, based on the seismic data of the Dongbei broadband seismic network that were used by Kim et al. (2017). We relocate the 2010 event using body waves and the North Korea's 2009 nuclear test as reference. The result shows that the 2010 event is located within a few hundred meters of the 2009 event and close to the north portal. Using a machine-learning phase picker – DiTingPicker and template matching respectively, we build a seismic event catalog for the region from 2006 and 2010 through scanning the continuous waveforms recorded by the network. Few earthquakes can be confirmed near the nuclear test. We will report the performance of various seismic discriminants built on the network data on classifying explosions and earthquakes in the region.

Theoretical Investigations of Earth- and Sea-Earth Coupled Very-Long Period Atmospheric Waves

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In the wake of the 2022 Tonga atmospheric explosion, we study a number of theoretical aspects of the structure of the very long period atmospheric gravity waves it generated, especially when coupled with an oceanic column. We base our investigations on two methodologies: Harkrider's [1964] algorithm, which extends to an atmospheric column the concept of a Haskell propagator for a flat-layered model; and Kanamori's code [pers. comm., 1977] for the computation of the Earth's spheroidal modes, adapted to an Earth structure featuring an atmosphere and possibly an oceanic column. Our principal results indicate that the eigenfunction of the gravity wave in the atmosphere is essentially independent of the presence of an oceanic layer and of its thickness. However the response of the water surface to the overpressure carried by the wave decreasses sharply with water depth, which is the opposite of the behavior of a classical tsunami obeying Green's Law, as confirmed by observations in the Bering Sea. We also show that the ratio between such sea surface amplitude and ocean-bottom overpressure is strongly dependent on the depth of the water column, thus rendering improper for the direct interpretation of ocean-coupled air waves the constant ratio of 1 cm/mbar, used in the routine reporting of DART data and valid only for tsunami waves under the shallow-water approximation. Finally, we investigate in detail the coupling of the atmosphere and the solid Earth in the absence of horizontal propagation, and show that the system resonates (as expected on physical grounds) at the Brunt-Väisälä frequency, rather than at the acoustic cutoff one, the latter suggested by Kanamori, Mori and Harkrider [1994].

Influence of Model Perturbation on Regional Ground Motions – a Numerical Experiment

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We are examining the attenuation characteristics for high-frequency regional Pn, Pg, Sn, Sg and Lg waves using numerical seismograms for generic 1D/2D/3D velocity models that extend into the mantle by several tens of kilometers. In this study, we use 1D FK/reflectivity, SPECFEM2D and SW4 codes to compare synthetic explosion seismograms at receivers every 50 km interval over a range of 100 to 1400 km. 1D FK/Reflectivity seismograms are used to establish the reliability of the upper limit of the frequency below which all regional seismograms computed using SW4 and SPECFEM2D are consistent in amplitude and the phase complexity. To the 3D and 2D models, we introduced velocity perturbation in the shallow crust, mid-crust and crust-mantle boundaries separately to generate extended high-frequency coda waves, thus enabling us to understand the various velocity perturbation effects on Pn, Pg, Sn and Sg and the Lg waves. We examined fine laminated structures in 1D model and in the same depth ranges to simulate high-frequency regional coda waves. We used these seismograms to validate for a fast computational method to accomplish the same objective. The upper frequency limit is dependent on the model discretization which is controlled by the available computational resource. Scattering was introduced by perturbing the geophysical parameters in various parts of the 3D model using criteria described in Frankel and Clayton (1986). von-Karman correlation function was used to specify the extent of the scatterers (Goff and Jordan, 1988). This provided an insight on how the regional body and Lg waves are influenced by the velocity perturbation in random locations. The SW4 model was optimally designed for large distances ensuring that seismograms do not suffer from boundary reflections. SPECFEM2D was used to generate 2D seismograms for similar models, were corrected for the point-source seismograms and compared to the equivalent 1D synthetic explosion seismograms.

Exploiting Explosion Sources: Advancements in Seismic Source Physics [Poster]

Poster Session • Wednesday 19 April

Conveners: Catherine M. Snelson, Los Alamos National Laboratory (snelsonc@lanl.gov); Jenna L. Faith, Los Alamos National Laboratory (jfaith@lanl.gov); William R. Walter, Lawrence Livermore National Laboratory (walter5@llnl.gov); Colin Pennington, Lawrence Livermore National Laboratory (pennington6@llnl.gov); Christian Stanciu, Sandia National Laboratories (astanci@sandia.gov); Elizabeth A. Silber, Sandia National Laboratories (esilbe@sandia.gov); Cleat P. Zeiler, Nevada National Security Site (zeilercp@nv.doe.gov)

Bayesian Optimal Experimental Design for Seismic and Infrasound Monitoring Networks

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The goal of Bayesian optimal experimental design (OED) is to find an experiment (e.g. the data gathering and processing methods) that maximizes the expected information gained about quantities of interest given prior knowledge and models of the environment. Within the context of monitoring, we can use Bayesian OED to evaluate and optimize sensor configurations for seismic and infrasound stations. This could mean choosing the station phenomenology, fidelity, location, sensor type, and outputs in order to optimize learning an event's characteristics such as location and/or magnitude. By developing Bayesian OED tools for analyzing and designing monitoring networks, we can explore many relevant questions such as: how can we combine data phenomenologies to reduce uncertainty, how much is gained by reducing sensor noise or earth model uncertainty, and how do sensor types, number, and locations influence uncertainty.

First, we will describe the general background theory of Bayesian OED and how to use it to formalize the study of monitoring networks. Then, we will discuss our OED framework and our associated source and propagation models that we can use to answer these types of questions in the context of seismic and infrasound stations. We will also demonstrate how our framework allows specifying prior information about sources, constraints on sensor placement locations and how these assumptions can significantly alter the optimal sensor configuration.

This research was funded by the National Nuclear Security Administration, Defense Nuclear Nonproliferation Research and Development (NNSA DNN R&D). The authors acknowledge important interdisciplinary collaboration with scientists and engineers from LANL, LLNL, MSTS, PNNL, and SNL. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Comparing Near and Far Field DAS Fiber Response for Monitoring Applications

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Distributed acoustic sensing data is increasingly used to monitor anthropogenic seismoacoustic sources. Previous work using chemical explosions for seismic and/or acoustic sources has shown that the seismoacoustic time series of the explosion-generated wavefield recorded on fiber does not match that from co-located geophones in the near-field. Conversely, the recorded wavefield time series does correlate well at far-field distances. Understanding the fiber response is critical for processing and analyzing this type of time series data. In this study we test if the poor correlation in the near-field is caused by incoherence at the scale of the gauge length and non-planar wavefront geometries. We analyze data recorded on co-located geophones, fiber, and seismic gradiometers to quantify the distances where the planar wavefront approximation becomes valid, resulting in coherent phase arrivals along the DAS gauge length. Our results may inform future fiber applications, particularly in cases where well-calibrated amplitudes are necessary. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Developing a Predictive Capability for P-to-S Discriminants

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Earthquakes sources produce greater shear wave (S) energy than explosions, which dominantly produce compressional wave (P) energy. The measured ratio of P to S energy (P-to-S phase amplitude ratios) has therefore served as discriminant between explosions and earthquakes at regional distances for decades. Recent work demonstrates that the power of this discriminant to be uncertain at local monitoring distances. Sparse station coverage and poor velocity model representation for crustal phases limits the ability to average observations over azimuths and increases travel time uncertainties. Discrimination between earthquakes and explosions at local distances therefore presents a continuing challenge for monitoring.

This work presents a probabilistic means to quantify discrimination performance at local distances. We demonstrate this method against a data set that includes thousands of picks from hundreds of analyst-reviewed waveforms that were sourced by both explosions and earthquakes in Nevada. Using this dataset, we first measure P-to-S discriminants across 10 frequency bands between 1 and 32 Hz at stations that were less than 405 km from source, and correct for path, site, and source effects. We then construct empirical density functions from these data and use probability theory to model them with validated parametric density functions. These density function models quantify our discrimination error rates. By setting an acceptable Type I error rate, we define objective thresholds for discrimination that predict our ability to discriminate between explosions and earthquakes, versus source magnitude. We lastly discuss schemes to forecast discrimination rates for new events.

Discriminating S-Wave Polarization Angles of Explosive and Earthquake Sources With 2D and 3D Simulations

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Distinguishing whether a recorded seismic event is an earthquake or explosion is a core problem in explosion monitoring. In a 1D flat layer model, earthquakes produce a predictable S-wavefield based off their radiation pattern while an explosion source will not produce S-wavefield. However, observations from nuclear tests have shown they are capable of producing significant S wave energy on both the radial and transverse components. In this study, we perform 2D and 3D numerical experiments using SPECFEM to better constrain the conditions in which an S-wavefield generated from an explosion might differ from one produced from an earthquake. We produce the S-wavefield for our explosions by placing the source location within a small region with large velocity and/or density heterogeneities. The wavelength of heterogeneities is smaller than the wavelength of the wavefield. We investigate isotropic and anisotropic anomalies with an average velocity that is the same as the background medium. Placing the source just outside the region produces a negligible S-wavefield while having the source surrounded but not within the heterogenous region also produces a much smaller S-wavefield. The relative amplitudes of the P and S wavefield depends on the size and strength of the anomalous region. Initial results in 2D demonstrates the anomalous region affects the P-S amplitude ratios of an explosion more than an earthquake of the same magnitude. The presence of strong anisotropic heterogeneities near the source can also produce a large S-wavefield for random VTI/HTI/TTI symmetries. We will expand this work into 3D simulations and analyze S-wave polarization angles as a function of azimuth and distance within realistic earth models. LA-UR-23-20265

End-to-end Numerical Simulation of Explosion Cavity Creation, Cavity Circulation Processes, Subsurface Gas Transport, and Prompt Atmospheric Releases

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A numerical study of conjugate flow, heat and mass transfer by natural convection of noble gases within an underground cavity partially filled with molten rock is presented. The molten rock is initially considered at rest at an initial temperature and concentration. The molten rock is viscous and possesses strength that is temperature, and crystal fraction dependent. Under natural conditions, convection cells are developed within the molten rock leading to circulation, mixing and degassing of the initially trapped gases. Furthermore, the molten rock as well the degassing enhances the conjugate convection flow in the air gap within the cavity. We illustrate the onset of the different regimes and their combined effect of flow, heat and mass transport of different gas species, the fraction of molten rock and their impact on the noble gas fractionation. We also present a sensitivity analysis of the effect of the outer cavity boundary condition on the heat loss and cooling to the adjacent rock formation and its eventual release to the atmosphere. We demonstrate several scenarios of underground prompt releases to the atmosphere using a first-ever fully coupled prompt subsurface-to-atmospheric transport without ad-hoc boundary conditions between physics-based domains, or handshakes between different numerical codes.

Evolution of the Seismic Source From Underground Explosions With Depth-of-burial

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The Rock Valley earthquake/explosion Direct Comparison (RV/DC) venture is the third phase of the Source Physics Experiments (SPE) which plans to directly compare an earthquake and an explosion, detonated in the same material and at the same depth for the first time. Because earthquakes usually occur at deeper depths and in different media than explosions, uncertainties remain as to how those two parameters play into the observed differences. A corollary of the main objective of RVDC is to improve our physical understanding of how deep underground explosions generate seismic waves. In this paper, we propose to perform numerical modeling using the Hybrid Optimization Suite Software (HOSS), a combined finite-discrete element method code developed at LANL, to model the near-source physics and the transition to the elastic regime. Our goal is to determine how the size of the seismic source and the seismic radiation pattern change with the depth of the source in a dolomite model representative of the basement rock in the RV/DC site.< /p>We will measure the elastic radius of our series of modeled explosions, either as the distance at which the Reduced Displacement Potential stabilizes or as the distance the plastic strain falls below a certain threshold or vanishes (Larmat et al., AGU 2022). We will also couple our modeling with the SPECFEM3D seismic code to look at wave propagation patterns. We will also look at cavity radius given some explosive emplacement hypothesis. This series of modeling will allow us to develop an understanding of how seismic sources evolve as the confining pressure increases and as in-situ tectonic stresses are considered. We finally will compare elastic and cavity radius results with models used in the monitoring community such as Müller (1973), Denny & Johnson (1992), Ford et al. (2012).

Gopher 2022: Close-in Signatures From Shallow Explosions in Unconsolidated Environments

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Our team at Los Alamos National Laboratory conducted two field-scale chemical high-explosive (HE) experiments in September 2022 nicknamed Gopher S and U (for Surface and Underground) to improve capability for rapidly conducting shallowly buried HE experiments and to provide novel close-in measurements of explosion phenomena from this emplacement scenario. Downhole diagnostics in the main borehole and satellite borehole included pressure transducers, thermocouples and downhole sampling for a suite of fission relevant gas tracers. Surface diagnostics included a 3-component accelerometer within the ejecta crater, high-speed video of the evolving surface disturbance, and a DAS cable deployed on the surface stretching from 5 to 100 meters in distance. A local permanent seismoacoustic network at LANL used for seismic hazards also recorded the explosions out to several kilometers. Downhole diagnostics (that were not damaged or ejected) recorded the explosive cavity formation and contraction as well as the tracer gas injection and migration. Post-shot recovery of the experiment canister provided additional information on the early-time behavior of the energy and material deposition in the sub-surface. Results from these experiments help to understand and predict the complex interaction of engineering and geology that define the explosive phenomena from shallowly buried explosions.

High Resolution Imagery of the Source Physics Experiment at Rock Valley

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We use several methods of seismic interferometry to obtain highly detailed images at the site of the Source Physics Experiment (SPE), with a particular focus on the site of the upcoming experiment at Rock Valley.

SPE is a series of experiments in varying geologies with the objective of obtaining a physics-based understanding of how seismic waves are created at and scattered near seismic sources. The first two phases were conducted in granite and alluvium geologies, respectively. The source for the final phase will be co-located with a known shallow earthquake, allowing direct comparison of earthquake and explosive sources.

A number of dense arrays have been deployed during the three phases of the SPE experiment, allowing refined imagery in the different environments. They resolve the spatial wavefield, allowing direct measurement of amplitudes and wavespeeds. This enables sharp imagery of the seismic velocities (Vs and Vp) and attenuation (Qs and Qp), which are then used in waveform modeling calculations and experimental predictions.

3D modeling was done using interferometry on a combination of active and passive seismic sources. Interferometry is a particularly powerful means of isolating the energy within the scattering wavefield, and obtains an estimate of the Green's function (GF). The GFs estimated using interferometry are very precise, any variations are directly related to changes in the subsurface over time.

We apply several interferometric techniques: Source interferometry (SI) uses the explosions as rich sources of high frequency, high signal energy. Coda interferometry (CI) isolates the energy from the scattered wavefield. Ambient noise correlation (ANC) uses the energy of the ambient background field. In each case, the data recorded at one seismometer are correlated with the data recorded at another to obtain an estimate of the Green's function (GF) between the two. These GFs are then inverted to obtain the final seismic image. The objective is to obtain a 3D model that is precise enough to calculate synthetics matching the scattering effects seen in the data.

Identifying and Characterizing Local Seismicity With a Dynamic Correlation Processor

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Detecting and classifying underground explosions are essential tasks for global security, but, particularly for small explosions that may only be recorded at local distances, they can be challenging ones. We seek to further our understanding of the capability to detect and characterize small, local, seismic events utilizing data from the Nevada National Security Site (NNSS) and surrounding area. As a first step to investigate the background seismicity in the region, we apply a Dynamic Correlation Processor (DCP) to the data. The DCP utilizes a bank of power and subspace detectors that grows in time as new waveform patterns are encountered. Correlation detection thresholds are determined dynamically in order to adjust to changes in background noise levels. We focus initially on a time period in June of 2019 which includes a large number of catalog events, including a known chemical explosion from the Source Physics Experiment, that can be compared to the results from the DCP. Future work will involve more detailed exploration of the resulting groups of detections, including relative magnitudes and discrimination analysis.Prepared by LLNL under Contract DE-AC52-07NA27344.

Joint Inversion of Seismic and Acoustic Time Series for Time-Variable Source Parameters of the Buried Chemical Explosion at the Source Physics Experiment Phases II: Dry Alluvium Geology

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The estimation of seismic source mechanisms usually relies on wavefield inversion. In the typical inversion scheme, the input data consists solely of seismograms and the forward model only predicts wave propagation in the solid Earth. However, for local-scale analysis of buried chemical explosions, restricting the data type to seismic alone only may potentially miss a portion of the wavefield that carries additional information about the physics of the source. Specifically, the acoustic wavefield generated by a buried explosion can help to resolve source mechanisms that are associated with the explosion directly as well as ancillary explosion-induced phenomena such as surface deformation (spall).

To this end, we developed a linear wavefield inversion technique that uses a fully coupled, three-dimensional elastic-acoustic forward model to predict the seismoacoustic wavefield in both the solid Earth and the atmosphere simultaneously. Our inversion assumes the source can be approximated as a set of six independent, time variable, buried force couples (a time-variable moment tensor) as well as a spall term, which we approximate as a time-variable force applied to the Earth's surface directly above the explosion. We use these seven source time functions (six from the buried source and one from the surface) to estimate the time-evolution of the source mechanism. Using synthetic data, we explore the ability of our method to resolve various source types as a function of time using various data time-series, seismic and acoustic, and spatial coverage. Finally, we use our method to analyze the seismic and acoustic data collected as part of the Source Physics Experiment Phase II Dry Alluvium Geology. We compare our results to those previously determined by inverting infrasonic time-series alone, where the source model consisted of a buried seismic source as well as a spall term.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Quantifying the Impact of Modeling Uncertainty on the Performance of Waveform-Based Bayesian Inference for Seismic Monitoring

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To detect and characterize small magnitude seismic events at local distances, monitoring networks are increasing looking to algorithms that extract more information from observed waveforms. Regardless of the processing method, e.g., whether using machine learning, Bayesian inversion, or some other algorithm, different sources of uncertainty imply information theoretic limits on how useful waveform-based methods can be. This leads to the foundational question of how much information the waveform contains about the underlying seismic event given various assumptions such as observed frequency ranges, earth model uncertainties, source uncertainties, and background noise processes. By understanding the utility of processing full-waveform data, we can then better understand whether the added data gathering, modeling, and computational costs for processing this type of data is worth it for a given application.

In this research, we specifically investigate two sources of uncertainty. First, we explore the impact of Earth model uncertainty by adding different stochastic perturbations to the AK135 model, simulating the associated waveforms, and finally then quantifying the resulting uncertainty on the waveforms. Secondly, we explore the impact of the background noise process by adding noise models from the literature with different magnitudes and frequency characteristics. Taking these sources of uncertainty, we use tools from Bayesian inference and experimental design to quantify how tuning each of these uncertainty models impacts how informative processing the full-waveform would be for seismic monitoring.

This research was funded by the National Nuclear Security Administration, Defense Nuclear Nonproliferation Research and Development (NNSA DNN R&D). The authors acknowledge important interdisciplinary collaboration with scientists and engineers from LANL, LLNL, MSTS, PNNL, and SNL. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Simulations and Predictions of the Source Physics Experiments Phase III (RVDC): Impact on Explosion Monitoring & Discrimination

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The Source Physics Experiments (SPE) are a series of controlled chemical explosions at the Nevada National Security Site to gather observations validate physics-based numerical models and understand the genesis of shear waves to improve nuclear discrimination and monitoring capabilities. Executed between 2011 and 2016, Phase I of SPE encompassed 6 collocated chemical explosions executed in hard granite with different yields at different depths. Phase II included 4 chemical explosions executed in 2018 and 2019 in soft dry alluvium. Phase III, however, includes 2 planned chemical explosions in a dominant dolomite geology and co-located with a 1993 shallow earthquake. LLNL has developed a comprehensive numerical framework to simulate from source-to-receivers, the waves generated from the non-linear explosion source-region to linear-elastic seismoacoustic distances. We present the analysis of SPE Phases I & II collected data, summarize how modeling predictions compared to observed data and draw lessons learned. We share insight on the main mechanisms of generating shear motions in granite, alluvium and dolomite. Moreover, we developed schemes of uncertainty propagation of the geological characterization and geophysical parameters. We present impacts of those uncertainties on designing of Phase III tests, predicting the near-field responses of planned tests, and enhancing source discrimination.

Thermochemical Modeling of a Series of Cavity-Decoupled Explosions at the Nevada National Security Site

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A simple thermochemical model has been developed for the post-detonation behavior of common and high performance explosives (e.g., TNT and RDX). Baseline calculations for equilibrium/quasistatic simulated detonations have been compared to a series of large-scale experiments done in the X-Tunnel complex at the Nevada National Security Site (NNSS). These simulations show the influence of nonequilibrium chemistry and the effects of non-reacting materials (e.g., metal explosive casing and mounting hardware) and how these materials affect the measured pressures and temperatures in an explosive chamber. The thermochemical model includes afterburn consideration in decoupled or open-air detonations and estimation of the total heat capacity of the contents of a decoupling cavity. Results from this new model will help define the energy creation and deposition from conventional explosives into the Earth and how these considerations can affect energy coupling in conventional or high energy detonations.

Time-Varying Source Processes of the Source Physics Experiment Explosions

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The Source Physics Experiment (SPE) was a series of planned chemical explosions at the Nevada National Security Site (NNSS). SPE Phase-I (2011-2016) provided a wealth of dense, local- to regional-distance observations suitable for characterizing shallow chemical explosions located within the same borehole. We investigate the time-dependent source processes of each chemical explosion using frequency-domain moment tensor inversion and relative source time function (RSTF) estimation using data from five linear seismometer profiles located between 100 and 2000 meters of the shot location. Our results from the frequency-domain moment tensor inversion suggest that we can determine the time-history of each source. However, the application of this inversion approach to the SPE tests is challenged by the limited frequency response of the seismometers and knowledge of fine scale heterogeneous Earth structure. We attempt to confront these limitations post-inversion by reconstructing relative source time functions (RSTF) to improve the resolution of time-dependent source processes. The RSTF estimates provide exceptional resolution to each explosion's time-history. Preliminary modeling efforts suggest these measurements may be useful for precise characterization of explosion processes and spallation. Using both moment tensor inversion and the relative source time functions allows us to expand our understanding of the SPE Phase-I explosion series. Application of these techniques contributes to our understanding of explosion source physics and facilitates future applications to additional seismic source experiments and phenomenology.

Transportable Absolute Yields of Underground Nuclear Explosions

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The framework developed and presented here provides a new and transportable method to determine the explosive yields of seismically recorded underground nuclear explosions. The key advantage of this method over other methods which estimate absolute explosive yields is that this method does not require any *a priori* calibration and can be immediately applied to any region of interest. This method uses the source information obtained from the spectral ratios of envelopes of measured seismic coda waves to simultaneously invert for the source parameters describing a set of seismic events including both explosions and earthquakes. The only requirement of this method is that the source region must contain several (>3) seismic sources which have been well recorded (SNR > 2) by a set of shared stations. For regions with only a few events and/or extremely band-limited observations, for which the depths of burial are unknown, an earthquake with a known magnitude may be required to obtain accurate and robust yield estimates. We apply this method to the six declared Democratic People's Republic of Korea nuclear tests and report new independent absolute yield and depth of burial estimates which are commensurate with previously determined source parameters.

Update on an Automated Method to Improve Seismic Array Observations

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We present advances in our Array QC method and an expansion on its potential utility. The method relies upon the singular value decomposition of seismic array channel waveforms in a jackknifing approach applied to sliding time windows, exploiting changes to the singular values of the system when intermittent noise contaminates a channel and potentially impacts the quality of array analysis results. This tool is written in Python and is driven by a GUI whose interface has recently been updated from Tkinter to PyQt5 for improved aesthetics, flexibility and functionality. We will discuss application of the tool to novel array and network systems, including such large datasets as DAS, SEG-Y supergathers or Large-N deployments.

From Earthquakes to Plate Boundaries: Insights Into Fault Behavior Spanning Seconds to Millennia

Oral Session • Thursday 20 April • 10:00 AM Pacific

Conveners: Nadine Reitman, U.S. Geological Survey (nreitman@usgs.gov); Chris Milliner, California Institute of Technology (milliner@caltech.edu); Austin Elliott, U.S. Geological Survey (ajelliott@usgs.gov); Marion Thomas, Earth Sciences Institute of Paris, Sorbonne Univeristé (marion.thomas@sorbonne-universite.fr)

Strain rates in the Anatolia-Caucasus Region from Sentinel-I InSAR and GNSS, and Integration with Earthquake Catalogues

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Geodetic measurements of surface deformation can provide crucial constraints on a region's tectonics and seismic hazard. To do so effectively, they need to be spatially dense (enough to highlight individual faults), spatially extensive (enough to capture the entirety of strain signals), temporally dense (enough that noise and nuisances can be understood), temporally extensive (enough to bring out gradual interseismic deformation), and accurate. A combination of InSAR and GNSS data is arguably the first data form that can be all five of these. In the Anatolia-Caucasus region, we are using Sentinel-IA InSAR frame velocities from the COMET LiCS system and pairing them with a high-quality GNSS velocity field to generate high-resolution maps of crustal deformation and strain rate. We find that the North Anatolian Fault is the dominant feature in the strain accumulation field, but also resolve deformation coinciding with other tectonic structures in western and southern Anatolia and throughout the Caucasus. To compare these strain rates with earthquake occurrence rates, we assemble an integrated earthquake catalogue for the region that covers many hundred years, and assess whether the moment release in earthquakes has kept up with the moment accumulation rates implied by our strain maps.

The Coseismic and Long-Term Roles of Earthquake Gates in Strike-Slip Faults

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Earthquake surface ruptures consist of fault segments bound by gaps, stepovers, and bends. Coseismically, these geometrical complexities, or earthquake gates, can act as barriers to rupture propagation, where the history of past earthquakes, material properties, and the availability and geometry of neighboring fault segments dictate the probability of throughgoing rupture. Over long timescales, these zones of geometrical complexity partly control the growth and evolution of the fault zone. In this contribution, we measure the passing probabilities of different earthquake gates as a function of their geometrical and stress attributes using the surface rupture maps of 31 strike-slip earthquakes from the Fault Displacement Hazard Initiative's rupture database. Fitting logistic models through our data, we find that step-overs and gaps exceeding widths and lengths of 1.5 km are breached less than half of the time, as are bends with angles exceeding 45 degrees. We estimate the event likelihood of each of the earthquakes considered as the joint probabilities of all the breached gates in that event. These likelihoods serve as a retrospective indicator of the magnitude an earthquake grew to as a function of the geometrical complexity of the host fault network. We find that likelihood decreases with increasing magnitude, where, for a given magnitude, earthquakes that occurred on more mature faults (larger cumulative displacement) have higher likelihoods. Last, we consider earthquake gates in the context of the modern

regional stress field and discuss the role of geometrical complexity in long-term fault stability.

Predicting Off-Fault Deformation Using Convolutional Neural Networks Trained on Experimental Strike-Slip Faults

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Surface offsets might not represent slip at seismogenic depths because ruptures produce shallow distributed off-fault deformation. Scaled physical experiments simulate off-fault deformation processes and provide direct observations of deformation partitioning during fault evolution. Using experimental fault maps, we train and test a 2D Convolutional Neural Network (CNN) that can predict off-fault deformation of strike-slip fault trace maps. The CNN predicts kinematic efficiency (KE), the ratio of strike-slip rate along the faults to the total velocity. High kinematic efficiency indicates mature and through-going fault surfaces that require less work to maintain deformation resulting in small off-fault deformation and limited shallow slip deficit. On the other hand, immature strike-slip faults with segmented and complex trace geometry produce greater off-fault deformation and larger shallow slip deficit.

We train the CNN on experimental strike-slip faults in both kaolin and sand with different loading rates and basal conditions to simulate a wide range of conditions that control evolution of fault geometry and off-fault deformation. The CNN hyperparameters minimize our custom loss function. We compare how the CNN trained on faults that grow in one rheology and boundary condition perform in predicting KE of unseen fault maps with different conditions to assess the predictive power of the CNN. All experimental fault maps are combined for training the CNN that incorporates expected variations in the crust and tested on crustal strike-slip fault maps of different maturity in southern California. This study shows the potential that deep learning trained on experimentally produced faults has in shedding insight into the strain partitioning of crustal faults.

Fault Coupling Controls Fine-Scale Fault Structure and Kinematics Along the San Andreas Fault

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The San Andreas Fault exhibits diverse modes of seismic and aseismic deformation along a highly localized fault zone. Although the main fault trace appears as a simple planar fault, small earthquakes exhibit highly complex fault geometry and slip motions. Here, we investigate the focal mechanisms, seismicity, and repeating earthquakes along a 6-km-wide 170-km-long segment of the central San Andreas Fault (CSAF) from 1984 to 2015 to investigate both the main fault coupling and potential as well as the variations of surrounding small earthquakes. We propose a mechanical model of a freely slipping shallow seismogenic layer with several locked patches and a 34mm/yr inter-seismic deep slip rate beneath the seismogenic layer. The simulated fault creep rate, creep direction, and surface deformation are consistent with those estimated from recurrence rate of repeating earthquakes, slip directions of repeating earthquake focal mechanisms, and the surface creep observed from INSAR data. The modeled off-fault stress field also shows high correlation with the variation of focal mechanism properties of M>=1 earthquakes around the fault. The results suggest that the variation of fault coupling along the CSAF play a primary role in the seismic and aseismic deformation patterns both on-fault and off-fault. The possible locked patches along the CSAF indicated from the model show large slip deficits that could potentially be compensated by moderate sized earthquakes or by accelerated afterslip following large earthquakes on the nearby fault segments.

Interplay of Seismic and Aseismic Slip on the San Andreas Fault Near San Juan Bautista, Central California

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The central creeping section of the San Andreas fault (SAF) from Parkfield in the south to San Juan Bautista (SJB) in the north is creeping aseismically and separates the locked portions of the fault that rupture in great earthquakes. The transition between creeping and locked fault sections is a preferential zone of earthquake nucleation, where frictional heterogeneity leads to a complicated relationship of seismic and aseismic slip. The location in a locking transition, numerous moderate-sized local earthquakes, a historical record of aseismic slip transients, and dense instrumentation near SJB make it an excellent natural laboratory to study the interplay of seismic and aseismic slip. Here we combine seismic and geodetic observations from 1993-2021 to study aseismic slip transients and their relationship to moderate-sized local earthquakes and address a number of fundamental questions: How often does aseismic slip lead to earthquakes, how often do these earthquakes lead to aseismic slip? What is the relationship between shallow and deep slip? What are the scales and patterns of spatiotemporal changes in creep rate along this locking transition? What is the largest earthquake we can expect in the region? We look at detailed spatial changes in earthquake statistics and repeating earthquakes and find an anomalous region potentially indicative of increased locking. We also explore spatiotemporal changes in frequency content of earthquakes that may illuminate variable frictional fault properties. We then combine these seismic observations with geodetic (i.e., cGPS, InSAR, creepmeters, borehole strainmeters) data to confirm apparent changes in creep rates and model aseismic slip transients. Further, we are installing new creepmeter pairs to capture propagation velocity of creep events along the SAF to better evaluate changes in creep rates along the fault. Studying the interplay of seismic and aseismic slip in this well-instrumented region may provide insights into other tectonic environments, particularly the offshore portion of subduction zones, where direct observations are limited.

Untangling Slab Geometry's Influences on the Megathrust Earthquake Cycle

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Across disparate tectonic settings, fault geometry plays a fundamental role in determining earthquake characteristics such as magnitude, rupture area, spatial distribution, radiated frequency content, and average recurrence interval. In subduction zones, observations of both slow and fast slip transients have led to proposals that aspects of megathrust fault geometry such as roughness or dip control the locations and slip behavior of slow-slip events, tremor, (very-)low-frequency earthquakes and large megathrust ruptures. Correlations between the magnitude and megathrust geometry of recorded $M_w > 8.5$ earthquakes suggest that larger events tend to rupture flatter, more shallowly dipping subduction interfaces with wider downdip seismogenic zones. However, the mechanisms and relative importance of these apparent geometric controls on maximum magnitude remain elusive. Here, we analyze the specific mechanisms and relative contributions of megathrust dip and curvature using self-consistent 2D discontinuous Galerkin finite-element models of sequences of earthquakes and aseismic slip. Our results suggest that the downdip seismogenic width and average slab dip determine the maximum possible earthquake magnitude for a given subduction zone, while sharper slab curvature increases megathrusts' rupture variability and reduces their tendency to slip in maximal events. These models support the hypothesis that increased megathrust geometric heterogeneity promotes rupture variability and more frequent smaller partial ruptures by enhancing interseismic strength and stress variability on the fault interface. This relationship between fault geometry and rupture variability suggests that a subduction zone's tendency to host full-margin ruptures may be limited by geometric heterogeneities like rough subducting seafloor or sharp variations in slab curvature, highlighting the importance of high-resolution imaging of these features.

Fast Crustal Slip Rates (Vertical and Horizontal) Revealed by Lidar Derived Topography Above the Subducted Chile Ridge, Patagonia

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The effect of an oceanic ridge spreading center being subducted on the overlying plate is poorly known and Chilean Patagonia is the perfect natural labora-

tory to evaluate this. At the Laguna San Rafael (~47 degrees Latitude South) in Chile's Aysen Region, we designed and collected a novel airborne light detection and ranging (lidar)-derived topographic models and drone photography-derived structure from motion (SfM) models, supported by field observations to map Quaternary deposits and bedrock geology displaced along the dominantly strike slip Liquiñe-Ofqui fault zone (LOFZ). The LOFZ accomodates oblique subduction here, is the limit of the Chiloe Microplate, and appears to control the surface location of volcanoes in the southern 600 km of the Southern Volcanic Zone, i.e. volcanic arc in Patagonia. The LOFZ is seismogenic and responsible for a damaging and fatal Mw 6.2 earthquake in 2007 that occured along a minor fault that intersects with the master fault. Dated glacier deposits, from the most equatorial glacier on Earth, the well-studied San Rafael, when combined with displacements we measured in the models and verified in the field, yield horizontal slip rates of 13.8 ± 4.9 and 14.1 ± 1.0 mm/yr. Holocene vertical rates are the fastest on Earth, ~6 ± 3 mm/yr, and these vertical rates are apparent in satelite observations nearby but outside of the lidar-swath (and at correspondingly lower resolution. Fault traces found in the tectonic geomorphology were traced to natural exposures of fault rocks which show a flower structure forming during transpression. Because the dip slip along the LOFZ is ~0 mm/yr 750 km to the north, the rapid neotectonic uplift here along the LOFZ is likely controlled by oblique subduction of the Chile Ridge and associated slab window, and contributes to some of the highest topography found in Patagonia (~4 km). These field data confirm seismic observations and geodetic models that suggest fast slip rates along the LOFZ here, and provide important insight into the seismic hazard in Patagonia as the master fault did not rupture in 2007, it presents a major source of seismic hazard.

Piecemeal Rupture of the Central Andes Subduction Zone Megathrust

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How megathrusts rupture in space and time to keep up with the long-term plate convergence along subduction zones is a key question in both plate boundary dynamics and seismic and tsunami hazard assessments. However, our understanding is limited and mainly based on numerical/conceptual models because cases of one or more earthquake ruptures filling long sections of megathrusts are either too few to cover the full spectrum or too imprecise to be reliable. An example of an imprecise case is the rupture history of the central Andes section of the Nazca–South America plate boundary. This megathrust section, which spans Southern Peru and Northern Chile, was recently ruptured by great earthquakes in 1995 (M8.1), 2001 (M8.4), and 2014 (M8.2), and by two much greater earthquakes (M8.5-9) in 1868 and 1877. However, current estimates of the 1868 and 1877 rupture areas using historical accounts of their effects vary by up to a factor of 3 so there is debate whether they include or not the rupture areas of the recent earthquakes. Here, we attempt to solve this issue by pinpointing the main area of slip in each earthquake using unambiguous tsunami waveforms instrumentally recorded to the north (San Francisco, United States) and south (Sydney, Australia) of their rupture zones. We found that while the 1868 rupture area filled the gap between the 2001 and 2014 earthquakes, the 1877 earthquake ruptured the gap between the 2014 and 1995 earthquakes. Thus, collectively and with limited overlap of the main slip areas, the 1868, 1877, 1995, 2001 and 2014 earthquakes ruptured the entire length (1000 km) of the central Andes Subduction Zone megathrust. Such a piecemeal rupture contrasts the one in the 1000-km southernmost section of the same plate boundary megathrust, which was last ruptured entirely by the 1960 (M9.5) earthquake alone

Coupling and Seismic Cycle Along the Hikurangi Subduction Zone

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Here, we study the Hikurangi subduction zone (North Island of New Zealand) from Nov. 2014 to Jan. 2022. InSAR studies in New Zealand are particularly challenging due to the dense vegetation cover. The numerous crop fields generate strong biases in the multilooked time series results. These biases can reach several centimeters in amplitude and can be mixed with the tectonic signals. We present a powerful strategy to mitigate these biases and correct their impact on our observations as much as possible. We correct this fading signal using a principal component analysis (PCA). This approach is applied directly to the displacement time series rather than the interferograms. We demonstrate how a PCA applied to the displacement time series can separate the spatial long-wavelength, the coherent tectonic signal, from the localized biases. We observe that this latter method yield is more reliable in reducing the impact of these environmental biases than the masking method. Furthermore, it allows us to isolate the interseismic signal across the Hikurangi subduction zone. Using these corrected displacement time series, we then study the inter-SSE period following the Kaikoura earthquake (Nov. 2016, Mw 8.1) to observe if this crustal earthquake has impacted the long-term plate coupling. We integrate the InSAR velocity map to compute a coupling model of the inter-SSE period. We then can extract and observe the signal from the Slow Slip Events (SSEs) and propose a first slip model using both InSAR and GNSS time series to obtain the slip at depth.

Deep Transient Deformation and Long-Distance Along-Slab Stress Interactions: The 2013 Seismic Activity and Slow Deformation Beneath Kamchatka and Okhotsk Sea.

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The discovery of slow slip events on subduction planes have triggered a new interest to deformation transients with time scale between regular earthquake and plate motion. The studies of initiation of large earthquakes are focused on frictional instabilities occurring in the near vicinity of the future rupture. Contributions of deeper transients and of long-distance interactions remain unknown. Here we analyze seismic catalogs and geodetic time series during a few months preceding the 2013 M = 8.3 deep-focus Okhotsk earthquake. This deep-focus event is preceded by four intense seismic clusters in the seismogenic zone. GNSS time series in Kamchatka revealed a transient landward motion episode one month prior to the mainshock, consistent with an increase of seismogenic zone loading. This transient loading episode is accompanied by a doubling of the intermediate depth seismicity rate suggesting a transient slab pull as the origin. These observations question the constant subducting velocity hypotheses and may have implications in the understanding of the long-distance along-slab stress interactions and in their contribution to initiation of large earthquakes, including deep-focus and shallow subduction events.

Assessing Distribution and Pattern of the Earthquake-Related Deformation Caused by Large Continental Normal Earthquakes Using Optical Image Correlation

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Earthquakes on normal faults in the continental setting are relatively uncommon. The scarcity of surface-rupturing events underpins an absence of surface displacement measurements. It is a common practice to use surface offset as a proxy to understand the fault structure at depth. Hence, the lack of comprehensive surface data impedes the subsurface reconstruction of seismogenic normal faults and prohibits the thorough assessment of earthquake hazards. To supplement the available surface displacement measurements and to make statistically significant inferences, we apply optical image correlation (OIC) methods to historical images from three large continental normal earthquakes in the western United States (1954 Dixie Valley (Mw 6.8) - Fairview Peak (Mw

7.1) earthquake sequence, the 1959 Mw 7.2 Hebgen Lake earthquake and the 1983 Mw 6.9 Borah Peak earthquake). The results of this study are displacement maps with three components of deformation from which we extract high-resolution 3-d measurements everywhere along the surface rupture.In this work, we quantify surface offset, fault zone width, and percentage of off-fault deformation. These parameters are used as a proxy to understand the subsurface geometry and structure of the fault. Our data confirm behaviours previously observed along strike-slip faults (e.g. magnitude of off-fault deformation is proportional to the rupture complexity). In addition, a comparative assessment of the results from the three study areas demonstrates that features such as excess slip detected close to the fault scarp are not unique and can be found along multiple dip-slip faults. Consequently, this study documents the variation of the quantifiable parameters along the normal faults. It suggests that while some parameters are a universal reflection of the fault characteristics, others vary according to the geology or topography in the area and should not be accepted without further investigation.

Late Pleistocene and Holocene Paleoseismology and Deformation Rates of the Pleasant Valley Fault (Nevada, USA)

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The Pleasant Valley Fault (PVF) generated a magnitude 7.3 earthquake on October 2nd, 1915. Scarps occurred along a set of 4 en-echelon arranged extending ~60 km long the west flank of the Tobin Range in Nevada. The earthquake was the first of a sequence of earthquakes that defines the Central Nevada Seismic Belt (CNSB), most prominent among them the ~M7 1932 Cedar Mountain, the 1954 Dixie Valley, and Fairview Peak earthquakes. Average displacements along the Pleasant Valley fault averaged ~2m (maximum 5.8 m) in 1915, commonly along preexisting scarps from yet earlier earthquakes.

We excavated 5 new paleoseismic trenches across the 1915 rupture, at 4 locations in the central two segments, exposing a colluvial stratigraphy showing multi-events at each site. The colluvial units are generally gravel to sandy sediments and at one site a tephra layer is present. The alluvial fan displaced and the colluvial units present different degrees of soil development, occasionally carbonate enriched. To constrain the paleoseismology timings, ~30 luminescence and one tephrochronology samples were collected. Preliminary results suggest 3 or 4 events pre-1915 during the last ~30 ka, suggesting a recurrence period of ~7 ka with the penultimate event to have occurred ~9 ka ago.

To estimate the ages of the alluvial fans displaced along the mountain front and calculate the long-term slip rates associated with the fault system, we sampled boulders (when available) and sediment for depth profiles for 36Cl terrestrial cosmogenic nuclide dating at 6 sites at relative different positions of the fans and fault system. Altogether, these results are the first to provide information about the timing, frequency, and spatial distribution of surface ruptures along the PVF during the Holocene and late Pleistocene and the average rate at which the PVF slips on the short and long term, thus filling a gap in the seismicity knowledge in the CNSB.

Quantifying Seismic Hazards in the Walker Lane Through Assimilation of Spaceborne InSAR Observations

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Over the past ten years, the border region of California and Nevada has experienced a number of significant earthquake sequences, including several prominent M5-M7 events. Earthquake hazard is severe near the metropolitan areas of Reno and Carson City, which are located within a complex tectonic setting known as the Walker Lane. In this region, earthquake hazard is comparable to sites along the San Andreas Fault in California but is not as well-studied through geodetic means. Here we present recent surface deformation observations covering the Walker Lane region derived from spaceborne Interferometric Synthetic Aperture Radar (InSAR) and Global Navigation Satellite System (GNSS) data. The use of both datasets in tandem provides complementary perspectives on the complexity of Earth's surface response after seismic events over time. We designed a InSAR processing strategy that accounts for region specific errors due to inaccuracies in the Digital Elevation Model (DEM); we then build time series where a wide range of slip behaviors (i.e., co-seismic, aseismic, and postseismic deformation) can be interpreted. Understanding the influence of slip behavior of this region will provide insight towards the space-time evolution of the strain field in the Walker Lane and its relation to seismic hazard and earthquake occurrence.

Using Dynamic Rupture Simulations to Explore Fault Segmentation and Rupture Length on the Sierra Madre Fault Zone

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The Sierra Madre Fault Zone (SMFZ) is a 125 km-long, north to northeast-dipping thrust fault which arcs along the southern edge of the San Gabriel and Santa Susana Mountains in Los Angeles and San Bernardino counties, southern California. Based on its length alone, it is capable of producing a ~M7.7 earthquake, but its discontinuous geometry may lead to it rupturing in multiple smaller (~M6-M7) events (such as the M6.6 1971 San Fernando earthquake). Given the SMFZ's location through the densely-populated San Fernando, San Gabriel, and San Bernardino valleys, even a smaller event on this fault would have major implications for human safety and infrastructure stability.

We conducted 3D dynamic rupture simulations on the SMFZ, which we parameterize with four separate segments, to assess plausible rupture behaviors and ground motion distributions for this fault system. We use Southern California Earthquake Center (SCEC) Community Fault Model geometry, SCEC Community Velocity Model surrounding rheology, and SCEC Community Stress Model regional stress orientations to ensure that our model setup is grounded in observation and that our results are realistic. We find that the segmented, nonplanar geometry of the SMFZ controls its possible rupture behaviors, with the nucleating segment playing the largest role. Ruptures that nucleate on the ends of the fault system are limited by stepovers, and do not allow more than a small amount of slip beyond the nucleating segment. Ruptures that nucleate in the center of the system propagate through at least two segments, and sometimes may grow into a wall-to-wall rupture of the whole fault system; this also depends strongly on nucleation location. The maximum magnitude of our simulations is M7.47; there are several different slip distributions for this magnitude, however, which produce different ground motion distributions and intensities. This suggests that the details of slip distribution and rupture directivity are critical for ground motion intensity estimates, both on the SMFZ and in general.

Towards Decadal Scale Global Geodynamic Models

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Our goal is to lay the foundations for a novel research field of *"Decadal Scale Global Geodynamics"* that connects deep mantle flow and plate boundary dynamics to changes in the uplift rates and stress patterns at the Earth's surface that occur on human timescales. With the precision and coverage of satellite remote sensing achieving accuracies below the millimetre scale, the fact that the solid Earth is an actively deforming fluid body is now a substantial correction that must be made before the details in these signals can be interpreted. For example, we can consider the interaction between short and long timescales in the great subduction systems, and how this changes the Earth's tectonically driven topography and stress field at human timescales.

First, we demonstrate that our large-deformation, particle-based tectonic modeling code (Underworld) can also be used to simulate aspects of the Earthquake cycle and we compare our outputs to those of the common benchmarks. In particular, we show how mesh / particle-field deformation affects (degrades) our ability to match those benchmarks. We consider which signals will be robust in large-deformation models.

Second, we consider the global surface relaxation problem which occurs at the intermediate timescale between the Earthquake cycle and the tectonic timescales. We consider the modelling tools that are needed to be able to connect the timescales and the trade-offs that we expect to find in developing these coupled methods.

From Earthquakes to Plate Boundaries: Insights Into Fault Behavior Spanning Seconds to Millennia [Poster]

Poster Session • Thursday 20 April

Conveners: Nadine Reitman, U.S. Geological Survey (nreitman@usgs.gov); Chris Milliner, California Institute of Technology (milliner@caltech.edu); Austin Elliott, U.S. Geological Survey (ajelliott@usgs.gov); Marion Thomas, Earth Sciences Institute of Paris, Sorbonne Univeristé (marion.thomas@sorbonne-universite.fr)

A New Model for the Strike-Slip Response of Entrenched Drainages Derived From an Alluvial Terrace Sequence at the Littlerock Creek Along the Mojave Section of the San Andreas Fault

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We explore how alluvial terraces form in the sheltered-corner (SC) of streams offset along strike slip faults as a function of the accumulation displacement (D) and of temporal variations of the stream erosive power (E). We combine new mapping and ^{10}Be dating of the Littlerock Creek (LRC) terrace sequence at its intersection with the San Andreas Fault (SAF), and analysis of published flume experiments of strike-slip displaced streams. River incision at LRC is driven by rapid uplift and transpression. Elevyn terraces abandoned between 36 and 12ka are preserved in the SC on the downstream side of the SAF, only two of which are preserved on the upstream side. The fluvial architecture shows two sets of narrow terraces that measured parallel to fault strike are elevated along a similar gradient of ~6º. These sets are separated by two terraces that are 3-times wider with much lower along-strike gradient, and correlate temporally with the upstream terraces.

Applying our analysis of the flume experiments to the LRC record, we propose that the steeper terrace gradient provides a measure of the ratio of the uplift to strike-slip component, and was acquired during steady-state intervals with equilibrium between E and D. The intervening two-terraces interval is interpreted as a transient period, during which the geomorphic system evolved from lower E and higher deflection angle (the angle the stream intersects the fault) to higher E and lower deflection angle, leading to the abandonment of the upstream terraces. This sequence of events is supported by independent paleoclimate records of water discharge along the LRC. These results suggest that the stream response to D is governed by the following feedbacks: (1) E determines the extent of upstream-facing scarp erosion, which in turn (2) controls the deflection angle, and hence (3) the geometry of the SC. Quantitative analysis of the SC terrace stratigraphy along strike-slip displaced entrenched drainages might thus be used to derive cumulative displacements even in the absence of upstream piercing-points.

Characterizing the Transition From Diffuse to Localized Deformation Using Optical Image Correlation: The 2021 Mw7.4 Maduo, Tibet, Earthquake

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The 2021 M_w7.4 Maduo earthquake generated a ~160 km-long fault rupture within the Eastern Tibetan plateau, at about 100-150 km to the south-west of the Eastern Kunlun fault. Fault slip measured on the field represents only 20% of the displacements from satellite Interferometric Synthetic Aperture Radar (InSAR) measurements, highlighting the primarily diffuse nature of the surface deformation for this earthquake. Most surface deformation associated with this event corresponds to diffuse shear, occurring over widths of a few hundreds of meters to a few kilometers, and sometimes associated with shearing and tensional cracks mapped in the field. In this study, we use sub-pixel correlation of Pleiades (0.5 m) and SPOT-6/7 (1.6 m) optical images to characterize the near-fault displacement patterns associated with the 2021 Maduo event. We also use other optical data to assess the impact of sensor resolution on the measurements. Our results cover three kilometers on both sides of the rupture area with a resolution of 0.5 m. These results show that, despite the large rupture gaps observed in the field, the shear deformation zone at the surface is continuous along the entire length of the 2021 rupture. Even though, we observe variations in the surface deformation patterns, with regions that present more localized deformation whereas others are primarily characterized by diffuse shear. Using the high-resolution displacement maps, we characterize the transitions from the localized to the diffuse shear along the rupture strike, and investigate the relations with the bulk rock properties, and coseismic slip distribution. We also determine the limit at which deformation starts to localize on fractures that are large enough to be visible in the field.

Early Postseismic Phase of the 2011 Tohoku-Oki Megathrust Earthquake: Observations by High-Rate Gps Solutions and Deformation Mechanisms Involved

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Post-seismic deformation involves several mechanisms (afterslip, poroelastic rebound, viscoelastic relaxation), acting at different spatial and temporal scales. The early post-seismic phase, from a few minutes to a few hours after the mainshock, is interesting because it marks the transition between rapid-coseismic slip and subsequent slow slip and aftershocks. Since it is characterized by high deformation rates, analyzing the deformation in this early period can bring strong constraints on the postseismic mechanisms. Yet, the early postseismic deformation has been little studied, because high-rate time series of the surface deformation in the vicinity of the rupture zone are not always available and time series are noisier that daily positioning.Here, we focus on the early postseismic of the 2011 Mw 9 Tohoku-Oki earthquake. A detailed analysis of the temporal evolution of the deformation, using high-rate GNSS time series over one month after the earthquake, is used to identify the underlying mechanisms at play at short time scale.Our result show that the temporal evolution of the early postseismic signal can be mostly explained by an Omori-like Transient Brittle Creep mechanism with a p-value around 0.75. The first 40 hours of signal are key to characterize this behavior. The spatial analysis reveals that the mainafterslip zone locates downdip from the main rupture. A secondary afterslip zone, close to the Ibaraki-Oki aftershock, has a distinct temporal evolution with a p value around 1.To interpret these p-values, we develop a simple numerical model that qualitatively reproduced p values lower than one. We show that performing a creep test in a progressive damage model including thermal activation allow to qualitatively reproduce the temporal evolution observed for the early postseismic signal of Tohoku. Finally, we compare the temporal evolution with the aftershock activity, and we also extend the GNSS analysis to longer time scales (9 years). Over longer time scales, we combine the transient brittle creep mechanism with viscoelastic relaxation to explain the surface displacements.

Finite Fault Inversion for M6.8 Luding Earthquake: Impact of Station Configuration on Inversion Robustness

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A strike-slip earthquake of M6.8 occurred in Luding County, Sichuan Province, China (102.08°E, 29.59°N), on September 5, 2022, with a focal depth of 16 km. The numerous strong-motion stations have provided valuable near-field observation data. Finite fault inversion is widely used to recover complex features of the rupture evolution. However, station configuration has impact on the stability of inversion results. In this paper, we applied the finite fault inversion to strong motion data of Luding earthquake, and the impact of station configuration was also explored. We found that the rupture process can be divided into two episodes. In the first episode, the initial rupture lasted for 3 second on a westward tilting fault plane. In the next episode, a shallow rupture started after the previous rupture and lasted for 4 second. As a result, the 2022 Luding earthquake failed to cascade up to a lager event. For the influence of stations configuration, the inversion using more stations provided more reliable models, but the waveforms of remote stations (epicenter distance > 200km) did not match well and contributed little information to the fault rupture. The azimuth angles of stations also affected the inversion results significantly due to the complex variations of tectonic environment from the east to the west of Sichuan Province. To gain reliable information during the inversion, an optimal station network needs to be automatically designed for robust finite fault inversion.

Geer Team Surface Fault Rupture Observations From the September 2022 Longitudinal Valley Earthquake Sequence, Eastern Taiwan

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We present observations of the September 2022 Longitudinal Valley surface ruptures with a focus on documenting and understanding triggered fault displacement, localized strain partitioning, and variability of repeated surface ruptures on the Chihshang segment of the Longitudinal Valley fault (LVF). The Longitudinal Valley of southeastern Taiwan represents the surface manifestation of a complex plate boundary fault system accommodating oblique sinistral shortening at rates of several centimeters per year between the Philippine Sea Plate and the Eurasian Plate. The 2022 Longitudinal Valley earthquake sequence initiated with an M_L 6.4 event on September 17th followed by an M_w 6.9 event on September 18th, with the latter event producing surface rupture along approximately 40 km of the plate boundary consisting of the east-dipping LVF and the west-dipping Central Range fault (CRF). Field observations from the October 2022 GEER reconnaissance indicate that the majority of surface rupture at the latitude of the epicenter occurred on the LVF rather than the adjacent and causative CRF. GEER team surface rupture observations documented oblique shortening on the LVF that was most commonly expressed as either pure shortening or pure translation with on-fault displacements typically ranging from a few tens of centimeters to nearly 1 m. Additionally, surface rupture from the September 2022 sequence was notable for its similarity to the surface rupture distribution during a prior LVF earthquake sequence in 1951. Surface rupture also occurred on the LVF in 2003 and March 23, 2022. Collectively, the 20th and 21st century events on the LVF afford a rare opportunity to understand the variability of surface fault rupture from historic documentation and eyewitness accounts rather than sole reliance on a millennial-scale paleoseismic record.

Geologic Context of the 2020 Mw 6.5 Stanley, Idaho Earthquake: Preliminary Paleoseismology of the Sawtooth Fault

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The 2020 M_W 6.5 Stanley, Idaho, earthquake occurred in a poorly understood area of oblique extension north of the 67-km-long Sawtooth fault, within the northwesternmost part of the Centennial Tectonic Belt. The dominantly left-lateral earthquake likely involved multiple, north-northwest (NNW) trending faults with blind rupture. To provide geologic context for this earthquake, we (1) mapped the surface traces of previously unknown faults in the epicentral region using 0.5-m-resolution lidar, and (2) excavated a trench across the northern extent of the Sawtooth fault at the Dutch Lake site, ~10 km south of the 2020 epicenter. Lidar mapping suggests that southwest–northeast oriented strain in the region is accommodated by a 5-km-wide overlapping left step between (1) NNW-trending and east-facing scarps at the northern terminus of the Sawtooth fault and (2) NNW- to north-trending and west-facing scarps along the 8–10-km-long Cape Horn fault. This pattern corresponds well with previous fault models for the 2020 earthquake showing lateral and normal slip on opposing, west- and east-dipping faults, respectively. We excavated a trench at the Dutch Lake site, within this left-stepping zone of slip transfer. The trench exposed postglacial alluvial-fan sediments vertically displaced 2.0–2.2 m by a single surface-faulting earthquake. Complex, likely normal-oblique faulting postdates surface formation at the site and predates charcoal-rich loess incorporated into surface sediments and scarp colluvium. Samples for ^{14}C, luminescence, and ^{10}Be cosmogenic dating will help resolve the timing of the prehistoric earthquake. We will explore scenarios of rupture length and displacement using the lateral continuity and vertical separation of scarps. Our preliminary results show that strain in the region is expressed along a complex, distributed zone of faults that have an unknown paleoseismic history compared to the rupture of the northern Sawtooth fault exposed at the Dutch Lake site.

Geomorphology May Be a Poor Recorder of Slip Distributions From Paleo Surface Ruptures

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Interpreting the geomorphic record of strike-slip earthquakes to infer slip in past events is complicated by the observed complexities of surface ruptures. Recent earthquakes show that slip variability in a rupture is on the order of 40-50%, distributed deformation is common and spatially variable, and rupture start and end points are not always at obvious section boundaries. Further complicating the record created by each surface rupture is climate's influence on the landscape. Offset features are modified by geomorphic processes between earthquakes, and the precipitation rate of a region may affect the distribution of offset features preserved along a fault. Here, we explore the limitations of the geomorphic record with offsets from 40 historical surface ruptures and synthetic elliptical and flat slip distributions with 0-50% noise to infer best practices for interpreting slip in past earthquakes (paleo slip distributions). Given typical variability levels of modern surface ruptures and rates of geomorphic change, we find that it is unlikely to accurately reconstruct more than one or two paleo slip distributions from offset geomorphic features except in unique cases. In cases where site-specific conditions or information allow for interpretation of more than two events, extrapolating that information along a fault is not straightforward because on-fault displacement and distributed deformation are often spatially variable. We apply these insights to interpret geomorphic offset data in 2D probability space using a Monte Carlo approach to construct slip distributions with uncertainty bounds. Applying this method to both the recent ruptures and geomorphic offset data for 20 strike-slip faults with evidence of multiple paleo earthquakes, we find that the prevalence of uniform, full-fault ruptures (i.e., the "Characteristic Earthquake Model" of Schwartz and Coppersmith 1984) is likely lower than previously interpreted from geomorphic offset data.

Linking Subduction-earthquake Supercycles with Coastal Uplift in South Chile

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Ranges in recurrence of megathrust earthquakes allows them to be grouped into earthquake cycles within supercycles. We use coastal stratigraphy and soils on raised intertidal deposits at Isla Guafo, 60 km landward of the south Chile trench, to infer land-level changes associated with great subduction earthquakes, and numerical models to infer the relations of the changes with plate-boundary slip. Guafo was uplifted ~4 m during the 1960 earthquake (M9.5) and has been subsiding rapidly since at ~16 mm/yr from continuous GPS. Subsidence was interrupted by 11 cm of uplift during the 2016 earthquake (M7.6). Five soils, each developed on coseismically uplifted intertidal deposits, were buried during the past 1.7 ka. The sequence of soils and deposits suggests land-level changes similar to those observed during and after 1960. Such repeated changes can be modeled as elastic strain accumulation and release in the shallow segment of the plate-boundary. However, distinct changes in coastal morphology and stratigraphy suggest Guafo was permanently uplifted during an earthquake in AD ~800. This age range overlaps the time when sequences of subsided buried soils at Chucalén and Maullín, located at 120 and 140 km from the trench, respectively, show an abrupt change in lithology suggesting uplift. If the change records permanent uplift at Maullín during the same earthquake, slip in the deeper segment of the plate boundary is required. However, we cannot yet determine if the uplift occurred during of shortly after the earthquake. Uplift at these three sites is associated with emerged coastal terraces, suggesting a link with permanent coastal uplift. Such events that slip (either co- or aseismically) down to the continental mantle apparently have millennial recurrence times instead of centuries as for 1960-type events rupturing the shallower segment.

New Evidence of Quaternary Faulting Along the Gore Range Frontal Fault, Summit County, Colorado

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The Gore Range Frontal fault (GRFF) is an east dipping, late Cenozoic normal fault that accommodates east-west extension associated with the northern Rio Grande Rift in central Colorado. The steep forested terrain along the eastern base of the Gore and Tenmile Ranges mask scarps within a complex geomorphic setting resulting from extensive landslides and multiple glaciations. Prior investigations have recognized sites with offset Quaternary deposits, principally along the northern section of the fault but have also shown that many of these sites are within or bounding large slope failures. USBR estimated a slip rate of 0.07 to 0.23 mm/yr on the northern part of the fault from scarp heights measured in glacial deposits and cosmogenic ^{10}Be surface exposure dating of a single site along South Rock Creek from studies in 2010 and 2014. Prior mapping along the southern sections of the fault has generally shown the fault as queried or uncertain within areas of Quaternary cover.

In this study, we use the publicly available Summit County 1m lidar data collected in 2016 to systematically map evidence of offset Quaternary landforms and scarps along the GRFF at a scale of 1:10,000 between Hoosier Pass and Spruce Creek over a length of ~60-70 km. Our mapping shows a nearly continuous en echelon alignment of short (< 2 km), left-stepping scarps for the southern 60 km. This includes previously unmapped scarps in Late Quaternary moraines east of Quandary Peak and within the recessional moraines adjacent to the town of Frisco. The largest scarps are associated with the highest set of undated Mid (?) and Late Quaternary surfaces and moraines along the northern part of the fault. Smaller scarps are present in younger moraines, but scarps appear to be absent in the youngest late Pleistocene recessional moraines and across the modern (Holocene) valley floors.

Shallow Creep-Rate Variability Along on Northern California Faults From Alos-2 InSAR Time Series

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Alignment arrays across the Maacama Fault Zone (MFZ) indicate surface creep rates of ~5 mm/yr, similar in magnitude to the well studied Hayward Fault. However, further refinement of lateral variability in creep rates and near fault deformation is limited. Interferometry with ALOS-2 ScanSAR data provides a spatially continuous dataset that extends observations of crustal deformation into typically hard-to-reach places, including densely vegetated, snow-covered, and steep regions. We present analysis using both InSAR time series and average velocity fields to constrain lateral variability of shallow fault slip along Northern California faults [including the Maacama, Rodgers Creek, Bartlett Springs, Green Valley, and San Andreas faults].

We carefully examine cross-fault time series and fault perpendicular velocity profiles exploring shallow fault creep, near-fault vertical motions and far-field deformation. Cross-fault differencing mitigates much of the temporal (atmospheric) noise and provides a more accurate estimate of fault creep. Non-tectonic features such as landslides and hydrological deformation can bias these results. We assess anomalous creep-rate values by inspecting profiles of fault parallel and vertical velocity fields to determine whether they correlate with tectonic or non-tectonic deformation. We explore the correlation between vertical deformation and changes in fault geometry on near- and far-field scales. We use a simple 2D dislocation model constrained by surface creep rates and far field average velocity fields to estimate creep and locking depths and compare them to complementary datasets.

The Impact of Fault Bends and Regional Stress Fields on the Strength of Strike-Slip Faults

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Earthquake gates, such as fault bends, can inhibit rupture propagation and thus exert a primary control on rupture length, and consequently, the final size of the earthquake. Therefore, investigating the mechanics of rupture propagation through bends is important for better constraining seismic hazard and potential earthquake magnitude maxima. Through analysis of geometrical and stress characteristics of thirty-one strike-slip earthquakes using the Fault Displacement Hazard Initiative (FDHI) surface rupture database, we revisit the role of fault bends and regional stress fields in long-term fault stability. We find that bends with an angle ≤ 30° are easily breached, allowing throughgoing rupture in most of our case studies. Bends with angles > 60° always inhibit rupture propagation, though we only sample a small number of bends > 50°. Additionally, we observe that the vast majority of our breached double bends had along-strike lengths ≤ 2km. The observed fault bend constraints highlight the vital role these geometric complexities play in rupture propagation in strike-slip fault networks. Considering these results, along with our measurements of the modern regional stress field, we discuss the role of geometrical complexity in the strength of strike-slip faults.

Three-Dimensional Visualization and Implications for Reconstruction of the Chalk Hill Paleoseismic Site on the Rodgers Creek Fault Near Windsor, California

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The Rodgers Creek fault is a primary strand of the northern San Andreas fault system, yet investigations of its recent slip history are limited and are mostly absent north of the city of Santa Rosa. Here we report results from a site located east of the town of Windsor at the Chalk Hill Winery, where we use 3-dimensional site reconstruction to integrate the results of multiple trenches across the main trace of the Rodgers Creek fault with ambiguous results from geomorphic analysis. At the site, an upstream-facing scarp and dextrally-offset landform appear to displace an abandoned channel of Windsor Creek by ~150 m. In detail, however, the channel margins and terrace risers used for reconstruction are inconsistent and leave significant ambiguity in site reconstructions for offset measurements. Three trenches excavated perpendicular to the scarp, spaced at ~10 m intervals, show a juxtaposition of laterally variable Holocene alluvial fill deposits against Plio-Pleistocene gravels. Within each trench, multiple fault strands display locally complex deformation histories with no clear earthquake horizons. At least one strand extends through agriculturally modified deposits and is visible in the modern surface, suggesting that it may accommodate ongoing creep, consistent with prior InSAR analysis on the northern Rodgers Creek fault. We use a virtual 3-dimensional site reconstruction to interpolate and project fault and stratigraphic surfaces between the trenches. This approach allows us to develop a coherent spatiotemporal understanding of site evolution, which helps illuminate the relationship between fault strands and elucidates potential displacement reconstructions at the site. We find that the 3D reconstruction also highlights the inherent assumptions required for site reconstruction and, in turn, provides a visual intuitive test of our assumptions and interpretations and their implications for deformation history at the site.

From Sensors and Networks to Site Characterization and Site Response: Coming Full Circle

Oral Session • Tuesday 18 April • 10:00 AM Pacific

Conveners: Lisa S. Schleicher, U.S. Geological Survey (lschleicher@usgs.gov); Sean Ahdi, U.S. Geological Survey (sahdi@usgs.gov); Olga-Joan Ktenidou, National Observatory of Athens (olga.ktenidou@noa.gr); Albert Kottke, Pacific Gas & Electric Company (arkk@pge.com)

Site Characterization by Means of Geophysical MASW Method at Designated Instrumented Sites of the Puerto Rico Strong Motion Program Seismic Network

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In the seismological and engineering community the influence of the local site effects are of special interest in obtaining reliable seismic records. Local site effects are associated on the records with the amplitude, duration, and frequency content of the seismic records and directly related to the morphological and mechanical properties of the ground, aimed at describing their effects on seismic ground motion for applications related to ground-motion studies and engineering seismology.

During the Fall of 2021, the working group of the Puerto Rico Strong Motion Program (PRSMP), conducted a Multichannel Analysis of Surface Waves (MASW) field work on eleven designated permanent sites instrumented with accelerometers of the PRSMP.

Active and Passive MASW measurements were taken in 24 geophones array spaced three meters each. For the active source mode (Active MASW), shots were hit with a 16lb sledge hammer at offsets of ±1.5m, ±3.0m, ±9.0m, ±21m, at both ends of the array and at 11 selected sites among the geophones. The ambient vibration measurements (Passive MASW) lasted up to one hour of record length.

The collected time series were processed to obtain the dispersion curves for the afterward inversion process in obtaining the site conditions in terms of the 2D V_S-Z profile. Preliminary results of the 2D V_S-Z profiles of this ongoing research of the studied sites and their site/soil classification according to NEHRP range from soil type D (Site UTD2,) and C for the majority of the sites. At the site FJR1, the shear wave velocity of its structure shallow portion averaged 450 m/s, and at the depth of 18 m the estimated shear wave velocity reached 920 m/s, however in terms of NEHERP V_{S30} the soil type classification still on the category of soil type C.

Noise-Based Estimation of Local Seismic Amplification in an Industrialized Area of the French Rhone Valley

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Shallow sedimentary layers may be responsible for dramatic ground motion amplification and increase the duration of shaking when an earthquake occurs. These local modifications of ground motion are usually associated with site effects. Often associated with sedimentary basins, site effects are due to the impedance contrast at the interface between soft soil layers filling the basin and the bedrock. For site effects assessment, methods based on ambient noise might be of great interest in low-to-moderate seismicity regions.In this study we evaluate the applicability of SSRn and SSRh (noise-based and hybrid Standard Spectral Ratio, Perron *et al.* 2018) to assess site effects in the Tricastin region in the French Rhone Valley. This area is prone to generate complicated site effects associated with the valley's incised geometry and the strong lithological contrast between the sedimentary filling and the bedrock. We recorded ambient noise between February to March 2020 on a 400-sensors array. Previous studies have shown that important source effects might bias the resulting amplification factor of SSRn above 1 Hz. To attenuate these local source effects, we introduced a two-step workflow based on the spectral characteristics of the signal. Our workflow relies on a careful time window discrimination for removing strong transient signals and an automatic data selection through a clustering algorithm. By applying this method, we were able to remove strong anthropic transient signals at some sites and therefore improve the amplification assessment above 1 Hz through SSRn and SSRh. We also show that some sites are biased by permanent sources that remain an issue in quantifying the amplification at larger scale. Finally, we explore new strategies based on interferometric methods to overcome the limitations of these approaches. By involving phase coherence, we expect the correlations to better filter uncoherent local sources and give better estimates of the amplification.

Empirical Site Response of Mexico City Developed From Regional Customization of Global Subduction Ground Motion Models

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We assemble a dataset of earthquake ground motions and site parameters from Mexico that extends data resources originally developed for Central America and Mexico for the NGA-Subduction (NGA-Sub) project database. We have used the data to provide regional customization of NGA-Sub global Ground Motion Models (GMMs) for application in Mexico, with a special focus on the site response of Mexico City (CDMX). The database for Mexico is extended by considering small magnitude (Mw < 6) events and three large events (Mw 7.2-8.3) in 2017 and 2018. The latter are particularly important, because they are well recorded over a broad distance range and apply for hazard-critical conditions. Here, we focus on presenting the site response observed in CDMX, which is modelled as a function of time-averaged shear wave velocity in the upper 30 m of the site (V_{S30}) and the intensity of shaking for reference site conditions (Peak Ground Acceleration at a Rock site, PGA_r).The proposed empirical model has several important differences from prior work. First, it is properly centered with respect to GMMs. Second, it is referenced to V_{S30}=760 m/s, which is much firmer than prior practice in which the reference site was taken from a location on the UNAM campus with V_{S30} ~300 m/s; this has the effect of increasing site response estimates. Third, site amplification is found to be nonlinear, whereas prior models have assumed linear response. The level of nonlinearity is characterized utilizing a seismic zonation that has been previously used for CDMX, being more pronounced for softer sites (e.g., Zone III) than stiffer sites (Zone I). The nonlinear effect is pronounced at short periods and disappears at long periods, as expected. Benefits of the provided model are that a common framework is used within and outside the Valley of Mexico (unlike current practice) and the model combines the applicable features of global models while providing appropriate regional and subregional customization.

Achieving Deep Site Characterization in Greater Vancouver, British Columbia, Canada

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Towards achieving seismic microzonation hazard mapping for Greater Vancouver, British Columbia, site characterization data collection spans 5 years and multiple non-invasive seismic field methods (https://metrovanmicromap.ca). This presentation focuses on our efforts to achieve deep (~1 km) shear-wave velocity (Vs) depth profiling at 6 large seismic array sites. Sites are selected to target Vs of the overlying 100's of meters of post-glacial or glacial sediments and into the underlying glacial sediments or rock, respectively. There are no Vs (some Vp) measurements of these deeper geologies in the region. All 6 large array sites are chosen based on our previous smaller-scale multi-method seismic data collection, i.e., previous Vs profiling achieved in the upper 10's to 100's of meters. We developed 13 seismometer deployment kits consisting of a DiGOS Data-Cube^3 digitizer, three-component 4.5 Hz geophone, external battery, GPS antennae, with metal chain and lock of the plastic housing for minimal security. At each large array site, two simultaneous ambient vibration arrays each consisting of 6 sensors with a 13th central sensor of 0.5 to 2 km circumradii were performed for a duration of 2-4 hours to obtain low frequency Rayleigh wave dispersion estimates, i.e., 3-4 arrays are accomplished per site over the field day. We present our preliminary one-

dimensional dispersion analyses of these data; future analyses will treat the data in three dimensions. We obtain dispersion estimates that transition into the higher velocity underlying layer at depth, albeit with significant variability (resolution error). We present the first kilometer(s) deep constrained Vs profiles for Greater Vancouver. This work is in combination with an ambient noise tomography experiment in which we deployed the 13 seismometer kits with 5 other broad-band seismometers across Metropolitan Vancouver for 60 days to update our three-dimensional Vs model beneath Greater Vancouver.

The Activities of the Emersito Ingv Emergency Task Force During the Marchigiana-Pesarese Offshore Seismic Sequence (Central Italy): Directional Amplification and Polarization Analyses

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Emersito (http://emersitoweb.rm.ingv.it/) is an emergency task force of the Istituto Nazionale di Geofisica e Vulcanologia (INGV), whose aim is to study the site seismic response immediately after significant earthquakes in Italy (M>5.0, or lower when noticeable damages are observed). Following the M_w 5.5 (M_L 5.7) seismic event occurred about 30 km offshore the Marchigiana-Pesarese coastline (central Italy) on November 9 2022, the *Emersito* task force installed a temporary seismic network to study site amplification effects in the municipal area of Ancona, which is the county seat of Marche region. With the aim of identifying representative sites lying in geological/lithological/structural conditions potentially prone to experience site amplification, sites selection was led by: i) PGA levels during the mainshock; ii) observed damage levels; iii) geological information provided by maps, microzonation studies and other prior investigations. Consequently, between November 13 and 17, eleven temporary seismic stations equipped with both velocimetric and accelerometric sensors were deployed, and the seismic network was registered as 6N (according to *Federation of Digital Seismograph Networks,* FDSN).

In this work we show preliminary results of directional amplification and ground motion polarization study, using both ambient noise and earthquake data. We also use data recorded at two stations of permanent Italian seismic networks IT and IV. Seven stations installed on alluvial Holocenic deposits, widespread in the studied area, show amplification peaks between 1 and 4 Hz, mostly directional. Station CMA10 was settled in a large and active landslide area that has been deeply studied in last decades. It has a clear directional peak over 7 Hz. Station CMA15 does not show any amplification effect, being installed on the Messinian Gessoso-Solfifera Formation (primary and resedimented evaporites with interbedded organic-rich shales). Stations CMA5 and CMA12 were installed on the Miocenic Schlier Formation (marly and clayey-marly lithofacies): they show no-directional peaks at 5 and 9 Hz, respectively.

Estimating Cross-Coupling in Site Response by Seismic Noise Interferometry: An Example From an Alpine Valley (Northeastern Italy)

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The assessment of site response is an important task for improved seismic hazard estimation. However, standard approaches for site response estimation generally neglect the cross-coupling effect among the three components of motion due to heterogeneities in the subsurface structure. The existing methods for estimating the 3D frequency response require the selection of data according to some restrictive criteria and they are difficult to be applied in areas of moderate seismicity. Moreover, they are based on the analysis of earthquake recordings and, therefore, the possibility of their application in large urban areas is hampered by the limitation of available recordings (mainly from ad-hoc installed temporary networks), and the strong seismic noise that can limit the detection capability.We propose a method for estimating cross-coupling effects by the inversion of the deconvolved wavefield derived from seismic noise analysis in which the 3-components of the ground motion recorded at one site are deconvolved with those recorded at a reference site. The procedure provides the 9-components of the frequency response function (and of the corresponding deconvolved wavefield) and allows the identification of possible cross-coupling effects. The procedure is applied to a set of recordings collected in the Sarca Valley (northeastern Italy) by a temporary seismometric network. The results show that at the studied site the components of cross-coupling are not-negligible and are related to the lateral variations of bedrock surface and the heterogeneities within the sedimentary cover. The application of semblance analysis allows the nature of the wavefield within the valley to be characterized. The results can be used to better constrain the subsurface model and thus improve the reliability of the synthetic seismograms.

Regional Seismic Site Characterization Maps of Massachusetts using a Depth to Bedrock and a Surficial Geology Map

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Site characterization maps are essential for regional planning and seismic hazard analyses and are most often represented in terms of *Vs30*-based NEHRP site classifications. Recent trends in engineering seismology have provided evidence that the site fundamental frequency (f_0) may be an additional (or alternative) site characterization parameter for seismic site response. In this work, we present regional seismic site classification maps in terms of both *Vs30* and f_0 for Massachusetts using the State 1:24,000-scale surficial geologic map (Stone and others, 2018) and the State 100-m resolution depth to bedrock map (Mabee and others, 2023). In addition to these maps, we also present 1342 HVSR f_0 measurements and 35 *Vs* profiles in the state. Massachusetts typically has soft glacial sediments overlying hard basement rock as a result of the Wisconsin glaciation. During the Wisconsin glaciation, the Laurentide ice sheet covered the state, clearing most of the existing pre-glacial materials and depositing glacial sediments on the cleared bedrock surface. With this unique high impedance contrast structure – soft, low velocity sediment over hard, high velocity bedrock – we model the overburden using a layer-over-halfspace model composed of an average overburden velocity (Vs_{avg}), a depth to bedrock (d_s) and a bedrock velocity (V_R). To estimate Vs_{avg} in the layer-over-halfspace model, we combine the surficial geologic map units into four groups based on their similar mechanical properties, group the *Vs* profile stations, and then fit a Vs_{avg} distribution to each grouping. To estimate d_s in the layer-over-halfspace model, we use the state depth to bedrock map of Mabee and others (2023) which includes depth to bedrock uncertainty. These two maps provide estimates of d_s and Vs_{avg} with uncertainty at each location in the state. Using the layer-over-halfspace model at a 100-m resolution grid, we develop high resolution maps of f_0 and *Vs30*. We present these regional maps of *Vs30* and f_0 and highlight differences within three subregions: Boston, Cape Cod, and the Connecticut River Valley.

USGS SmartSolo Seismometer Arrays in the Upper Mississippi Embayment

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We present early results from two seismic arrays utilizing SmartSolo three-component, 5-Hz seismometers in the upper Mississippi Embayment. SmartSolo seismometers are self-contained units that can record GPS locations and ground motions for up to 30 days. The arrays operated in the summer and fall of 2022, and data will be available soon to the scientific community. The first array is an 18-km-long East–West-trending array of 60 seismometers (recording at 500 samples/second) deployed west of Memphis, Tennessee, for 30 days in July and August. The second array is a 285-km-long, East–West-trending array to the north at about 36-degrees latitude spanning the entire embayment. It consisted of 64 seismometers recording at 250 samples/second for about 30 days in September and October. We present preliminary results from these arrays. Initial analyses show signals from local earthquakes beneath and near the arrays, and a strong peak in the horizontal-to-vertical spectral ratios, presumably due to the significant impedance contrast at the top of basement rocks. The peak frequency (f_{Peak}), ranging from about 0.25 Hz to 38 Hz, decreases with increasing sediment thickness (h), and there is distinct structure in f_{Peak} vs. h, suggesting some lateral and/or depth variability in velocity structure. We expect these datasets to be a valuable resource for the seismology community, with the aim of improving characterization of earthquake ground motions in the upper Mississippi Embayment.

Seismic Monitoring of Fragile Geologic Features Near Avila Beach, California

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Fragile Geologic Features (FGF's) are increasingly being investigated to provide independent constraints on seismic hazard analysis results, and in particular estimates of the elapsed time period (fragility age) since the occurrence of ground shaking strong enough to knock down the feature. In places where the hazard curves for ground motion exceedance are inconsistent with the length of time a feature has been exposed to those ground motions, seismic monitoring experiments can provide insights into the local site response in the vicinity and adjacent to these features, which can reduce uncertainty in the hazard analysis and improve information gained from the FGF survival. In this experiment, multiple FGF's are located on a chert formation that protrudes out of the surrounding marine terrace sediments. Seismic instruments have been deployed at three sites on the marine terrace around the chert formation and on two distinct chert outcrops adjacent to the FGF's. The terrace sites includes both 3-component surface accelerometers and 3-component broadband seismometers. The outcrop sites are 3-component accelerometers, anchored to the chert. The array consists of 24 channels total sampled continuously at 200 sps, and transmitted real-time to UCSB via IP radio and cellular telemetry. The terrace stations form an approximate isosceles triangle, 130 meters on each side, with one station within 10 meters of the western most FGF, and the other FGF outcrop along the center of the southern side of the triangle. Extensive site characterization has been conducted using non-invasive multi-method surface techniques to determine the subsurface structure around these sites. While seismic activity is relatively quiet in this part of the California central coast, there have been a number of regional events, and a few small local events that have been recorded since the array was deployed in late 2018. We provide an overview of the array and present site response analysis of the events recorded to date. The event data are available at the UCSB data portal, https://neesbolt.eri.ucsb.edu/data-portal.

Capturing Spatial Variability of Site Effects: from Geology to Proxy Considerations to inform Spatial Ground Motion Correlation Models

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Local soil conditions depict an important role in regional/system-level seismic hazard assessments due to their influence on earthquake-induced ground shaking and deformation. Site effects correlate with the concentration of damages in areas prone to ground motion (GM) amplification as documented after past earthquakes. Evaluating spatially variable GMs is also essential when investigating large, distributed civil infrastructure systems. Because soil properties can be spatially correlated at nearby locations, the expected site response will also be spatially correlated. This study focuses on the evaluation of spatial correlations in site parameters from the Japanese databases, Kyoshin Network (K-Net) and Kiban-Kyoshin Network (KiK-net), and their comparison to the observed spatial correlation of multiple ground motion intensity measures from the 2011 Tohoku Mw 9.1. Current spatial correlation models treat site effects either as a fixed amplification factor or as randomized amplifications, but site effects are neither fixed nor random. Hence, geostatistical methods are used here to estimate spatial correlations between parameters that control site response and integrate their effects on resulting spatially variable ground motions. In this work, we use kriging to evaluate the significance of the spatial correlation for different site parameters with respect to the GM amplification IMs for the 2011 Tohoku earthquake.

From Sensors and Networks to Site Characterization and Site Response: Coming Full Circle [Poster]

Poster Session • Tuesday 18 April

Conveners: Lisa S. Schleicher, U.S. Geological Survey (lschleicher@usgs.gov); Sean Ahdi, U.S. Geological Survey (sahdi@usgs.gov); Olga-Joan Ktenidou, National Observatory of Athens (olga.ktenidou@noa.gr); Albert Kottke, Pacific Gas & Electric Company (arkk@pge.com)

A Rugged, Portable and Intelligent Analogue Seismometer for Future and Pre-Existing Arrays – Güralp Certis

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Seismic networks often face logistical and financial challenges that require portability, longevity and interoperability with existing equipment.

Güralp have combined proven ocean bottom, borehole and digitiser technology to produce an analogue seismometer with intelligence that benefits networks of all sizes. The Güralp Certis is a broadband analogue instrument that incorporates specific aspects of its sister digital instrument (Certimus) while still remaining compatible with third-party digitisers.

Each Certis stores its own serial number, calibration and response parameters internally and will automatically communicate these to a connected Minimus digitiser. This allows seismometer-digitiser pairings to be changed without manual entry of new parameters. If using GDI-link streaming protocol with the Minimus, these metadata parameters are transmitted within (and therefore inseparable from) the datastream itself. Therefore, this small piece of intelligence in the analogue sensor removes the need for any manual re-entry of response parameters anywhere along the sensor-digitiser-client chain.

Certis enables users to install in locations with poor horizontal stability (e.g., glaciers, dynamic landslide scarps, water-saturated soils), without the need for cement bases or precise levelling, as the sensor can be deployed at any angle regardless of which model digitiser is connected. Due to its small size, low weight and ultra-low power consumption, Certis significantly reduces logistical efforts and makes short term temporary deployments far easier.

Certis addresses many challenges of traditional seismometer deployments, including cost, but provides a flexible and simple solution for seismic monitoring applications across all disciplines.

Application of Parametric and Non-Parametric Git in Low to Moderate Seismic Context: Case of Mainland France Earthquake Ground Motion for 1996-2021 Period.

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One of the stakes in Seismic Hazard Assessment (SHA) is to develop realistic ground motion models (GMM). This requires characterizing the main components of the ground motion and their variability. In this work, we address this issue by performing spectral decomposition of the ground motion recordings into its three main contributing terms: source, attenuation and site. This is performed at the regional scale by applying an empirical approach named Generalized Inversion Technique (GIT). This method has shown reliable results in moderate to high seismicity area, with dense seismic network coverage such as Italy and Japan. However, GIT application in low to moderate seismicity context, e.g., mainland France, remains challenging due to the sparsity of earthquake recordings available in these regions. Hence, we apply here two alternative approaches of GIT: a parametric one following the algorithm implemented by Grendas et al. (2021), and a non-parametric approach developed by Oth et al. (2011), on the ground motion dataset implemented for mainland France over the period 1996-2019 by Traversa et al. (2020). This database was recently updated up to the end of 2021 (Buscetti et al., in prep.) and is composed of more than 15,000 records of earthquakes with local magnitude ML in the range 2.5 to 5.2 (with majority of ML 3.0-3.5), and epicentral distances span in the range 1 to 300 km. Results from parametric and non-parametric inversions are discussed, as well as the limits and reliability of each approach, depending on the geometry and characteristics of the dataset used. This work is a first step in the improvement of the seismological models for mainland France. It will contribute to constraining empirical region and site-specific GMM and ground motion simulations, and thus to improve their representativity for low to moderate seismicity areas. These results allow improving the understanding of ground motion contributions and variability in a low to moderate seismicity region as mainland France.

Framework for Incorporating Site Characteristic Information at Advanced National Seismic System Sites into the Center for Engineering Strong Motion Data

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Knowledge of the near-surface characteristics at seismic stations improves our ability to separate the sources of energy in seismic records into contributions from the earthquake source, the path and ground-motion attenuation, and the local site response. Our recent compilation of geologic and seismic velocity characteristics at Advanced National Seismic System (ANSS) strong motion accelerometer sites aggregates measurements of shear-wave velocity (V_S) characteristics in the upper 30 m (V_{S30}), three different V_{S30} proxies (based on geology, terrain, and a hybrid approach), V_S profile data from compilations, statistics on V_{S30} uncertainty, and preferred values determined from site databases of large-scale ground motion model development efforts (i.e. most recent regional Next Generation Attenuation [NGA] Model projects). The motivation for this effort is to make the contents of this compilation more easily accessible on station information pages and webservices at the Center for Engineering Strong Motion Datacenter (CESMD). Our framework incorporates the preferred V_{S30} value identified either by the local regional seismic network (RSN) or the most recent regional NGA projects and highlights when new measured shear-wave velocity information is available in the ANSS compilation. For stations that have not been used by an NGA project or where a preferred V_{S30} values has been identified by the RSN, we display the geometric mean of available V_{S30} measurements or the three proxy-based V_{S30} values. We also link to the V_S data profile database at vspdb.org. We encourage users to consider the V_{S30} values at CESMD as a summarized resource and to consult the full contents of the ANSS compilation for greater detail on the site characterization information. Our most recent effort includes adding the maximum recorded peak ground acceleration and number of records at each station to facilitate planning and prioritization for making new field measurements.

On the Study of Amplification in the Cerro Prieto Volcano, Mexicali Valley, Mexico Using Cross- and Auto-Power Spectrum Technique

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Based on previous reports of amplification on the Cerro Prieto volcano, we used a cross- and auto-power spectrum technique to corroborate this amplification. Due to the nonexistence of a reference site (with no amplification), to be used in the area of the volcano to know its true amplification; we tested the use of the spectral ratios (SR) of the cross-power (XP) spectrum of horizontal (H) and vertical (V) components (XPHV) and the auto-power (AP) spectrum of the vertical component (APV). The purpose is to find the true amplification on the volcano. We used time series of ambient noise and earthquake data recorded at ground surface to compute the spectral ratio between SR-XPHV/APV using ambient noise and earthquake data. Next, we compute similar Horizontal/Vertical Spectral Ratio (HVSR) but now among the Power Spectral Density (PSD) spectrum of horizontal and vertical components, we termed this variation the modified Nakamura Method when using ambient vibration data.

Preliminary results show that at the fundamental vibration frequency, the peak spectral amplitude when using SR-XPHV/APV are smaller when compared with the HVSR´s using PSD spectra. The fundamental frequencies obtained with both methods agree quite well. As an example, for one of the experimental sites (VCP) the obtained amplification factor is around 10 using earthquake data. However, when using ambient noise data the amplitude of the SR-XPHV/APV are at lower amplitude values; but the relative amplification when comparing with experimental sites between higher and low elevations, the amplification factor is around 11. In this way, the amplification on the Cerro Prieto volcano is corroborated using an alternative SR-XPHV/APV method. It is also noticed that when using ambient noise, the SR-XPHV/APV the spectral amplitudes at lower frequencies (~0.1Hz) are significant smaller in comparison with the ones obtained with the traditional HVSR using the PSD spectrum. The phase and coherence of the XPHV spectrum is also analyzed in terms of the energy correlation between the horizontal and the vertical signals.

Site Characterizations and Linear Site Responses at Selected Borehole Strong-Motion Arrays From the United States and Japan

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The increase of shear-wave impedance (ρVs) with depth leads to site response: the modification of ground motion in terms of spectral content, amplitude, and duration. Site response can be quantified by the borehole transfer function (*TF*) and characterized by two parameter pairs of primary importance: the fundamental-mode (i.e., first mode) frequency (f_0) and its associated amplification (A_0) and peak-mode frequency (f_p) and its associated amplification (A_p). To explore the relationship between site characteristics and site response, we characterized the *Vs* profile using the shear-wave impedance ratio (*IR*) and velocity ratio (*VR*). *IR* is defined as the ratio of the layer impedance below the interface *j* (ρ_jVsj) to the average impedance above the interface (ρ_{ja}Vsja). ρ_{ja} is the average density above the interface, and ρ_j is the layer density below the interface *j*. *VR* is defined as the ratio of the layer shear-wave velocity below the interface *j* (*Vsj*) to the average shear-wave velocity above the interface (*Vsja*). In this study, we selected 54 borehole arrays penetrating bedrock from the United States and Japan and calculated *IR*s and *VR*s for all the *Vs* profiles. We also derived linear empirical and theoretical *TF*s for all selected arrays using the weak ground motions and 1D site-response analyses. Our results demonstrated that site response is controlled predominantly by each site's *Vs* profile,

the *IR*s or *VR*s distribution and maximum impedance or velocity ratio (IR_{max} or VR_{max}) in particular. Our results also demonstrated that the *Vs* profiles can be characterized by 1) resonant dominance having IR_{max}≥3.8 or R_{max}≥3.3, 2) complex or weak resonance having 3.5≤IR_{max}<3.8 or 2.9≤ R_{max}<3.3, and 3) weak or non-resonance having IR_{max}<3.3 or R_{max}<2.9. This site characterization has a practical application in engineering because site resonance is of primary interest. Thus, it is essential to obtain a reliable *Vs* profile down to bedrock for accurate site response quantification.

Vs30 at Two Seismic Stations in the Central Valley of California Using S-Wave Refraction Tomography and Masw

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We estimate V_{S30} from acquired active-source seismic data near two seismic stations in the California Central Valley towns of Fresno (BK.KARE) and Visalia (BK.LIND). Prior site response studies indicate areas with low V_{S30} experience greater ground shaking and structural damage during earthquakes; thus, V_{S30} measurements help us understand the potential for amplified ground shaking. We recorded both body and surface waves along linear profiles within 10 m of the stations and used 2D refraction tomography and multichannel analysis of surface waves (MASW) methods to evaluate Rayleigh- and Love-wave-based shear-wave velocities. We calculate V_{S30} at every meter along the seismic profiles and compare V_{S30} results among the different methods. Preliminary results from surface wave methods show average V_{S30} for Fresno seismic station is 573 m/s (Rayleigh-wave) and 390 m/s (Love-wave), and the average V_{S30} for the Visalia seismic station is 808 m/s (Rayleigh-wave) and 683 m/s (Love-wave). Our Love-wave models show lower shear-wave velocities, which is generally consistent with our prior V_{S30} studies in California. We find that V_{S30} for the Fresno Rayleigh-wave model varies by 5.4% across the profile whereas the Love-wave model varies by up to 9.2%. Our Visalia Rayleigh-wave model shows V_{S30} varies by up to 13.7% across the profile whereas V_{S30} varies by up to 12.7% for the Love-wave model. The average V_{S30} from our refraction tomography model is 404 m/s for the Fresno seismic station and 1063 m/s for the Visalia seismic station. Finally, comparison among refraction tomography and surface wave models shows average V_{S30} differs by up to 34.6% (Rayleigh-wave) and 3.52% (Love-wave) for the Fresno profile, whereas average V_{S30} differs by up to 27.3% (Rayleigh-wave) and 43.5% (Love-wave) relative to refraction-tomography-based V_{S30} for the Visalia profile. Our results suggest lateral changes in subsurface geology and bedrock structures account for the differences in V_{S30} across the profiles and among different methods; thus, conventional 1D V_{S30} would not accurately characterize local sites.

Vs30 Site Characterization in the City of St. Helena, Napa County, California Using Active-Source Refraction Tomography

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As part of the USGS' efforts to characterize strong-motion recording sites in northern California, on August 8, 2022, we conducted a shallow-depth, active-source seismic survey to evaluate time-averaged shear-wave velocities in the upper 30 m (Vs_{30}) near strong-motion seismometer NP-1764 in the city of St. Helena, Napa County, California. Shear wave measurements are used to determine soil densities based on National Earthquake Reduction Program (NEHRP) site characterization chart. We recorded seismic data using 47 SmartSolo three-component nodal seismometers, placed along a 92-m-long (2-m spacing) linear array. We used a hammer and plate combination to generate seismic sources at each seismometer. Compressional and Rayleigh waves were generated from vertical strikes on an aluminum plate, and shear and Love waves were generated from horizontal strikes on an aluminum block, anchored to the ground with a metal rod. We developed two-dimensional P- and S-wave refraction tomography velocity (*Vp* and *Vs*, respectively) models. *Vp* ranges from 1000 m/s to 4500 m/s along the profile, and *Vs* ranges from 420 m/s to 800 m/s. We evaluated Vs_{30} at each seismometer location and found that Vs_{30} ranges from 521 m/s to 660 m/s along the profile, with the mean average velocity at 580 m/s. For the seismometer closest to strong-motion station NP-1764, we determined Vs_{30} to be 541 m/s, indicating a NEHRP site classification of C (dense soil, soft rock). Geologic mapping shows the site to consist of surficial Quaternary alluvial deposits, underlain by Tertiary basement volcanic rocks. The 1500 m/s velocity contour in our *Vp* model suggests that the groundwater table is about ~11 m deep. We also developed *Vp*/*Vs* ratio and Poisson's ratio models for the profile, with *Vp*/*Vs* ratios (2 to 3) and Poisson's ratios (0.3 to 0.4) being highest in the upper 3 m along the profile and at depth near the west end of the profile, between meter 1 and 20.

Future Directions in Physics-based Ground-motion Modeling in Preparation for the Fall 2023 Meeting

Oral Session • Tuesday 18 April • 04:30 PM Pacific

Conveners: Hiroshi Kawase, Disaster Prevention Research Institute, Kyoto University (kawase@zeisei.dpri.kyoto-u.ac.jp); Annemarie Baltay, U.S. Geological Survey (abaltay@usgs.gov); Zhigang Peng, Georgia Institute Technology (zpeng@gatech.edu)

Updated Broadband Cybershake PSHA Model for Southern California

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The CyberShake platform, developed by the Southern California Earthquake Center, performs physics-based probabilistic seismic hazard analysis using 3D wave propagation simulations with reciprocity to synthesize seismograms. We have extended CyberShake using modules from the SCEC Broadband Platform (BBP), combining low-frequency deterministic simulations with high-frequency stochastic simulations up to 50 Hz to include a broad range of frequencies of engineering interest. The Broadband CyberShake platform has undergone validation testing using the BBP and data from historic events including Northridge and Landers.Recently we began our latest Broadband CyberShake campaign, Study 22.12. This study produces broadband seismograms up to 50 Hz for about 625,000 events for each of 335 sites in Southern California. New updates in this study include 1) high-frequency modules from the latest BBP release, v22.4.0; 2) the current version of the Graves & Pitarka rupture generator, v5.5.2, which includes larger correlation between slip and rise time; 3) modifications to the near-surface velocity model to incorporate Vs30 information and reduce large near-surface Vs values outside of basins; 4) sampling variability in rupture velocity; and 5) increased hypocentral sampling resolution. We present low-frequency (≤1 Hz) and broadband (0-50 Hz) results from this study, including comparisons with GMMs and comparisons with previous CyberShake results in this region. We find a general trend of reduced hazard as compared to previous CyberShake studies, and improved spectral continuity in the 1-3 second range compared to previous Broadband CyberShake results.

Virtual Earthquake Analysis of Future Alpine Fault Earthquakes and Ground-Shaking Using the Southern Alps Long Skinny Array (SALSA)

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A challenge in seismic hazard forecasting is to evaluate the ground motions likely to be produced in an earthquake without knowing which of many geologically- and geophysically-plausible scenarios will eventuate. Time is of particular essence in the case of the central Alpine Fault, New Zealand, which is recognized as being late in the typical interseismic phase of its 249±58 earthquake cycle, having last ruptured 306 years ago. The likelihood of a M_w>7.5 Central Section earthquake occurring in the next 50 years ~75% (29–99%; 95% confidence interval), and the likelihood of this earthquake also rupturing the South Westland Section in a M_w~8 event is ~82% (Howarth et al., 2021).

Previous models of Alpine Fault earthquakes have addressed only idealized scenarios that ignore recognized along-strike and down-dip variations in fault geometry, present-day microseismicity, or thermal regime that likely influence coseismic rupture. To investigate the effects of these and other factors such as the direction and speed of rupture on ground motions, we are undertaking virtual earthquake analysis (Denolle et al., 2014, 2018) using data from the Southern Alps Long Skinny Array (SALSA). SALSA consists of 56 seismometers (42 temporary and 14 permanent, 40 broadband and 16 short-period) deployed along a ~450 km length of the Alpine Fault: 45 of the seismometers are installed within ~3 km of the fault trace, primarily on the hanging-wall, at 10 km nominal spacing. SALSA noise recordings will be combined with data from seismometers throughout southern New Zealand to synthesize Green's functions representing the farfield response to incremental slip anywhere on the fault. By convolving these with kinematic rupture models incorporating empirical constraints on fault-zone structure and properties, we can compute ground motions at locations of interest in response to large numbers (millions) of plausible ruptures. This enables us to efficiently explore the range of ground motions consistent with measurements made along the length of the Alpine Fault, and to quantify the epistemic uncertainties in existing ground motion estimates.

Prediction of Near-Field Time-Histories Using Machine Learning and a Hybrid Dataset (Calibrated Physics-Based Ground-Motion Simulations and Observations)

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Despite the continuous increase in the number of ground motion stations and the amount of recorded ground motion data in recent years, we still face observational gaps in earthquake records for large-magnitude and small-distance events. The gaps stem from the complexity of fault systems and the lack of stations in the vicinity of earthquake sources. Physics-based simulations of recent earthquakes have been capable of reproducing the ground shaking recorded by near-field accelerometric stations but also predicting ground motions in other locations. In this work, we first develop a hybrid database combining such "calibrated" simulations and observed ground motions. This hybrid dataset consists of real and near-source events records and physics-based simulations.

In the second step, a ground-motion model is calibrated on the hybrid datasets. The model simulates nonstationary ground motion recordings using the recently developed TFCGAN method (Esfahani et al., 2022). This method combines a conditional generative adversarial network to predict the amplitude part of the time-frequency representation (TFR) of ground-motion recordings and a phase retrieval method. This model simulates the amplitude and frequency contents of ground-motion data in the TFR as a function of earthquake moment magnitude, source-to-site distance, and a random vector called latent space. After generating the phaseless amplitude of the TFR, the phase of the TFR is estimated by minimizing all differences between the observed and reconstructed spectrograms. The simulated accelerograms produced by the proposed method show similar characteristics to conventional ground-motion models in terms of their mean values and standard deviations for peak ground accelerations and Fourier amplitude spectral values. We will finally discuss the opportunities and challenges associated with the update of such a hybrid dataset using the latest generation of physics-based models.

The i-FSC Proxy: A Physics-Based Model for Predicting Near Field Topographic Site Effects and Studying Earthquake-Induced Landslide Distributions

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Our study focuses on predicting the ground motion seismic amplification caused by the surface topography during an earthquake. This thematic is directly motivated by one of the consequences of the topographic site effects variations: the high variability in the damage distributions (structural damage and coseismic landslides), observed at fine spatial scales in the near-field regions of earthquakes in mountainous areas. The effect of the surface topography has long been documented but is still poorly understood and rarely considered in buildings specification codes. Our study relies on the neural network analysis of data obtained from 3D numerical simulation of seismic wave propagation to derive a physics-based estimator of topographic site effects in the near field (the i-FSC proxy: illuminated Frequency-Scaled Curvature proxy). The proxy relies on the S-wavelength value, the topographic curvature of the free surface, and a novel quantitative parameter called normalized illumination angle that allows to quantify the slope exposure to the incoming wavefield. The estimator is a user-friendly tool that only uses a digital elevation map (DEM), a seismic source position, and the studied S-wavelength value to predict the amplification factors at any given point of the DEM. Besides the fact that it does not require high computational resources, it enables researchers to investigate the amplification variations caused by a nearby seismic source. This is a significant breakthrough since the areas that sustain the most damage during earthquakes are those that are closest to the fault. The obtained results open direct perspectives for predicting seismic hazards and studying earthquake-induced landslides in mountainous areas.

Evaluation of the Impacts on Risk Assessments for Distributed Infrastructure Systems from Ground Motion Median, Variability, and Spatial Correlation in CyberShake Simulations

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The SCEC CyberShake platform provides 3D physics-based simulations that better capture the local source, path, and site effects for probabilistic hazard assessment than traditional ground motion models (GMMs). Previously, we examined the impact of CyberShake Study 15.12 simulations on Probabilistic Seismic Risk Assessment (PSRA) of the underground transmission water pipeline network for the City of Los Angeles. Significant differences in estimated pipeline network seismic risks – measured by the expected number of pipeline repairs – were found between CyberShake and GMMs, with significant implications on public policies concerning seismic risks and on estimates of resources needed for agencies to adequately plan and mitigate the risks to meet system-wide resilience criteria.

Physics-based earthquake simulations and traditional GMM-based approaches differ in three main characteristics: median ground motions for a given source and site, ground motion variability, and spatial correlation. All these characteristics can significantly influence system-level risk estimates of a spatially distributed system. To further understand the causes of the differences in the resulting risk outcomes, in this study, we utilize a common set of earthquake ruptures and the identical pipeline damage models for all system risk calculations, using the earthquake simulations from CyberShake Study 22.12 and the empirical GMMs, respectively. To separate the impacts from ground motion median, variability, and spatial correlation, we conduct a suite of progressive risk analyses in several steps, with each step designed to incorporate one ground motion characteristic at a time. These analyses will allow us to systematically investigate the role of each of the ground motion components on the system risk results and provide an increased understanding of the

CyberShake approach compared with the traditional GMM-based approach in characterizing regional ground motion inputs for seismic risk assessments of spatially distributed infrastructure, and guide future research and necessary validations of the technology for crucial real-world applications.

Future Directions in Physics-based Ground-motion Modeling in Preparation for the Fall 2023 Meeting [Poster]

Poster Session • Tuesday 18 April

Conveners: Hiroshi Kawase, Disaster Prevention Research Institute, Kyoto University (kawase@zeisei.dpri.kyoto-u.ac.jp); Annemarie Baltay, U.S. Geological Survey (abaltay@usgs.gov); Zhigang Peng, Georgia Institute Technology (zpeng@gatech.edu)

Averaged S-Wave Site Amplification Factors for Sites With Vs30 ≥ 760 M/s Derived From Git Analysis of K-Net and KiK-Net Ground Motions and Its Consequence for Ground Motion Modeling

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We have been studying horizontal site amplification factors (HSAFs) from the observed strong motions by K-NET and KiK-net of the National Institute of Earthquake Research and Disaster Resilience by using the so-called generalized spectral inversion technique (GIT, Nakano, et al., BSSA, 2015). We have used a reference site where we extracted the site amplification at a KiK-net site using a theoretical transfer function to get the outcrop motion with the S-wave velocity (Vs) of 3.45 km/s. Thanks to this reference site's condition, our separated HSAFs are the largest and our separated acceleration source spectra of events (ASSs) are the smallest in amplitude among GIT studies conducted for a similar dataset. The choice of the reference site condition determines the relative contribution between HSAFs and ASSs, however, the importance of the choice seems to be underestimated in the past. The reference site condition is important because any HSAF at the reference site will be automatically mapped onto all the ASSs in GIT. The situation is the same for GMPE analyses. In this report, we showed the averaged HSAFs of our GIT results as a function of Vs30 at K-NET and KiK-net sites. The purpose of this analysis is not to recommend the use of the binned averages as a substitute for a site-specific HSAF, but to investigate quantitatively the risk of a reference site or sites that is(are) not considered to be site-effect free. We calculated geometrical averages of HSAFs with Vs30 in the ranges of Vs30<180 m/s (Class E), 180≤Vs30<360 m/s (Class D), 360≤Vs30<760 m/s (Class C), 760≤Vs30<1,000 m/s (Class B2), and 1,000 m/s≤Vs30 (Class B1 to A). We found that the average HSAF for Class B2 has 2.0 at 1 Hz and more than 3.0 at 10 Hz. Therefore, if we use a site as hard as Class B2 as a reference, this level of amplification will be mapped onto the ASSs and will result in a higher stress-drop estimate because of higher high-frequency amplitude in ASSs.

Basin Effects From 3D Simulations in Southern California: Basin-Depth Scaling and Nonergodic Site Adjustments

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We develop basin-depth scaling models and nonergodic site adjustments from the synthetic ground motions of the Southern California Earthquake Center (SCEC) CyberShake project. Calculations use the NGA-West-2 ground-motion models (GMMs) and are developed from a large subset (>600,000) of ground-motion residuals. We explore two approaches to the treatment of by using either site-specific values or using a uniform value that is consistent with the minimum shear-wave velocity of the 3D simulations. Overall, basin-depth scaling in the simulations is similar to the empirical GMMs. However, simulated ground motions within southern California basins are uniformly higher than GMM predictions and show weaker scaling at periods less than 4 s. We explore several options for addressing the uncertainty in absolute ground-motion level—by directly using the simulated ground motions, by constraining the ground motions to match empirical GMMs where differential basin depths are zero, and by using empirical adjustments from recent results in southern California; ultimately, we recommend the latter approach due to its agreement with observational data. We implement the simulation-derived basin-depth scaling models into the *nshmp-haz* code for use in the 2023 U.S. National Seismic Hazard Model. We find minor differences in probabilistic seismic hazard between the simulation-derived and empirical models. Hazard differences can be explained by differences in the strength of basin-depth scaling and maximum basin amplifications. We also explore methods to incorporate spatially varying adjustments to site terms using the simulated data set. The nonergodic adjustments indicate period-dependent differences in the amplification of the Ventura and Los Angeles basins that cannot be explained by basin depth alone and are likely caused by the effects of 3D geometry or complex wave-propagation effects.

Strong-Motion Simulation of the 1944 Tonankai Earthquake Along the Philippine Sea Plate Based on the Damage Ratios of Wooden Houses With In-Situ Measurements of Microtremors at the Population Centers of Heavily-Damaged Villages and Towns

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For precise prediction of the future megathrust earthquakes along the Philippine Sea Plate in western Japan, we need both representation of the complex source process and Green's function from the fault to the sites. The latter can be obtained through a statistical analysis of many observed records, as Nakano et al. (BSSA, 2015) did by using the generalized inversion technique, while the former needs delineation of the source processes for earthquakes that occurred in the past. It is necessary to construct source processes for not only earthquakes with strong-motion data but also those without because they occurred before the deployment of strong-motion networks. For those old earthquakes, we need to use observed structural damage ratios (SDR) as a substitute for strong-motion seismometers in the heavily-damaged areas. As the first step of investigations, we performed a parametric study for the 1944 Tonankai earthquake (M8.0) to find the best scenario (Ito et al., SSA meeting, 2021).

We found that we could reproduce observed SDRs up to 40%, however, we underestimated SDRs at several villages and towns with higher SDRs. In the first stage, we used horizontal site amplification factors (HSAFs) at these sites based on the theoretical 1D transfer function with empirical correction. To fill the gap, we measured single-station microtremors at the population centers of the heavily-damaged villages and towns in March 2022. From microtremor H/V ratios we converted them into pseudo earthquake H/V ratios and then we applied the VACF method (Ito et al, BSSA 2020) to convert them into HSAFs. With these observed HSAFs, we tried to reproduce the SDRs for the same best source model. As a result, the SDRs by new HSAFs slightly increased, however, there remain differences at higher SDR sites. This means that we need to explore further the possibility of improvement for the empirical correction scheme on the soil nonlinearity at these sites, which reduced amplitude significantly.

The Impact of the Three-Dimensional Structure of a Subduction Zone on Time-Dependent Crustal Deformation Measured by HR-GNSS

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Accurately modeling coseismic time-dependent crustal deformation as observed on high-rate Global Navigation Satellite System (HR-GNSS) lends insight into earthquake source processes, as well as improves local earthquake and tsunami warning algorithms. Currently, time-dependent crustal deformation modeling relies most frequently on simplified 1D radially symmetric Earth models. However, for shallow subduction zone earthquakes, even low-frequency shaking is likely affected by the many strongly heterogeneous structures such as the wedge, the slab, and the overlying crustal structure. We demonstrate that including such a 3D structure in a subduction zone improves the estimation of key features of coseismic HR-GNSS time series, such as the peak ground displacement (PGD), the time it takes to reach the PGD (t_{PGD}), static displacements, and cross correlation values. We computed 0.25 and 0.5 Hz 1D and 3D synthetic waveforms at HR-GNSS stations for four M7.3+ earthquakes in Japan using MudPy and SW4, respectively. From these synthetics, we computed intensity-measure residuals between the synthetic and observed GNSS waveforms. Comparing 1D and 3D residuals, we observed that the 3D simulations show improved fits to the PGD and t_{PGD} in the observed waveforms than the 1D simulations. Our results also show that the reduction of the PGD residuals in the 3D simulations is a combined effect of both shallow and deep 3D structures; hence incorporating only the upper 30 km 3D structure will still improve the fit to the observed PGD values. Our results demonstrate that 3D simulations significantly improve models of GNSS waveform characteristics and will help understand the underlying processes and improve the warning of tsunami earthquakes.

The Future of Tsunami Science, Preparedness and Response

Oral Session • Wednesday 19 April • 04:30 PM Pacific

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The Potential for Sediment Transport During Earthquake-Tsunami Multi-Hazards

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During strong earthquake shaking, sand beds may liquefy. Then, after strong shaking ceases, the sand beds resediment as excess pore water pressures dissipate. During ensuing tsunami attack, sediment transport occurs (onshore during runup and offshore during drawdown), and during tsunami drawdown, the sand may also re-liquefy. During the preceding process, sediment transport potential may either increase or decrease based on the size of the earthquake motion, the duration of the quiescent period, and the tsunami inundation time series. To understand the foregoing physics, we developed a model in the finite element framework OpenSees to estimate the pore water pressure response during and after earthquake shaking, and tsunami attack. We used a finite difference scheme to estimate tsunami loading along the Pacific Northwest shoreline given different rupture scenarios, and we used an earthquake motion recorded during the 2011 Great East Japan Earthquake to estimate the pore water pressure response in the sand bed during earthquake loading. The results show that the pore water pressure response during earthquake loading has a significant effect on the pore water response during the subsequent tsunami attack. Furthermore, the duration of the quiescent period, i.e., the time between the end of strong earthquake shaking and beginning of tsunami attack, has a significant impact on the pore water pressure response during tsunami loading. During the correct physical circumstances (e.g., small hydraulic conductivity, large tsunami flow height with quick drawdown velocity), the sand also liquefies during tsunami drawdown, which exacerbates sediment transport potential. To capture the significance of the results, we developed a modified Sleath parameter, to incorporate the pore water pressure response in sand beds during tsunami loading. The results and modified Sleath parameters have implications for engineers who design and retrofit coastal infrastructure, as well as paleoseismologists who retrodict the size of previous earthquakes based on observations of historic tsunami deposits.

History and Future of Tsunami Warning System: Toward Timely, Accurate and Reliable Systems

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Following the 1896 and 1933 Sanriku tsunamis, each caused thousands of casualties, Japan Meteorological Agency (JMA) started a tsunami warning system in 1941 for the Sanriku coast, and the near-field tsunami warning system covered the entire Japanese coast in 1950. The tsunami warning system for far-field tsunamis was established in 1962, following the 1960 Chilean tsunami. Since 1999, JMA adopts numerical simulation and its database to improve accuracy. Once the location and magnitude are determined in 3 to 5 minutes after an earthquake, the database is searched to predict tsunami coastal arrival times and heights. Following the 2022 tsunami from Tonga eruption, which started several hours earlier than the expected tsunami arrival time, JMA now announces arrival times of atmospheric pressure waves for large-scale volcanic eruptions in the world.For timely and accurate issuance of a tsunami warning, seismic and/or geodetic observations are essential. The database search requires an accurate estimate of location and magnitude, including those for tsunami earthquakes. A reliable warning should be based on observations of tsunamis, i.e., sea level. Recent deployments of offshore bottom pressure gauges help to confirm tsunami generation and propagation and improve the reliability of the warning. JMA adopts the tFISH system, which inverts offshore tsunami waveforms to estimate the tsunami source then coastal heights. The Recent deployment of dense networks such as S-net or DONET makes it possible to issue a warning based on tsunami data assimilation, without estimating the tsunami source.

Sensor Monitoring and Reliable Telecommunications (SMART) Cables: Integration of Environmental Sensors Into Submarine Telecommunications Cables for Improved Tsunami Science and Response

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Innovative deep ocean monitoring technologies are crucial to catalyzing fundamental improvements in mitigating natural disasters, reducing human vulnerabilities, and determining environmental threats. An attractive but untapped resource is the global submarine fiber optic cable network, which carries over 95% of international internet traffic. Key components of undersea fiber optic cable systems are repeaters, which are placed every 60-100 km along the cable to provide optical signal amplification. Integrating environmental sensors into these repeaters could enable real-time data collection for environmental and infrastructure threat reduction, natural disaster mitigation, cable system monitoring, and new scientific discoveries.In its original form, the SMART Cable concept (J. You, Nature, 2010) advocated that seismic, pressure, and temperature sensors should be integrated into submarine fiber cables, leveraging power and communications from the repeater. Despite significant advocacy from a broad range of the scientific community, no commercial supplier came forward to allocate the resources to produce a SMART repeater. Recognizing the potential for SMART Cables to revolutionize the utility of submarine fiber cables and transform an industry, Subsea Data Systems was formed to catalyze the rapid development of SMART repeater sensor systems. Leveraging NSF SBIR funding, we developed a fully operational benchtop prototype SMART repeater sensor system in ~6 months. Our system comprises a Silicon Audio 3-axis high-resolution, low-noise broadband seismometer, a Paroscientific absolute pressure gauge, and a Sea-Bird glass coated thermistor. The system is currently streaming real-time data to the NSF's SAGE facility. In this presentation, we will discuss the utility of SMART Cables as a unique technology that will improve tsunami science and significantly enhance tsunami monitoring and response. We will also discuss the first comprehensive SMART Cable system (CAM: Continent - Azores - Madeira) currently being developed by Portugal to be ready for service by 2026.

Caribe Wave: A Decade of Tsunami Exercises for Validating the Tsunami Warning System for the Caribbean and Adjacent Regions

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Annual tsunami exercises are crucial to validating the Tsunami Warning System for the Caribbean and Adjacent Regions. Every year in March, the UNESCO Intergovernmental Oceanographic Commission Coordination Group for Tsunamis and Other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (ICG CARIBE/EWS) conducts the CARIBE WAVE exercise. Since 2011, the exercises have helped identify the strengths and gaps at the regional, national, and local levels. The exercise provides one or more hypothetical tsunami sources defined through a collaborative effort between seismic, volcano and tsunami experts from the CARIBE EWS using historical data, scientific research, and numerical modeling of tsunami inundation to highlight potential areas at risk. The Pacific Tsunami Warning Center (PTWC), the designated regional Tsunami Service Provider (TSP), and more recently, the Central America Tsunami Advisory Center (CATAC), a proposed TSP, develop the simulated text and graphical products for the corresponding tsunami sources. Each of the 48 Member States and Territories then decides which scenario it will use for its national activities. On the day of the exercise, the PTWC issues a test message through all the channels it would use for a real event to test communication systems. The simulated products are disseminated only to the Tsunami Warning Focal Points (TWFPs) and National Tsunami Warning Centers (NTWCs). Each Member State and Territory is responsible for determining further actions, like issuing simulated tsunami alerts in their area of authority. CARIBE WAVE provides a framework for TWFPs, NTWCs, and Emergency Management Organizations to test their operational lines of communication, practice their emergency response plans, and promote tsunami awareness. Consequently, considerable advances in tsunami products and preparedness were achieved. This presentation will review the history and results of the exercises, which have activated hundreds of thousands of people throughout the region over the past decade.

Analyzing Behavioral Responses Caught on Video to the Hunga Tonga–Hunga Ha'apai Eruption, Atmospheric Shockwaves, and Tsunami

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The 15 January 2022 eruption of Hunga volcano,Tonga, generated atmospheric shockwaves recorded around the globe and a Pacific-wide tsunami. There was widespread documentation of these events via smartphones and closed-circuit television (CCTV) footage, with dozens of videos posted online. These videos offer a significant source of data about physical phenomena and human behavior. This research is critical as little is currently known about human reaction to volcanic eruptions followed by tsunami of these magnitudes, this footage offers an important source of data. Our research team collected an archive of more than 100 videos posted voluntarily to social media sites (Twitter, Reddit, TikTok, YouTube) over a period of 90 days post-event that contained more than 460 individual separate recordings; new videos were uploaded in a staggered fashion and sometimes deleted quickly. This data set offers novel information about people's reactions to the eruption, shockwaves, and attendant tsunami obtained from different nations throughout the Pacific Ocean basin. We present results of audio-visual data, utilizing methods recently developed for similar analysis of social-media-sourced footage from major earthquakes in New Zealand, and the United States and Puerto Rico. We find that larger groups didnot move to evacuate from the beach as quickly as smaller groups of people, even when volcano and tsunami related alerts are clearly distributed and received. Further, the presence of children slowed the taking of protective action. Our findings can inform future education and outreach efforts that assist in strengthening standardized protective actions for the impacted regions, as well as potentially exploring multi-hazard drills.

The Future of Tsunami Science, Preparedness and Response [Poster]

Poster Session • Wednesday 19 April

Conveners: Diego Melgar, University of Oregon (dmelgarm@uoregon.edu); Summer J. Ohlendorf, National Oceanic and Atmospheric Administration (summer.ohlendorf@noaa.gov); Yajie Lee, ImageCAT (yjl@imagecatinc.com); Elyssa Tappero, Washington Emergency Management Division (elyssa.tappero@mil.wa.gov)

Empowering Young People in Haiti to Play Key Roles in Disaster Risk Reduction

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GeoHazards International (GHI) conceived and implemented Timoun an Aksyon! (Kids in Action!), a 3-year, child-focused and youth-led program designed to empower young people in northern Haiti to make their communities safer from seismic risks and coastal hazards. Nearly half of Haiti's population is under the age of 20. GHI's approach involved young people in the design and delivery of resilience efforts in Cap-Haïtien. It cultivated their natural enthusiasm to learn, enabled them to take small steps toward a safer future, engaged the community, and supported the youths' interests in creating impact through action. The program brought together a diverse group of students across public and private schools and at elementary and secondary levels. Youth participants in the program saw their impact as leaders in risk reduction, and can continue this into the future.

The program accomplished four main goals. 1) Increased over 11,000 young peoples' scientific understanding of local risks, and how they can take action to make their community safer. 2) Cultivated a group of 40+ Youth Club members that developed and implemented creative ways to increase disaster resilience, including performances by winners of a disaster-themed slam contest, theater and dance performances, painting displays, and public murals painted by club members with critical tsunami evacuation messages. 3) Empowered young people to share their knowledge, in their own voices, through messages and activities for peers and the public. 4) Increased preparedness of local school children through trainings, and more than 4,000 students evacuated schools during a major city-scale earthquake exercise. Program activities have inspired Youth Club members to create their own sister organization to continue empowering youth.

Expedited Tsunami Warning Alerts Along the US West Coast Using Earthquake Early Warning Tools

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Tsunamis cause significant damage and loss of life, particularly for communities closest to the source, where the tsunami may arrive in a matter of minutes. These near field communities often do not receive an informed or timely alert under traditional warning pathways. In response, numerous tsunami early warning (TEW) algorithms have been developed with the goal of providing informed tsunami source characterization within minutes for use in localized warning. However, an overlooked aspect of TEW is the mechanism that this crucial information is received by individuals. Current operations focus heavily on the time an alert is issued from a warning center. Before that warning is conveyed to affected communities, it first travels a serpentine path through state and local contact points, which can create further delays, reducing the timeliness of alerts. In this presentation, we provide the framework and advocate for the use of rapid dissemination tools prevalent in earthquake early warning (EEW) systems to provide timely, clear, and consistent alerts to the public. We illustrate the need for rapid alerting strategies through the analysis of multiple prospective tsunamigenic earthquakes rupturing on the west coast of the United States in the Cascadia subduction zone.

Implementing Tsunami Ready: An Overview of the Community Awareness and Preparedness Program in the Caribbean and Adjacent Regions

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Over the past 500 years, tsunamis generated from different sources have affected the Caribbean and Adjacent Regions causing significant deaths and destruction. Tsunami preparedness is necessary to mitigate the effects of future events and the implementation of voluntary performance-based programs such as the UNESCO Intergovernmental Oceanographic Commission (IOC) Tsunami Ready Recognition Programme is key to achieve this. The program, which was approved in 2022 after a decade of piloting, consists of 12 indicators categorized into Assessment, Preparedness, and Response. In coordination with national authorities, interested communities need to meet all indicators to obtain the Tsunami Ready recognition. One of the first steps of the implementation process is the identification of tsunami hazard zones following guidelines on numerical or non-numerical modeling approaches. The hazard assessment information is used to determine the population at risk, develop evacuation maps and signage plan for education and outreach and conducting exercises such as CARIBE WAVE. In parallel and informed by the hazard analysis, national and local emergency response plans are also developed. The completion of these indicators also enhances collaborations and communications between international emergency managers and tsunami service providers, scientists, community stakeholders, and national authorities. The Tsunami Ready program has been supporting coastal communities in the Caribbean in the process of strengthening their preparedness and capacity development since 2011, with communities in 12 countries recognized to date in the region. This effort also contributes to one of the goals of the 2021-2030 United Nations Decade of Ocean Science for Sustainable Development Tsunami Program: 100 percent of communities at risk of tsunamis to be prepared and resilient by 2030. An overview on the implementation process, as well as ongoing efforts, challenges, and deliverables will be presented.

Integrating Volcanic Sources into the Tsunami Warning System for the Caribbean and Adjacent Regions

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One of the goals of the UN Decade Ocean Science Tsunami Programme is that by 2030 actionable notifications are issued for all tsunamis, irrespective of source. In the Caribbean, 14% of all probable and definite historical tsunamis are associated with volcanoes (NOAA National Centers for Environmental Information). A tsunami triggered by the the Hunga Tonga Hunga Ha'apai eruption of January 15, 2022, was the most recent to be observed in the Caribbean and adjacent regions. This event as well as the eruption and related tsunami at Anak Krakatau (2018) and the eruptions of Kick'em Jenny (2015, 2017, 2018, 2020), Saint Vincent (2020) and La Palma (2021) reinforced the need for a tsunami warning system that can handle such non-seismic events.
The UNESCO/IOC Intergovernmental Coordination Group for the Tsunami and Other Coastal Hazards Warning System for the Caribbean and Adjacent Regions was established in 2005. It coordinates tsunami warning and mitigation activities, including the issuance of tsunami bulletins for its 48 Member States and territories. Following the eruptions of Kick'em Jenny in 2015, it established the Volcanic Sources Task Team to address the challenge of these non-seismic sources. A warning system, as the one operated by Tsunami Service Providers, (TSP, ie, the Pacific Tsunami Warning Center), is classically based on seismic and sea level data. Determined earthquake locations and magnitudes trigger initial action from the TSP, while sea level data confirm tsunami generation and help refine forecasts. For volcano sources, the task team has proposed that volcano observatories send messages to the TSP's alerting them to potential and ongoing eruptions. These messages, vis a vis seismic information, would be the basis for TSP's to issue initial standardized bulletins and products. The 2019 and 2023 CARIBE WAVE exercises included scenarios to test products and procedures for volcanic sources. However, more actions are required, including advancing the modeling of volcano scenarios and forecasting of triggered tsunamis, as well as expanding observations, including seismic and geodetic.

Korea Meteorological Administration's Tsunami Forecast and Early-warning System Improvements for Tsunami Preparedness

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Around Pacific Ocean is part of several seismic hotspots around the globe and there has been a lot of seismic activity around plate boundary as the 'Ring of Fire', could generated a massive Tsunami across the Pacific Ocean. Korea Meteological Administration(KMA) need to establish Tsunami forecasting, early warning, monitoring and detection system for major Tsunami threat cause Korea peninsula is surrounded by water on three sides. We already has Earthquake early-warning(EEW) system to forecast large earthquake and Tsunami and to pass produced Tsunami forecast information for maximum tsunami height and estimated arrival time each predicting stations. An earthquake with magnitude of 6.0 or greater threat alert announced automatically through established scenario database(DB) system to minimizing property damage throught the issuance of timely, effective Tsunami warnings and threat messages. And we can re-analysize real earthquake information based numerical Tsunami simulation using fault mechanism and analysed earthquake result. Using this results we produces more accurate expected arrival time, maximum Tsunami height and propagation map. While expanding the range of Tsunami numerical simulations from Northeast Asia to the global area, we can produce automatically large-scale of Tsunami forecast information(from Chile to Korea) is also predictable. Moreover Tsunami forecasting system can analysize Tsunami amplitude height over time to predict impact of 3,450 predicting stations in Korea and Japan coast. KMA has been monitoring tidal wave using three type of ocean wave observation equipment(tide gauge, Coastal Disaster Prevention System, wave height meter). Also twenty-four seven fully operate real-time observation data based Tsunami monitoring and detection system. We estimate threshold sea level value each monitoring stations in detection system. Recently Hunga Tonga–Hunga Ha'apai eruption in 15 January 2022 generated mega Tsunami across Pacific ocean. We prove whether Tsunami reach by Tonga eruption some of southernmost station using Tsuami detection system.

Ongoing Work by a Powell Center Working Group on Tsunami Sources for Hazards Mitigation in the United States

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Members of the National Tsunami Hazard Mitigation Program and other researchers have convened a multidisciplinary working group on tsunami sources, partially supported by the USGS Powell Center. The goal is to define and implement a transparent and scientifically-based methodology and evaluation process for characterizing historical and realistic hypothetical sources of tsunamis that pose a potential hazard to U.S. populations, commerce, and infrastructure. Using a logic tree process, and including regional experts, the working group is synthesizing existing peer reviewed geological and geophysical knowledge of submarine earthquake faults and coastal landslide sources to produce a database of source models for use in creating hazards assessments for risk reduction. The vehicle is a series of collaborative working meetings at the Powell Center, followed by additional work to complete the logic trees.

The first week-long meeting, in April 2018, adopted a probabilistic evaluation process where possible. Ensuing meetings, with reports underway, focused on Alaska-Aleutian subduction zone tsunami sources, Cascadia subduction zone tsunami sources, and tsunami sources that impact the U.S. East Coast, Gulf Coast, and Caribbean Territories. A meeting on Pacific tsunami sources, other than the Cascadia and Alaska-Aleutian subduction zones, is scheduled for March 2023, and will include a discussion of volcanic tsunami sources. Lessons learned from developing the logic tree for Alaska-Aleutian tsunami sources have been applied to developing logic trees for the other regions. Results and discussions from the meetings are being used to understand and help fill knowledge gaps within the earthquake and tsunami modeling communities.

Operationalization of Koeri Tsunami Warning System in the Eastern Mediterranean and Its Connected Seas: A Decade of Achievements and Challenges

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Kandilli Observatory and Earthquake Research Institute (KOERI) tsunami warning system provides services in the Eastern Mediterranean, Aegean, Marmara and Black Seas under the UNESCO Intergovernmental Oceanographic Commission (IOC) - Intergovernmental Coordination Group (ICG) for the Tsunami Early Warning and Mitigation System in the North-Eastern Atlantic, the Mediterranean and Connected Seas (NEAMTWS). KOERI's Regional Earthquake and Tsunami Monitoring Center (RETMC) was established on the foundations of the KOERI National Earthquake Monitoring Center (NEMC) by adding observation, analysis and operational capability related to tsunami early warnings after an extensive preparatory period between 2009 and 2011. The center initiated its test-mode 7/24 operational status as a national tsunami warning center in 2011, and after a one-year period it became operational as a candidate tsunami warning center for NEAMTWS on 1 July 2012. KOERI celebrated its ten years of operational status with a number of activities performed on the 5th November 2022, World Tusnami Awareness Day (WTAD). KOERI continues monitoring and disseminating messages in the NEAM region together with other TSPs; CENALT (Centre d'Alerte aux Tsunamis-France), NOA (National Observatory of Athens-Greece), INGV (Instituto Nazionale di Geofisica e Vulcanologia-Italy), and IPMA (Instituto Português do Mar e da Atmosfera-Portugal), completing full coverage of the tsunami-prone regions monitored by NEAMTWS. An overview of the progress and continuous improvement of KOERI's tsunami early warning system will be presented, together with lessons learned from 42 events that tsunami warning message disseminated during the last ten years, especially for the important tsunamigenic events, such as the 20 July 2017 Bodrum–Kos Mw 6.6 and 30 October 2020 Samos–Izmir Mw 6.9 earthquakes.

State of California's Third Generation Tsunami Hazard Maps for Emergency Response Planning

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The California Tsunami Program (CTP) has completed it's third-generation, statewide update to the Tsunami Hazard Area maps for emergency response planning (tsunami.ca.gov). The California Geological Survey (CGS), the California Governor's Office of Emergency Services, and the NOAA National Weather Service led the statewide update with support from coastal county emergency managers. Updated Tsunami Hazard Area maps and data are used by local decision-makers as a basis to inform decisions regarding evacuation planning.

Advancements in tsunami modeling, source characterization, and digital elevation models have been made since publication of the State of California's second-generation 2009 tsunami hazard maps. Previous deterministic models for local and distant tsunami sources were generated using a 30- to 90-m resolution grid. New tsunami inundation models follow a probabilistic tsunami hazard analysis (PTHA) approach, generated using a 10-meter resolution grid. This PTHA uses sources that represent events equivalent to the 975-year average return period (ARP). Tsunami Hazard Area maps incorporate an approach that defines a maximum hazard area. We define the landward extent of inundation that includes both PTHA results (enhanced using lidar elevation data) and the 2009 deterministic local- and distant-source models. Local stakeholders, emergency managers, first responders, and tsunami hazard subject matter experts are consulted about the placement of the final hazard area boundary. With this consultation, we consider the organization of the evacuation from an emergency management perspective as well as the ease of evacuation from the public's perspective. Following the map and data release, the CTP continues to support local agencies use of the updated Tsunami Hazard Area maps with their tsunami preparedness, mitigation, and response activities.

Transforming Research Into Resiliency: The Intersection of Science and Emergency Management in Tsunami Preparedness, Mitigation, Education, and Response Efforts in Washington State

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In the face of natural hazards, community resilience requires a collaborative relationship between research and emergency management. Together, natural and social science provide a solid research foundation that is critical for understanding communities' risk profile, including expected impacts and social vulnerability, and building best practices that strengthen communities' overall resilience to natural hazards. Emergency management helps translate this information into actionable and targeted mitigation, education, alert and warning, response, and recovery efforts which help address identified vulnerabilities for long-term improvement. Neither discipline alone provides the required breadth of knowledge, skill, and subject matter expertise essential in accomplishing these efforts, but combined they ensure all factors are addressed for the best possible outcome.

Washington Emergency Management Division's tsunami program will discuss ongoing projects in the state that increase the resilience of Washington's high-risk coastal communities to devastating local and distant tsunamis. These projects represent a united effort between state, tribal, and local emergency management, the Washington Geological Survey, the University of Washington, Washington Sea Grant, NOAA's Pacific Marine Environmental Laboratory, and other vital partners across the spectrum of emergency management and research fields. The presentation will include an overview of how Washington utilizes research findings and data to strengthen its tsunami maritime response and mitigation strategies, evacuation route wayfinding assessments, and Hazus earthquake and tsunami risk assessments, as well as some of the uses of the information collected during these projects.

Tsunami Sources in the Caribbean and Eastern US

POWELL CENTER WORKING GROUP ON TSUNAMI SOURCES, U.S. Geological Survey, Colorado, USA, thio@mac.com

In 2019 the Powell Center Working Group on Tsunami Sources held a meeting on Caribbean, East Coast, and Gulf Coast tsunami sources with the aim of synthesizing the current state of knowledge of the tsunamigenic sources in the region, identifying gaps in our understanding of the various processes and data, and initiating the development of a source model for future hazard studies. The character of the tsunami hazard in these regions is somewhat different from the Pacific zones because submarine landslides may be significant for the hazard in the Caribbean at return periods of typical engineering interest (e.g. 2500 year).

For earthquake generated tsunamis, we compiled an inventory of potential sources, focusing on the Antilles subduction zone, Muertos trough and associated structures as well as crustal sources throughout the area (e.g. Mona Passage, Anegada Passage).

An important aspect of these models is the segmentation of the Caribbean-Atlantic plate boundary, which governs the maximum magnitude that can occur on these structures. Especially on the Lesser Antilles Trench, there is little direct data to constrain deformation rates and coupling, but paleoseismic data, such as uplifted coral reefs, start to fill in some of these gaps. In other areas such as the Muertos Trough, geodetic data indicate that there is a significant lateral variation in geodetic rates along strike, suggesting a segmentation of this structure. We will present the preliminary source model.

The issue of submarine landslides is complex since we have very few direct observations of these processes, and there are large uncertainties in their dynamic properties, their locations, volume and rates of occurrence. These sources are significant for the Caribbean and may dominate the hazard along the Eastern seaboard. The discussions highlighted the progress in this field and helped identify current gaps that need to be resolved before a comprehensive PTHA can be performed.

General Seismology [Poster]

Poster Session • Tuesday 18 April

Conveners: Elizabeth A. Vanacore, University of Puerto Rico, Mayagüez (elizabeth.vanacore@upr.edu); Xyoli Pérez-Campos, Universidad Nacional Autónoma de México (xyoli@igeofisica.unam.mx)

Insight, 2018-2022: Results From the First Mission With a Primary Focus on the Interior of Mars

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InSight landed on Mars in November, 2018, and spent the next few months deploying a sensitive seismometer package and a heat flow probe to the surface. Following that, InSight kept gathering geophysical data from Mars until the end of surface operations in December, 2022, providing for the first time a powerful, detailed view of the interior of another planet based on surface geophysical measurements. The InSight mission was unique in that it was the first landed mission primarily focused on in situ geophysical measurements of another planet. It also constituted the first long-lived stationary lander on Mars since Viking, as well as the first operational planetary seismic experiment of any kind since Viking. Its primary payload, consisting of a very-broad-band seismometer, a precision tracking system, and a heat flow probe, was tightly focused on meeting ten specific scientific objectives related to the deep interior structure and dynamics of Mars. Although the dusty atmosphere of Mars eventually obscured the solar arrays enough to end operations in late 2022, InSight managed to record over 1300 marsquakes, and used the data from that and the other instrumentation aboard the lander to determine key parameters needed to better understand Mars, including its seismic activity level; information about its crust, mantle, and core; and observations of seismic signals from impacts. While the data will undoubtedly continue to be analyzed and reanalyzed in years to come, this presentation will focus on an overview of the major results of the mission during its time operating on the surface of Mars.

Pn Wave Attenuation Beneath the Caribbean Plate

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The Caribbean plate is trapped among the North and South American continental plates and the Atlantic and Pacific oceanic plates (Freeland and Dietz, 1971). It suffers from the north-south trend squeeze from continental lithospheres and the east-west trend subduction of the oceanic plates, respectively (e.g., Stein et al., 1988). Therefore, the deformed Caribbean lithosphere is composed of terrains of different types tectonically squeezed together. The dynamic processes caused the upwelling of deep mantle materials and dramatically changed the property of the crust and uppermost mantle in this region. We use Pn-wave attenuation to investigate the thermal distribution in the uppermost mantle and provide seismological constraints on the mechanism of dynamic processes. Based on 19,200 broadband vertical-component digital seismograms, we investigate both the Pn-wave geometric spreading and attenuation in the Caribbean region. We extract Pn signals using a 0.7 km/s group-velocity window around their first arrival times obtained based on the machine learning, followed by measuring Pn spectra within the 0.5 to 10.0 Hz band. A frequency-dependent Pn geometric spreading function is obtained by fitting the observed Pn spectra. Then, a preliminary Pn attenuation model can be obtained from the two-station Pn spectra data. A frequency-dependent Pn-wave Q tomography is conducted based on both two-station and single-station data to construct the uppermost mantle Q model beneath the Caribbean plate (Yang et al., 2022; Zhao et al., 2015). Strong Pn attenuation can be observed beneath the Venezuela Basin, the southern part of the Colombia Basin, and the northern South American plate. Strong Pn attenuation in the junction area among the Venezuela Basin, the Atlantic subduction plate, and the northern South American plate, combining with previous velocity and anisotropy studies, reveals that there seems to be uppermost mantle flow in this region (Braszus et al., 2021; Growdon et al., 2009). This work is supported by the National Natural Science Foundation of China (grants U2139206, 41974054, 41974061).

Variations of the System Properties of a High-Rise Building Over 1 Year Using a Single Station 6c Approach.

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We demonstrate that the dynamic response of an engineered structure, including modeshape identification, can be obtained from just a single measurement at one position - if rotation is recorded in combination with translation.

Such a single-station approach can save significant time, effort and cost when compared with traditional structural characterization using horizontal arrays. In our contribution we will focus on the monitoring of a high-rise building by tracking its dynamic properties and their variations due to environmental (e.g. temperature) and operational (e.g. wind) conditions (EOCs) over a 1-year period. We present a real-case structural identification procedure on the Prime Tower in Zurich. This is a 36-story tower of 126 m height, with a poured-in-place-concrete core and floors and precast-concrete columns; this concrete core structure, surrounded by a triple-glazed facade, is the third highest building in Switzerland.

The building has been continuously monitored, by an accelerometer (EpiSensor), a co-located rotational sensor (BlueSeis) and a weather station located near the building center on the roof. Roof and vertical seismic arrays were deployed for short periods. The motion on the tower roof includes significant rotation as well as translation, which can be precisely captured by the monitoring station. More than 20 structural modes, including the first 6 primary modes, where translations are coupled with rotations, are tracked between 0.3 – 14 Hz. We will also show the variation of natural frequencies due to seasonal but also more short-term effects, in an effort to understand the effect of EOC variability on structural deformation and response. Additionally, an amplification of the modes, during strong winds and a couple of Mw 4.0 - 4.4 earthquakes at regional distance has been observed and analysed. The frequency band between 0.3 and 10 Hz is of key interest for earthquake excitation, making an investigation thereof essential. The work closes with a summary of the main benefits and potential in adopting collocated rotation and acceleration sensing for geo-infrastructure monitoring purposes.

Vertical Component Impulse Response Functions in a High-Rise From Earthquake and Ambient Vibration Data

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Increasingly, interferometric techniques are being used to study the impulse response of engineering structures (bridges, tall buildings, etc.) and conducting structural health monitoring. Most of these studies have focused on the horizontal components, while little attention has been paid to the vertical components. These techniques are applied to data from Community Seismic Network MEMS accelerometers permanently installed on nearly every floor of a 52-story steel moment-and-braced frame building in downtown Los Angeles. The sensors relay continuous 24/7/365 acceleration waveform data and shaking intensity parameters using a cloud computing environment. Wavefield data from the instrumented high-rise from before, during, and after the 2019 M7.1 Ridgecrest, M6.4 Ridgecrest, and M4.5 El Monte, California earthquakes are processed for vertical component impulse response functions (IRFs), which show a distinct behavior from the horizontal IRFs. First, the wave speeds are of the order of 2000 m/s, while they are around 200 m/s for the horizontal components. The fundamental mode frequency of the vertical components (in line with the velocity) is an order of magnitude higher than that of the horizontal components (2 Hz vs. 0.2 Hz). The vertical component IRFs show a complicated behavior, including a discontinuous nature, as opposed to a very continuous IRFs observed for the horizontal components. We present observational as well as numerical constraints on the vertical IRFs to better understand their behavior and potential for structural health monitoring. For example they may lead to observations of the effects of cyclic loading due to longitudinal modes, including strength and stiffness degradation in connections when resonant amplitudes are large or long-duration, and activated during multiple earthquakes.

Geophysical Data Analysis in Cloud Computing Environments [Poster]

Poster Session • Tuesday 18 April

Conveners: Chad Trabant, Incorporated Research Institutions for Seismology (chad.trabant@iris.edu); Henry Berglund, UNAVCO (henry.berglund@unavco.org)

A Cloud Ecosystem for Data and Software Developed by SCOPED

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Observational seismology favors distributed memory workflows and embarrassing parallelization, for which cloud computing has an optimal architecture. Cloud computing offers horizontal scalability for computing workflows suited for single-station analysis. The orchestration of software, data, and resources on the cloud requires some thinking about the design. We present the initial experimentation of the SCOPED project. The SCOPED software ecosystem uses a base container and software-specific containers built on top, forming a registry of containers deployable on cloud instances. The SCOPED data uses S3-like objects, using mSEED files for raw seismic data and tileDB (the new Earthscope Consortium Cloud store) for data products. We propose the first cloudstore for Distributed Acoustic Sensing data. We illustrate the workflows using canonical examples in observational seismology: ambient-noise seismology and machine-learning earthquake workflows.

Constructing Cloud Resources for the Individual Researcher From the Ground Up: An Example of Earthquake Detection in the Cloud

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The commercial cloud could potentially unlock boundless seismic processing at scale. However, only a few introductory educational examples of cloud-based workflows exist that fit the specific needs of most independent seismic researchers. To this end, we share our experience simultaneously storing large time-series datasets and distributing their processing across many individual cloud computing instances on the Microsoft Azure cloud computing platform. Our data processing workflow performs earthquake detection using both template-matching, through EQcorrscan (Chamberlain et al., 2018), and a machine learning detector, Earthquake Transformer (Mousavi et al., 2020), with the ability to flexibly scale computation by varying individual virtual machine and machine pool sizes. Our documented example shows how to containerize locally-developed codes and manage their use with cloud-stored data and cloud-hosted computing pools. We explore how the performance of CPU-only pools compares to GPU pools and examine whether the speed-up from GPU resources justifies their higher development and deployment cost. We highlight the complexity of navigating commercial cloud resources as an individual researcher and discuss how contrasting workflow set-ups, i.e. a few large computing nodes versus a big network of small instances, can be equally appropriate depending on the researcher's time constraints and technical ability. The presented work is both a commercial cloud resource structure that can be readily modified by other researchers, and a preliminary comparison of two highly effective but rarely compared earthquake detection methods.

Leveraging Cloud Services for the Earthscope Data Repositories

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EarthScope Data Service Staff are designing and developing a cloud-based platform to replace on-premise systems that historically have been operated by the UNAVCO and IRIS facilities under the SAGE and GAGE awards. Our goals for this Common Cloud Platform (CCP) project include leveraging cloud services to implement operational improvements such as on-demand scalability, increased robustness, and improved data accessibility. The focus of our work to date has prioritized three main areas of development. We are replacing the core of our existing real-time data ingestion and distribution system using AWS managed Kafka streams. Kafka's Pub/Sub capabilities let us capture data that is then consumed by multiple downstream processes, such as archiving, derivative product generation, stream exports, etc. Joining these streams allow us to dynamically modify combined streams as we add, delete or modify stations. We use container-based consumers, managed in ECS, together with topic partitions to support horizontal scaling of computationally expensive operations. Additionally, Kafka's append-only design lets us operate without interruption during updates. We are also developing new Analysis Ready, Cloud Optimized (ARCO) geophysical data containers based on TileDB multidimensional arrays. We will use these containers to store geophysical datasets in normalized formats, better enabling export to multiple target formats (e.g RINEX 2, 3, & 4, SEG-Y, miniSEED). TileDB support for multidimensional slicing, compression, and optimization for access in object storage, make it an attractive option for storing and performantly accessing complex data. Furthermore, we are replacing our primary dataflow system with a fully serverless event based design. The serverless architecture scales dynamically in order to accommodate transient spikes in batch dataflow submissions and will also be utilized to Extract, Transform, and Load (ETL) our existing data assets into the new system. We are excited to present our successes and challenges as we transition from on-prem hosting to a cloud native environment.

Seismic Networks in the Cloud

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Traditional earthquake data processing is carried out on dedicated hardware in a data center run by the operator of the seismic network. Such specialized data centers have to be carefully planned, and hardware resources must be purchased in advance or constantly aggregated/modified/updated. Traditionally, private leased lines, satellite, and/or cellular networks build the communication backbone. Over the years, the internet has become a significant carrier for seismic data directly from the field as well as between institutions. With the evolution of the internet as the backbone of international data exchange, multi-tenant data centers started to evolve in many scientific fields, leading to virtualized cloud computing. However, implementing a process-based seismic real-time data center with 24/7 operation requires additional considerations. Nevertheless, the modular infrastructure of a virtual data center allows the flexible scaling of processes when more data has to be processed. And cloud data centers allow easy horizontal scaling without limits for computational and storage resources. Adopting cloud services is neither straight nor easy, and scaling and flexibility come with a price. The radical change towards a pay-per-use infrastructure versus the traditional investment makes obsolete several consolidated paradigms. The budget shift imposed by cloud services from capital investment to operational costs requires adapting the traditional budgeting processes. In a conventional data center (covered by the initial investment), practices with negligible expenses could be costly in the cloud environment where customers are charged per use. The presentation compares systematically and financially two cloud configurations: one for a small scientific network with a few data users and a very large national network with many stakeholders, from the network operators to emergency officers.

Ground Truthing Multidimensional Site Response Analyses at Borehole Array Sites

Oral Session • Thursday 20 April • 04:30 PM Pacific

Conveners: Mohamad M. Hallal, University of California, Berkeley (mhallal@utexas.edu); Brady R. Cox, Utah State University (brady.cox@usu.edu)

Benchmarking Multidimensional Ground Response Analyses at the Treasure Island Borehole Array Site Using Different Commercial and Open-Source Software

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Over the past decade, numerous studies have examined ground motions recorded at borehole array sites and found that, on average, more than 50% of these sites are poorly modeled using one-dimensional (1D) ground response analyses (GRAs). These discrepancies have been attributed to limitations of conventional 1D GRAs, which inherently disregard complex wave propagation effects resulting from laterally variable subsurface conditions, among other factors. Given these findings, as well as the increasing body of research literature and consulting practice that are implementing multidimensional GRAs, proper modeling of laterally variable subsurface conditions is an important step toward improving seismic hazard assessment and risk mitigation. This presentation will share findings from an ongoing research effort aimed at ground truthing multidimensional GRAs. The study is working toward providing a well-documented and openly accessible set of benchmarking cases that can serve as a resource for practitioners and researchers to calibrate their own analyses. The benchmark cases range in complexity from a single soil column with a single uniform soil layer to a 4000-m wide 2D cross-section with site-specific subsurface spatial variability representing the Treasure Island Downhole Array (TIDA). Collaborators from academia and industry have modeled these cases using different commercial and open-source software (e.g., OpenSees, Sesimo-VLab, FLAC, LS-DYNA). By qualitatively and quantitatively comparing the numerical results across different software platforms and by ground truthing the results against recorded ground motions at TIDA, we share insights on the relative strengths and limitations of each software in terms of accuracy and challenges associated with implementing multidimension GRAs, such as modeling boundary conditions and computational costs.

Inherent Limitations of One-Dimensional Ground Response Analyses

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The first computational model of elastic wave propagation in horizontally layered media was proposed 70 years ago by Haskell and Thomson. Later, ground motion modelers further simplified the horizontally layered model for *vertical* wave propagation by assuming deep seismic sources and low-velocity near-surface layers. This simplification reduces the governing 3D vector wave equation, which involves diffraction, reflection-transmission, and conversion of *P* and *S* body and surface waves, to a 1D scalar wave equation that only contains the reflection-transmission of *S* waves. Such 1D models have been utilized as "reasonable" tools for ground response analyses because of the higher computational cost of 2D/3D models and the lack of adequate subsurface data. Recent advancements in computational science and ambient noise subsurface inversion, however, have alleviated the limitations posed by computational cost and insufficient subsurface data and made true ground response analyses more feasible. In this study, we model seismic wave propagation in the Treasure Island Downhole Array site using both 1D and 2D representative soil profiles and discuss the inherent limitations of 1D models. We use the finite volume code FLAC, which combines the simplicity and robustness of finite difference method with the geometric flexibility of finite element method. The velocity model shows a bedrock layer in the form of an embedded single slope. We use high-frequency excitations to "decouple" various components of the scattered wavefield and reveal their interactions in forming the observed ground response. Part of the vertically propagating shear wave is diffracted at the tip and toe of the single slope bedrock and further propagates toward the ground surface as cylindrical *P* and *S* body waves. These obliquely incident body waves will then generate surface *P* and *S* waves that travel in the downhill direction. While these 2D surface waves give rise to a better match between field recordings and numerical simulations, we still need to consider 3D out-of-plane effects and non-vertical excitations to adequately capture the true response.

Ground Truthing Multidimensional Site Response Analyses Using Ls-Dyna

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A current research study is being conducted with collaborators from research and industry to ground truth multidimensional GRAs at the Treasure Island Downhole Array (TIDA). A large-scale, site-specific 3D subsurface model is now available for this site and multidimensional GRAs have proven that site response recorded in the borehole array is influenced by subsurface spatial variability at distances over 1 km away. Several teams have performed multidimensional GRAs for the TIDA site using different commercial and open-source software (e.g., OpenSees, Sesimo-VLab, FLAC, LS-DYNA). This study covers the methodologies and outcomes obtained using the software package LS-DYNA for the various analysis cases considered in the wider collaborative study. Special attention is given to Rayleigh damping implementation techniques, impacts of element formulations, hourglass control, boundary conditions, and analysis runtimes for a given hardware set. A discussion of the various analytical results and the unique considerations associated with leveraging LS-DYNA for GRA is provided.

Quantifying the Influence of Multi-Dimensional Effects in Site Response Analyses Using 2D and 3D Simulations in Sedimentary Basins of Wellington, New Zealand

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Several recent studies have concluded that multi-dimensional wave propagation effects can have a significant influence on site response and that 1D site-response modelling techniques often fail to capture the observed site response due to their inability to model such phenomena. This study aims to quantify the influence of multi-dimensional effects on the observed site response in the Wellington region of New Zealand by comparing results from different simulation approaches. We first discuss the effects of using various boundary conditions for modeling 2D site response at borehole arrays sites in California, including comparisons of massive column elements and free field boundary conditions using the software OpenSees at the Treasure Island Downhole Array. Then, we present results from basin modeling in the Wellington region. Amplification functions from 1D site-response analyses are compared to those from 2D site-response models and 3D physics-based ground-motion simulations to illustrate the magnitude and spatial distribution of multi-dimensional effects. Surface-to-borehole (i.e., “within”) transfer functions, which are often used in site response validation studies, are extracted from 1D and 2D site-response models to show their sensitivity to subsurface stratigraphy and surface topography. This is consistent with findings from recent global efforts illustrating that a significant percentage of sites do not display surface-to-borehole transfer functions that are consistent with those from 1D analyses.

Seismo-Vlab: An Open-Source Finite Element Platform for Site Response Analyses of Km-Scale Features With Random Properties

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We present, Seismo-VLAB (SVL), an open-source C++ multi-platform finite element software designed to optimize km-scale (mesoscale) simulations of nonlinear wave propagation and dynamic response of earth systems and structures. High-fidelity simulations of such problems require advanced models that can capture the heterogeneity, geometric irregularity and nonlinearity of soils; and parallel computing capabilities to optimize the computational cost. These features are not generally available in open-source earthquake engineering software packages. SVL uses state-of-the-art tools to achieve optimal reliability and efficiency of nonlinear wave propagation problem solving; all the while staying centered on object-oriented paradigms to maintain a simple, fast,and extendable design. The most important features of the software include dynamic nonlinear solvers for time-domain analyses of inelastic problems; cutting edge parallel linear system solvers, Message Passing Interface (MPI) parallelization, and domain decomposition for computational efficiency; perfectly matched layer (PML) absorbing boundary conditions; domain reduction for modeling wave-field incoherency in truncated domains; and plasticity models of soils and structures that require few parameters for calibration. In this presentation, we use SVL to compute the dynamic response of earth systems with surface and subsurface topographic irregularities and random properties.

Ground Truthing Multidimensional Site Response Analyses at Borehole Array Sites [Poster]

Poster Session • Thursday 20 April

Conveners: Mohamad M. Hallal, University of California, Berkeley (mhallal@utexas.edu); Brady R. Cox, Utah State University (brady.cox@usu.edu)

Investigating the Influence of Site-Specific Spatial Variability on Ground Motion Intensity Measures via Multidimensional Site Response Analyses at the Treasure Island Downhole Array

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Multidimensional ground response analyses (GRAs) are gradually gaining more interest due to the growing evidence that demonstrates the imperfect ability of one-dimensional (1D) GRAs to match recorded ground motions at many borehole array sites. However, there is rarely a multidimensional subsurface model available for these analyses. The lack of affordable and reliable site characterization methods to quantify spatial variability in subsurface conditions, particularly regarding shear wave velocity (Vs) measurements needed for GRAs, hinders future progress in accurate seismic site response modeling. We present a framework called the ‘H/V geostatistical approach’ that can be used to develop site-specific three-dimensional (3D) Vs models and we share insights that have been gained from implementing these 3D Vs models in multidimensional GRAs at the Treasure Island Downhole Array (TIDA). Using the H/V geostatistical approach, a site-specific, large-scale, 3D Vs model has been developed to a depth of 150 m over the entirety of Treasure Island (an area approximately 1.6 km x 1.0 km). By performing multidimensional finite element analyses using the recorded ‘rock’ ground motions at the TIDA, we investigate the influence of subsurface spatial variability on different ground motion intensity measures, and we ground truth these results against recorded surface ground motions at the TIDA. We show that the site-specific 3D Vs model is capable of replicating wave scattering and more complex wave propagation phenomena observed in the recorded ground motions at the TIDA.

High-frequency Ground Motion Measurements, Assessments and Predictions

Oral Session • Tuesday 18 April • 08:00 AM Pacific

Conveners: Chunyang Ji, North Carolina State University (cji3@ncsu.edu); Marco Pilz, GFZ Potsdam (pilz@gfz-potsdam.de); Ashly Cabas, North Carolina State University (amcabasm@ncsu.edu); Albert Kottke, Pacific Gas and Electric Company (albert.kottke@gmail.com); Kenneth Campbell, CoreLogic (ken.w.campbell@comcast.net)

A Model for Small-Strain Damping for the Groningen Field Constrained by Vertical Array Measurements

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The incorporation of site effects into seismic hazard assessments requires the characterization of stiffness and attenuation (i.e., damping). This study presents the derivation of a model for small-strain damping for the seismic hazard assessment of the Groningen gas field in the Netherlands. The model is constrained by ground motion measurements over a large network of 200 m deep vertical arrays. Measurements of the seismic quality factor Q at the vertical arrays were conducted by first applying seismic interferometry by deconvolution to estimate the local transfer function. Two approaches were then used: the first by measuring the amplitude decay of the retrieved upgo-

ing wave, and the second by measuring the amplitude difference between the upgoing and downgoing waves at a single geophone. The second approach has the advantage that corrections for elastic propagation are not needed; consequently, the use of this approach resulted in more robust measurements of Q. Moreover, the second approach is less sensitive to small differences in effective response functions of geophones at different depths because it relies on measurements at a single geophone. The measurements of Q at the vertical arrays were then used to build a model for the entire study area, which covers a region of approximately 40 by 50 km. The model was based on scaling small-strain damping models from the geotechnical engineering literature, which are based on geotechnical index properties, to match the measured Q values at the downhole arrays. This was possible because of the existence of a geostatistical model (the GeoTOP model) that provides estimates of geotechnical index properties for the entire study region. The scaling factor was determined by equating estimates of site kappa obtained using: a) the measured Q values and b) damping profiles obtained from the geotechnical damping models. We observed that the scaling factor is strongly correlated to the average shear wave velocity over the upper 30 m (V_{S30}). Q values at depths lower than the vertical arrays were derived from the attenuation of the microseism measured over the study region.

High Frequency Attenuation of Seismic Waves Due to the Heterogeneous Nature of the Crust : Theoretical Developments and Numerical Investigations

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Predicting the observed attenuation at high frequency remains an open issue of strong ground motion modeling due to its dependence on many factors (such as intrinsic attenuation, crustal heterogeneities, source rupture mechanism and so on). In practice this phenomenon is taken into account via empirical parameter such as so-called kappa.In this work, we proposed to study the high frequency attenuation using high fidelity earthquake numerical simulation at regional scale and theoretical developments of the elastodynamic equations in order to show the impact of crustal heterogeneities on the traveling wave.First, the theoretical developments are done taking into account the heterogeneities of the medium considering randomly fluctuating mechanical properties. From the stochastic differential equations, the results obtained gives the transmitted coefficient which can be directly linked to the high frequency attenuation.Secondly, the numerical simulations lead to study the high frequency attenuation on a broad band (0.1-20Hz) based on the computation of kappa parameter applied to synthetic data generated for different realizations of the mechanical properties. The computation of kappa is done at different locations for different realizations in order to highlight the impact of the random properties on the frequency content.

Finally, an estimation of the kappa value is provided based on synthetic data and compared to the theoretical formula obtained from stochastic differential equations. The high frequency decay obtained numerically is close to the analytic results considering a regional attenuation.

Empirical Correlations of Response Spectral Ordinates, Arias Intensity (AI) and Cumulative Absolute Velocity (CAV) With Fourier Spectral Ordinates of Ground-Motion and Associated Variabilities

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Empirical correlations between various ground-motion intensity measures (IMs) are of particular interest in engineering applications such as conditional ground-motion selection and vector probabilistic seismic hazard analysis (VPSHA). Past studies have mostly examined the inter-period correlation of response spectral ordinates e.g., pseudo spectral acceleration (PSA) and the correlation of non-spectral IMs such as arias intensity (AI) and cumulative absolute velocity (CAV) with PSA. However, from the perspective of engineering seismology it is rather enigmatic how these engineering IMs are correlated with Fourier spectral ordinates -in other words- with the seismological parameters that determine amplitude and shape of Fourier spectrum of input ground-motion.Bora et al. (2016) presented a theoretical analysis using random vibration theory (RVT) to decipher the complex relationship between response spectral ordinates (e.g., PSAs) and the Fourier amplitude spectrum of the input ground-motion. In the present study, I present empirical correlations of PSAs, AI and CAV with Fourier spectral amplitudes of acceleration ground-motion. The correlations are examined in terms of residual correlations between the chosen IMs obtained from the NGA-West2 database . The residual correlations are investigated separately for between-event and within-event residuals of ground-motion. For that purpose, the PSA ground-motion model (GMM) of Abrahamson et al. (2014), Fourier model of Bora et al. (2019) and AI-CAV models of Campbell and Bozorgnia (2019) are considered. In addition to validating the inferences from Bora et al. (2016), the correlation results clearly identify the frequency range in the input ground-motion that dominates the IMs such as PGA, PGV, AI and CAV. Furthermore, I also examine the scenario-dependence of such correlations in addition to investigating regional variations. The results presented in this study have significant implications for host-to-target adjustment of ground-motion models mainly for site-specific hazard analysis and physics-based numerical simulation of ground-motions.

Broadband Ground Motion Synthesis via Generative Adversarial Neural Operators

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We present a data-driven framework for 3-component ground motion synthesis intended for engineering applications. Leveraging the increase of ground-motion data from seismic networks and recent advancements in Machine Learning, we train a Generative Adversarial Neural Operator (GANO) to produce realistic three-component velocity time histories conditioned on moment magnitude, rupture distance, Vs30, and tectonic environment type of earthquakes. Neural operators allow for the sampling of functions by learning push-forward operator maps in infinite-dimensional spaces, rendering our model resolution-invariant. We train the GANO on two 50K ground motion datasets harvested from the Japanese Strong Motion Network KiK-Net (M 4.5-8.0) and the Southern California Earthquake Data Center (M 4.0-7.5) correspondingly; and show that the framework can recover the imposed magnitude, distance, and Vs30 scaling of Fourier and response spectral acceleration components. We evaluated our model through residual analysis with the empirical dataset as well as by comparisons with conventional GMMs for selected ground motion scenarios; results show that our model recovers both the mean value and aleatory variability of the evaluated ground-motion parameters. In particular, quantitative measures of Fourier and response spectral amplitude residuals for the said datasets indicate that the GANO generated ground motions are unbiased in the frequency range of 0.1-20Hz for the horizontal component and 0.1-30Hz for the vertical component. Potential applications of the presented framework include: (i) design ground motions for earthquake scenarios not represented in empirical datasets, (ii) risk-targeted ground motions for site-specific and system-level engineering applications, and (iii) high-frequency components of simulated ground motions when regional-scale velocity models lack the appropriate spatial resolution in the shallow crust.

Rupture Directivity Effects Observed in Ground Motions From the 2022 M5.1 Alum Rock Earthquake

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We present evidence for southeastward rupture directivity during the October 25, 2022, M5.1 strike-slip Alum Rock earthquake on the Calaveras fault. The average recorded ground motions were a factor of 3 less than the expected median shaking. However, there was large variability controlled by site azimuth, with over an order of magnitude between motions recorded at the same source-to-site distance but at different azimuths. This was observed for peak ground acceleration and velocity, and at all considered oscillator periods from 0.01-5s, with peak variability at 1s. To understand if this was controlled by directivity, azimuthal path effects, or site effects, we examine ground motions from 5 smaller earthquakes (M<4.1) with epicenters within 3km of that of the M5.1 event. We assume that these events had no directivity and use them to estimate repeatable path and site effects. We adjust residuals from the M5.1 event using these path and site terms to isolate directivity effects. We find that azimuthal trends persist in the adjusted residuals, and that directivity was responsible for both a factor of 5 amplification and de-amplification. Earthquake simulations confirm this, with a point-source model fitting the observed ground motion amplitudes to the south of the epicenter, but significantly over-predicting amplitudes to the north, while a kinematic model with unilateral rupture to the south at 2.5 km/s improves the match at all azimuths. By inverting the peak ground motions, we fit a line source with southeastward directivity at the same velocity as the kinematic model (Boatwright, 2007). The same sense of directivity is observed for the 2007 M5.6 Alum Rock and 1984 M6.2 Morgan Hill earthquakes (Hartzell and Heaton, 1986), potentially indicating consistent fault properties in this section of the Calaveras. This underscores the importance of considering directivity in seismic hazard analysis, as directivity in even moderate magnitude earthquakes can lead to dramatic differences in shaking depending on site azimuth, all else being equal.

High-frequency Ground Motion Measurements, Assessments and Predictions [Poster]

Poster Session • Tuesday 18 April

Conveners: Chunyang Ji, North Carolina State University (cji3@ncsu.edu); Marco Pilz, GFZ Potsdam (pilz@gfz-potsdam.de); Ashly Cabas, North Carolina State University (amcabasm@ncsu.edu); Albert Kottke, Pacific Gas and Electric Company (albert.kottke@gmail.com); Kenneth Campbell, CoreLogic (ken.w.campbell@comcast.net)

Combined Effect of Brittle Off-Fault Damage and Fault Roughness on Earthquake Rupture Dynamics.

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Natural fault zone are complex objects. They not only consist of a fine-grained narrow fault core where the extensive shearing is observed, but it is also surrounded by pervasively fractured rocks, within an intricate 3-D geometry. If fault slip behavior is intrinsically linked to the properties of the fault core, the complex structure of fault zone systems impacts the rheological properties of the bulk, which influence the modes of deformation, and slip, as underlined by recent observations. Fault zone structure is therefore of key importance to understand the mechanics of faulting. Within the framework of a micro-mechanics based constitutive model that accounts for off-fault damage at high-strain rates, this numerical study aims to assess the interplay between earthquake ruptures along non-planar fault and the dynamically evolving off-fault medium. We consider 2D inplane models, with a 1D self-similar fault having a root mean square (rms) height fluctuations of order 10^{-3} to 10^{-2} times the profile length. We explore the dynamic effect of fault-roughness on off-fault damage structure and on earthquake rupture dynamics. We observe a high-frequency content in the radiated ground motion, consistent with strong motion records. It results from the combined effect of roughness-related accelerations and decelerations of fault rupture and slip rate oscillations due to the dynamic evolution of elastic moduli. These scenarios underline the importance of incorporating the complex structure of fault zone systems in dynamic models of earthquakes, with a particular emphasis on seismic hazard assessment.

Estimation of Kappa (κ_0) and Associated Uncertainties in Iran Using Broadband Inversion Method

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Abstract kappa (κ) (Anderson and Hough, 1984), and its site-specific component (κ_0) at a given location, is an important spectral parameter for the characterization of the high-frequency shape of the Fourier acceleration spectrum, predicting and simulating high-frequency ground motion and is usually modeled in log-linear space. For our analysis, we use 2798 acceleration time histories from 325 earthquakes (between 1976 and 2020) in the moment magnitude range M3.5–7.4 and at Epicentral distances (Repi) up to 100 km. Using the broadband inversion approach, we study the spectral decay parameter κ using S-wave recordings at 285 stations in Iran. Here, the κ estimated by Davatgari Tafreshi et al. (2022) using Anderson and Hough's (1984) high-frequency linear fit method is compared with our κ estimation using the FAS broadband inversion approach as described in Edwards and Fäh (2013a); Bora et al. (2015) and Bora et al. (2017) for three major seismotectonic regimes in Iran, namely northern Iran, Zagros, and central-east Iran. In the broadband approach, the FAS at all frequencies is fit to a point-source model using a least-squares fit. For site-specific seismic hazard analyses, κ_0 should be estimated at locations away from an accelerogram location. For this purpose, for site-specific seismic hazard analyses, κ_0 can be inferred from the correlations with V_{S30}. We correlate the site component of κ (κ_0) with V_{S30} and f_0 of the site. Our findings show a weak but negative correlation between κ_0 and V_{S30} for three subregions under study. Researchers have studied site-to-site (between-station variability) and model-to-model variability of κ. Still, the uncertainties in κ estimation at a selected site associated with various events (within-station variability) remain uncharacterized. We have estimated a mean κ_0 and its uncertainty for stations with at least 5 records in our dataset, which may be useful for future site-specific seismic hazard analyses. Keywords: Kappa; Site effects; Attenuation; Broadband Inversion Method

How Well We Are Predicting High-Frequency Response Spectra for the CEUS?

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Analysis of the NGA-East database developed in 2014 shows clear deficiency in high frequency recordings in the CEUS with less than 40 records with Mw>5.0 at distances R<100 km. In the meantime, nuclear industry is using Westinghouse AP1000 Hard Rock High Frequency (HRHF) response spectrum (developed before 2009) for nuclear power plants design and license applications. Horizontal HRHF peaks at 30 Hz while vertical one at ~45 Hz. The HRHF spectrum was developed based on a limited amount of data before NGA-East was made available. This raises the question: Is HRHF needs to be updated in light of new data?

Ground Motion Models (GMMs) G-16 and G-16v2 (Graizer, 2016 and 2017) were developed using the NGA-East database. It was recently validated against strong motion recordings from the 2016 Oklahoma Cushing M_W 5.0 and Pawnee M_W 5.8 earthquakes. In the constantly updated Center for Engineering Strong Motion Data (CESMD) database we found only two earthquakes in the CEUS with $M_W \geq 5.0$ well recorded in the vicinities of the epicenters by modern digital accelerographs with a relatively high sampling rate of 200 samples/sec. Cushing event has 6 recordings at epicentral distances of 1.6 to 84 km and Pawnee has 19 recordings at 42.8 to 163 km. It was shown that both G-16 and G-16v2 models perform well compared to high quality recorded strong motion data. The G-16v2 model has overall lower residuals especially at high (10-100 Hz) and low (0.1-1.0 Hz) frequency ranges.

G-16 and G-16v2 models were used to calculate CEUS spectral shapes for earthquakes with $5 \leq M_W \leq 8$ and distances 1-400 km for soil (Vs=300 m/s), B-C boundary (Vs=760 m/s) and rock (Vs=2800 m/s) profiles. We concluded that HRHF spectral shape is shifted too much toward high frequencies, most importantly not enveloping average hard rock spectrum around 7-20 Hz. We recommend reassessing the HRHF based on the currently available information. We also recommend recording all earthquake strong motion data in the CEUS with a sampling rate not less than 200 samples/sec to allow constraining high frequency spectral models.

Lateral Variations of Attenuation in the Crust of Alaska Using Lg Q Tomography

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We have conducted a crustal seismic (Q_{Lg}) attenuation tomography study across Alaska using recordings from the EarthScope USArray from 2014-2019. The resolving power of the inversion is 75X75 km, except for the west and far north of Alaska due to the lack of seismicity in those areas. Numerous fault systems and high mountain ranges are present across Alaska and accommodate compression in the north-south direction and shearing of southern Alaska towards the west. These mountain ranges include the Brooks Range in the North, the Alaska Range in central Alaska, and the Aleutian Range in the southwest. The average Lg Q for all of Alaska is significantly higher than in the western U.S. and Canada. This lower average attenuation impacts seismic hazard estimates for the region. According to the tomographic results, we see a significant variation of the values from low to high across the southern part of the Brooks Range. Also, we found higher attenuation in the southeast region of Alaska, where the Wrangell Volcanoes are located. Moreover, we see an area of lower attenuation associated with weak frequency dependence in the south-central region of Alaska next to Anchorage. Another anomaly with lower attenuation can be seen extending from central Alaska to southeast Alaska, possibly associated with the Yukon–Tanana Terrane. There are a few areas like southwest Alaska associated with the Togiak Terrane and an area next to Fairbanks in Alaska's interior which shows lower attenuation with lower frequency dependence and higher attenuation with higher frequency

dependence, respectively, for low frequencies up to 3Hz. Our model's highest η zones (η ≥ 95) are mostly confined to major tectonic terranes and other major tectonic elements like faults and fractures. Regional variations in crustal attenuation can impact local seismic hazard estimates if incorporated into the hazard analysis.

Separating Broad-Band Site Response From Single-Station Seismograms

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We develop a deep-learning model, SeismAmp, to disentangle site effects in a broad frequency range (0.2 - ~20 Hz) from source and path effects in single-station seismograms (features). Ground-truth data (labels) are homogeneously created using a classical multi-station approach - the generalized spectral inversion at a total number of 1725 sites in the Fourier domain. We tested different feature representations and found that the individual components of each record carry salient information on site response, especially at high frequencies. However, part of the information is lost in its horizontal-to-vertical spectral ratio. The impacts of the number of recordings per site and record selection criteria (by earthquake magnitude, hypocentral distance, focal depth, or at random) are also investigated. When tested at new sites, SeismAmp achieves the lowest standard deviation among tested single-station techniques. SeismAmp could lead to improved site-specific earthquake hazard prediction in cases where site-specific recordings are available or can be collected. It is also a convenient tool to remove repeatable site effects from ground motions, which may benefit other applications, e.g., improving the retrieval of seismic source parameters.

Stochastic Finite-fault Ground Motion Simulation of the 2021 Mw5.9 Woods Point Earthquake: Facilitating Local Probabilistic Seismic Hazard Assessment

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The 2021 M_W5.9 Woods Point earthquake is the largest event in south-eastern Australia (SEA) recorded history since European settlement. To study its source and ground-motion characteristics and to extract information for local seismic hazard assessment, we employ a stochastic finite-fault simulation approach to simulate ground motions for this event based on the observations collected from 36 onshore stations. We determine the regional distance-dependent attenuation parameters using the horizontal Fourier acceleration amplitude spectrum (FAS) in the frequency range of 0.1-20 Hz. We parameterize the path parameters using different models to consider uncertainties and sensitivities. To investigate local site effects, we construct a local V_{S30}-based site amplification model. Source parameters are then obtained by fitting the theoretical Brune's ω^2 model with a reference Fourier source spectrum at 1.0 km. The κ_0 value of the reference rock site is estimated as 0.01 s, and the dynamic stress drop is found to be 41.0 MPa by minimizing the overall absolute residual of 5%-damped pseudo-spectral acceleration (PSA). We validate the simulations by comparing simulated and observed ground motions in terms of various intensity measurements; analyses of residuals show that the simulations are in good agreement with observations (average residual close to 0). To facilitate future probabilistic seismic hazard assessment (PSHA), six selected ground motion models (GMMs) are ranked using the deviance information criteria (DIC) based on an independent dataset of field observations and synthetic ground motions.

Understanding the Origin of High-Frequency Ground Motions of Earthquakes in California and Nevada

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Understanding the cause of damaging high-frequency earthquake ground motions is important from both a fundamental physics perspective and to better prepare for earthquake hazards. There are several competing theories over the origin of high-frequency ground motions. The standard paradigm is related to heterogeneity in slip on the rupture plane, but it remains challenging for these models to explain the variety of observed high-frequency ground motions with physically consistent parameters like stress drop and fault roughness. Alternatively, high-frequency earthquake radiation has recently been associated with fault complexity, though the underlying physical mechanisms are still not well understood. To untangle this problem, we measure response spectral accelerations at different periods for small and moderate earthquakes in California and Nevada and compare these measurements to predicted values from NGA-West2 ground motion models. We then use a mixed-effects decomposition method to decompose the residuals into event, site and path terms. We examine correlations between event terms at different periods and both source and fault zone characteristics, with the ultimate aim to better understand how high-frequency ground motions are generated in natural fault systems.

It's All About Relocation, Relocation, Relocation

Oral Session • Thursday 20 April • 04:30 PM Pacific

Conveners: Cleat Zeiler, Nevada National Security Site (zeilercp@nv.doe.gov); Michelle Scalise, Nevada National Security Site (scalisme@nv.doe.gov); Ting Chen, Los Alamos National Laboratory (tchen@lanl.gov); Moira Pyle, Lawrence Livermore National Laboratory (pyle4@llnl.gov); Leiph Preston, Sandia National Laboratories (lpresto@sandia.gov)

Considerations for Optimally Combining Local, Regional, and Teleseismic Data in Single Event Locations

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The U.S. Geological Survey National Earthquake Information Center's (NEIC) mission requires that it rapidly estimates earthquake locations using a spatially diverse set of seismic stations and a wide range of phase arrival-time observations. In some cases, like for many midocean ridge earthquakes, the NEIC primarily uses a distributed set of teleseismic observations. In other cases, such as for small domestic earthquakes, the NEIC uses a small set of local-to-regional observations. In most cases, the NEIC must rely on a varied combination of local, regional, and teleseismic arrival-time observations.
Given the heterogeneity of potential observations, it is challenging to ensure data is optimally weighted to ensure high-quality event locations and minimize potential velocity model and observation density biases. The NEIC locator currently uses a range of techniques aimed at improving event locations, including decimating dense observations, down weighting correlated observations, and weighting observations based on expected arrival-time uncertainties. Many of these techniques were developed before NEIC had access to a robust set of local observations, and therefore are less appropriate for the current state on NEIC's monitoring system. As a result, locations can underweight local observations and overweight regional observations that may have large velocity model biases. Here, we leverage a global catalog of calibrated earthquake locations to evaluate how to optimally combine observations at local to teleseismic distances. We re-evaluate how phase, distance and azimuth effect the covariance of arrival-time observations. We also re-evaluate phase specific arrival-time statistics (e.g., bias, spread). We demonstrate the effect of changes to these underlying statistics in the results from the NEIC locator.

How Good Is Your Location? Comparing and Understanding the Uncertainties in Locations of a Sequence of Events in Nevada

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Event location is an essential function of seismology. In this study, we are motivated to better understand the uncertainties of event location as part of

the Source Physics Experiments (SPE). The SPE were designed to improve our physics-based understanding and modeling capabilities of explosion seismic sources. Phase III of SPE will provide a direct comparison of earthquake and explosion sources by co-locating a chemical explosion with the hypocenter of a shallow earthquake and recording both events at a common set of sensors. For this endeavor, a shallow sequence of earthquakes that occurred in 1993 at the Rock Valley Fault Zone on the Nevada National Security Site (formerly the Nevada Test Site) has been targeted. 12 events in the sequence were large enough to be recorded both locally and regionally at distances of 200 km or greater. A temporary seismic station deployed directly over the sequence by the University of Nevada, Reno recorded short S-P arrival times confirming the shallow origins of the sequence.

In order to select a site for drilling, best estimates of the earthquakes locations and depths were required, as well as an understanding of the uncertainties involved. To address these issues, we examined relocations of nine of the events using four different location algorithms, multiple independent sets of phase picks, and a variety of regional and local velocity models. Results using different combinations of the algorithms, picks, and velocity models generally gave locations within approximately 1-2 km of each other. Narrowing to a single set of picks from correlation alignment and a common station constellation typically produced epicentral differences on the order of a few hundreds of meters and depth differences of a couple of kilometers for any single velocity model. S-P times at the closest station were used to further refine depth estimates to within one kilometer, depending on the velocity model. M. L. Pyle portion prepared by LLNL under Contract DE-AC52-07NA27344.SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Computation of High-Precision, Deep Magnitude Earthquake Catalogs on a Massive Scale

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The tremendous growth and availability of continuous seismic data over the past decades have posed challenges to building comprehensive catalogs of reliable earthquake parameters. But it also sparked the development of new methods for efficiently computing such catalogs at unprecedented resolution and scales, including millions of earthquakes and billions of measurements, and spanning decades of observations at local to plate tectonic scales. Here we show results from using supervised machine learning (ML) and waveform cross-correlation for (sub-noise) event detection and phase arrival and delay time measurement, unsupervised ML for event characterization and discrimination, inversion and grid search methods for accurate absolute hypocenter location, and double-difference methods for precise relative location. These tools are tailored and combined in computational workflows that efficiently handle massive amounts of data, both for retro-active and real-time processing, in regions of high-rate/high-density (e.g., volcano, induced) and low-rate/low-density seismic activity (e.g., stable continental regions). We focus here on one of the most challenging tasks, the assessment of robustness and effective resolution of the resulting catalogs. It is often unfeasible to obtain formal errors at these scales, but we show how statistical resampling methods can be used to evaluate the sensitivity of location estimates to measurement errors and choices of apriori information, and how the complementary nature of our data can be harnessed to evaluate estimates of measurement uncertainties. Finally, the accuracy of any earthquake catalog should be evaluated with respect to the scientific questions it is used to address, therefore additional information about the source (e.g., for studies of earthquake interaction) or tectonic setting (for fault studies) need to be incorporated. Several of the methods we discuss here are extensively used worldwide, and ongoing efforts within the SCOPED project focus on implementing these workflows on a hybrid cloud+HPC computational platform for use by the broader scientific community.

Manual Correlation of Seismic Arrivals to Improve Hypocenter Locations for the 1993 Rock Valley Sequence in Nevada

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Correlation analysis of the timing of seismic arrivals is a common procedure to improve locations, but can only be performed on events with similar magnitudes and that are near each other. The series of shallow events that occurred during the 1993 Rock Valley sequence in Nevada is targeted for investigating the difference between natural and explosive sources. These historic waveforms provide magnitudes up to ml 4.3 and we focus on a subset of wellrecorded events in the range of ml 2.5–4.3. Most of the waveforms for these largest events are clipped at the nearest stations, however, due to the geologic complexity of the region, traditional correlation methods were unable to provide consistent new arrival times. A consortium of scientists from five institutions individually picked the subset of events and produced an average pick difference of 0.05 s and median error of 0.02 s (when all 5 institutions provided picks). To build a common set of reviewed picks, the waveforms were manually correlated and visually inspected to provide a common pick within two samples for each event and station. When used to relocate the events, the common set of picks provided locations that trended closer to the expected fault orientations. These improved locations were then used to help provide constraints for the development of a testbed at Rock Valley to conduct chemical explosive tests for comparison to the earthquake events. *This work was done by Mission Support and Test Services, LLC, under Contract No. DE-NA0003624 with the U.S. Department of Energy and the NNSA Office of Defense Nuclear Nonproliferation. DOE/NV/03624–1538. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525*

Using Dense Nodal Geophone Data to Refine Rock Valley Fault Zone Earthquake Locations

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Analysis of earthquake locations using spatially distributed broadband seismic network stations provides well constrained hypocenters but can produce uncertainties of a few kilometers. To refine earthquake locations in the Rock Valley Fault Zone (RVFZ), we leverage a dense 3 component nodal geophone array to augment the regional seismic network operated by the University of Nevada, Reno (UNR). The geophone array is configured with 2 north-south trending lines approximately 5 km long, and 3 east-west trending lines ranging from 1 to 2 km in length. Geophone timing is evaluated against the permanent seismic station RTPP, located within 100 meters of the nodal array. Geophone arrivals are auto-picked using the Machine Learning (ML) application Earthquake Transformer (ET) for events, and event times from the UNR regional earthquake catalog. Quality metrics are applied to the ET geophone picks, including omitting stations with unfavorable noise characteristics or where the pick time deviates substantially from those made manually at station RTPP. Since this data set includes earthquakes as small as ml -0.5+ in the RVFZ, relatively fewer geophone picks are available for small events. Locations using both network and geophone array picks provide refined depth estimates and reduced error ellipses relative to locations using only network picks. Results are integrated into the Geologic Framework Model (GFM) of Rock Valley, a 3D earth model that includes seismo-stratigraphic surfaces and 3D fault models.

This work was done by Mission Support and Test Services, LLC, under Contract No. DE-NA0003624 with the U.S. Department of Energy and the NNSA Office of Defense Nuclear Nonproliferation. DOE/NV/03624--1539.

It's All About Relocation, Relocation, Relocation [Poster]

Poster Session • Thursday 20 April

Conveners: Cleat Zeiler, Nevada National Security Site (zeilercp@nv.doe.gov); Michelle Scalise, Nevada National Security Site (scalisme@nv.doe.gov); Ting Chen, Los Alamos National Laboratory (tchen@lanl.gov); Moira Pyle, Lawrence Livermore National Laboratory (pyle4@llnl.gov); Leiph Preston, Sandia National Laboratories (lpresto@sandia.gov)

A Comparison of High Precision Relocation Methods Applied to the June 2021 Mount Hood, Oregon Sequence

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High-precision earthquake locations can illuminate seismogenic structures at depth, elucidate the spatial and temporal history of those structures, and can aid in source determination. This is especially important near volcanic centers considering their geological complexity and the significant volcanic hazards. In this study, we compare three approaches to perform high-precision earthquake relocation using our enhanced Mount Hood earthquake catalog to analyze their efficacy in determining locations for low magnitude events and events with few observations, and discuss the generality and scalability of each method. The enhanced earthquake catalog includes the 166 earthquakes located by the Pacific Northwest Seismic Network to routine operations and 1572 detected earthquakes derived from waveform template matching. Since monitoring began in 1979, the June 2021 sequence is both the best recorded and the most seismically productive sequence at Mount Hood. We relocate events using three different methods: absolute (NonLinLoc SSST + Coherence), hierarchical clustering (GrowClust), and double-difference (HypoDD). Across the methods, it is clear there are at least two clusters of earthquakes, a large cluster 1-2 km from the summit to the southeast and a smaller cluster at the summit. Based on our preliminary analysis NonLinLoc SSST + Coherence locations produced precise earthquake locations on par with the relative relocation methods. The fact that this method preserves the absolute location of earthquakes in geographical space is an asset.

Absolute Relocations of a Machine Learning Catalog of the Utah Magna Earthquake Sequence Using Nonlinloc-Ssst-Coherence

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On March 18, 2020, a magnitude 5.7 earthquake hit the Salt Lake Valley in the state of Utah, USA. This mainshock triggered approximately 2600 locatable aftershocks over the following 18 months, a small but significant number of which were felt by the local population. Using a dense geophone deployment and machine learning (ML), an additional several thousand events were detected and located. Currently, both the mainshock and the majority of the aftershocks are suspected to have occurred on or near a deeper portion of the Salt Lake Segment of the Wasatch Fault, part of a large range-bounding fault system thought to be capable of generating a Mw 7.2 earthquake. However, a small subset of aftershocks may have occurred on a portion of the more steeply, eastern dipping and poorly understood West Valley Fault. Unfortunately, the catalog locations and lack of resulting focal mechanisms for this subset of aftershocks provides only a crude constraint on the true fault structure. To better illuminate structure, we relocate the UUSS catalog and larger ML generated catalog using: 1) NonLinLoc, a nonlinear location algorithm, 2) source-specific station terms (SSST), and 3) waveform coherence. We use the same regional 1D velocity model as is used for routine location in Utah for non-basin stations and a modified version of the model that includes a low velocity layer for stations located in the Salt Lake Valley basin. The locations achieved in this study suggest that the eastern events may have occurred on the Wasatch Fault, and indicate distinct, shallowly dipping, near-parallel planes in the seismicity near the mainshock, suggestive of multiple slip surfaces. These findings have direct implications to seismic hazard in the Salt Lake City metropolitan area. This research was funded by the National Nuclear Security Administration, Defense Nuclear Nonproliferation Research and Development (NNSA DNN R&D). The authors acknowledge important interdisciplinary collaboration with scientists and engineers from LANL, LLNL, MSTS, PNNL, and SNL. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Minimum 1D P- and S- Velocity Models Derived From Aftershocks of the March 31st, 2020 Stanley, Idaho Earthquake

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On March 31st of 2020, a magnitude 6.5 earthquake occurred in Central Idaho, 30 km northwest of Stanley, Idaho. To date, the main shock and the aftershocks have not been mapped to any known fault and understanding of the subsurface geology is sparse. For these reasons, a high-resolution 3D tomography model of this region is considered high priority. In preparation for the 3D tomography study, around 1,000 aftershocks were located using 13 temporary stations. These events were used to calculate a minimum 1D velocity model. The final catalog for this study includes 868 events all of which used at least 6 phases to locate the earthquake. A velocity model derived from a recent receiver function study was used for the initial locations. The final 1D minimum model was derived using the iterative VELEST software. Comparison between the initial locations and the relocations using the newly derived 1D model show a significant improvement in the quality of hypocenter parameters of the earthquakes using the in study. Since a minimum 1D model represents a solution to the coupled hypocenter-velocity problem, the final velocity model will be used in further analysis of earthquakes in Central Idaho. It is also an appropriate reference model for 3D tomography modeling using a larger earthquake catalog.

Relocation of Earthquakes in the Southern Korean Peninsula During 2017 and 2020 Using a 3D Velocity Model

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Improving the accuracy of hypocenter parameters, especially focal depth, is crucial for understanding seismotectonic characteristics of a region. In this study, we investigate the benefits of applying a three-dimensional (3D) velocity model to relocate the hypocenter of earthquakes occurred in the southern Korean Peninsula from 2017 to 2020. The availability of a denser seismic network in South Korea after two earthquakes of Mw 5.5 in 2016 and 2017 provides more direct phases close to the hypocenter, which can help to constrain the focal depth. After picking Pg and Sg phases within an epicentral distance of 80 km, we located earthquakes with local one-dimensional (1D) velocity models and a recently developed high-resolution 3D model for the peninsula. Earthquake location using 1D models was carried out by Hypoellipse (Lahr, 1999) and NonLinLoc (Lomax et al., 2000) algorithm was employed for the location using 1D and 3D models. It was found that the focal depths of earthquakes occurred in the southern Korean Peninsula show systematic discrepancies between the depths obtained from the 3D model and those from 1D models, which are consistent with the geological characteristics of the peninsula. This shows that the hypocenters determined from a 3D model would be useful to better understand the seismotectonics in the southern Korean Peninsula.

Uncertainty in Source Location Estimates Using a Single Seismic Station

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Poorly recorded seismic events, particularly small magnitude events occurring in regions with sparse station coverage, are often difficult or impossible to relocate using standard methods based on seismic arrival times. When data are only available from a single seismic station, distance and backazimuth may be estimated from the three-component waveforms, however polarization analyses and particle motion are highly sensitive to local variations in the wavefield. These localized variations make it necessary to include robust estimations of uncertainty when using these methods to identify the source region for a small natural or anthropogenic seismic event. Here we present single-station estimates of backazimuth and distance for a variety of well-recorded seismic events in the western U.S. to investigate the uncertainty associated with these source location estimates. We consider sensitivity parameters associated with data quality control (QC) and processing of the three-component waveforms for a range of source types including shallow crustal earthquakes, borehole explosions, and mining-related surface explosions. We utilize data recorded as part of the EarthScope Idaho-Oregon (IDOR) project as well as regional monitoring network data from Utah and Nevada. We compare results for backazimuth predictions from approximately co-located explosive and earthquake sources, as well as variations in the accuracy of source location estimations from stations at local to regional distances for a single event.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Legacy Seismic Data Collections: The Present State of and Future Outlook for Data from the Past

Oral Session • Tuesday 18 April • 02:00 PM Pacific

Conveners: Thomas A. Lee, Harvard University (thomasandrewlee@g.harvard.edu); Allison Bent, Natural Resources Canada (allison.bent@nrcan-rncan.gc.ca); Paul G. Richards, Columbia University Lamont-Doherty Earth Observatory (richards@ldeo.columbia.edu); Adam Ringler, U.S. Geological Survey Albuquerque Seismological Laboratory (aringler@usgs.gov)

Historical Seismograms of the South Pacific - Preserving and Utilizing a Unique 100-Year Continuous Record of Earth Observations

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Historic seismograms in New Zealand (NZ) are maintained by GNS Science as part of the nationally significant Earthquake Information Database (EID). The EID holds a unique, non-repeatable record of New Zealand and South Pacific seismicity dating back over 100 years. These original paper seismograms were recorded from 1900 to 2005 and extend across all of mainland New Zealand. It also includes records from nearby South Pacific Islands to Antarctica and consists of over 1,000,000 individual records.

Preservation of these records is particularly critical in the South Pacific because researchers need to utilize all available information for understanding historic long cycle geological events. This is especially true in a place like NZ with a relatively short history of human occupation but frequent damaging geohazard events. Ongoing research into historic NZ seismicity requires a well-managed, curated, and publicly searchable collection of records. Recently GNS Science has embarked on efforts to catalog all predigital instrumental records, digitize published bulletins, scan significant earthquake collections, and publish a report documenting instrument metadata and deployment dates. This fundamental information about the collection is available online.

Increasing the utility of our paper seismogram collection and felt reports will enable future research and facilitate investment in digitizing records. We will summarize some challenges and successes during recent digitization work including a case study on a pair of tsunami earthquakes from 1947. This is to highlight our efforts to encourage investigations into historic seismicity by early career researchers and ultimately safeguard these records through their utilization.

European Efforts for Legacy Seismograms Preservation and Use: The Esc Wg on Seismological Legacy Data and the Seismostorm Project

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Pre-digital ground-motion recordings were mostly made with ink on white paper, scratching black-smoked paper, or light on photographic paper. While analog seismic records provide unique continuous observations from the last century, the majority of them are now stacked and archived in boxes, potentially vulnerable to physical decay and permanent loss. It is critical to scan and digitize those records in order to preserve them and eventually subject them to modern methods of analysis. The ESC Working Group 02-12 "Preservation, valorization and analysis of seismological legacy data", is working on activities to improve the preservation and valorization of legacy seismograms and related documents. We discuss the current status of some of these activities, particularly an updated census for legacy seismological data in order to generate an updated inventory of such data preserved in Europe, of which we present the main elements and preliminary results. Its global expansion in the near future is expected. The WG also works on stimulating new research using legacy seismograms, defining preservation methods and scanning standards, and improving methods for automatic digitization/vectorization. In that context, we also present the SeismoStorm project, a Belgium-funded project that connects seismology with legacy data and ocean climate science. A method for extracting microseismic ground-motion periods and amplitudes from paper seismograms was developed by first using image processing and machine learning to digitize seismic time series. The project focused on legacy data from Belgium's Royal Observatory to extract power spectral densities generated by major storms over the last century. These were compared to modeled microseism levels computed using a numerical ocean wave model. The results demonstrate how digitizing analog seismograms not only preserves scientific legacy but also allows for new research by bringing analog data into the digital age.

The Electronic Archive of Printed Station/Network Bulletins at the ISC

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The International Seismological Centre (ISC, www.isc.ac.uk) has recently launched a new service, the ISC Electronic Archive of Printed and Network Bulletins (Di Giacomo et al., 2022). The archive allows users to obtain scans of instrumental seismic bulletins containing parametric data of either a single station or a network. The search for scans is based on the location of the town of an institution that produced a bulletin. As such, the electronic archive is easy to use and is likely to facilitate the work of a wide community interested in studying past earthquakes and involved in preservation and digitization of analogue recordings. We shall provide examples illustrating this service. Although the ISC archive is likely to be the most comprehensive of its kind, we know that many more bulletins could be added and certain gaps in scans could be filled. Hence we invite contributions from archives around the world as well as from individual investigators that wish to preserve and allow use of printed bulletins to the geoscience community for years to come. References: Di Giacomo, D., Olaru, D., Armstrong, A., Harris, J. and Storchak, D.A. (2022). The ISC Electronic Archive of Printed Station and Network Bulletins, Seism. Res. Lett., 93 (2a), 749-752, doi: https://doi.org/10.1785/0220210262

The Air Force Technical Application Center Efforts to Collect, Preserve and Integrate Historic Geophysical Data

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During the past decades, AFTAC geophysicists, recognizing the importance of preserving analog historic data, have led various internal efforts to rescue and preserve legacy geophysical records. We will discuss the efforts and approaches we use to collect and integrate historical nuclear explosion data into our systems and to leverage its use to support our operational and research needs. The development and use of uniform and systematic quality control measures and metadata standards is an integral part of our prioritization processes for inclusion of event data into a curated reference database. We also developed procedures to identify 'continuous stations' (stations that recorded historic events and continue to operate in the present) that may provide long-term empirical data. In addition, we will share some of the challenges and lessons learned in our race against time to preserve and maximize the use of this unique, invaluable, and irreplaceable resource while facilitating the transfer of technical and scientific knowledge from older to younger generations.

An Update on the Development of the Digitseis Software

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Legacy seismic data are a valuable resource for studying seismically recorded events from the past century and long-term processes such as the earthquake cycle or climate change. However, before legacy data can be processed using modern analysis techniques, they must be converted from their analog form to a digital image and then digitized into time series. Furthermore, working with the analog seismograms will become more difficult with time as they are deteriorating rapidly with age. The enormous number of analog recordings that exist around the world in combination with deterioration and increasing costs associated with storage, mean that many of these seismograms are in danger of being lost.

Efficient and accurate digitization software is crucial to efforts to save and utilize these historical seismograms. DigitSeis is one of several softwares which can take a digital image and convert it into either digital time series or a set of xy-position values of the seismic traces. Since it was first released in 2016, continuous improvements have been made to this software. These improvements have targeted functionality, efficiency, accuracy, and robustness as well as usability.

Here, we overview a sampling of records which showcase some key features and capabilities of DigitSeis. In particular, we examine several records from both the Harvard Seismographic Observatory (HRV) and the World-Wide Standardized Seismographic Network (WWSSN) that demonstrate how these new features allow for easier handling of crossing traces as well as displaying convincing replication of original records. We also present a few records showing features of paper records or their scans that can be problematic for digitization, highlighting the need for careful handling and attention to detail in preservation. Finally, we provide a look at the directions in which DigitSeis is being further developed.

Legacy Seismic Data Collections: The Present State of and Future Outlook for Data from the Past [Poster]

Poster Session • Tuesday 18 April

Conveners: Thomas A. Lee, Harvard University (thomasandrewlee@g.harvard.edu); Allison Bent, Natural Resources Canada (allison.bent@nrcan-rncan.gc.ca); Paul G. Richards, Columbia University Lamont-Doherty Earth Observatory (richards@ldeo.columbia.edu); Adam Ringler, U.S. Geological Survey Albuquerque Seismological Laboratory (aringler@usgs.gov)

Historical Nuclear Event and Collapse Data From the Livermore Nevada Network Between 1979- 1992

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Historical geophysical data recorded during the peak of nuclear testing is rare and limited. Efforts have been made to preserve and digitize data but have minimal quality control from decades of lost history and retiring personnel. Furthermore, recent research into the subsequent collapses of cavities is stifled by the lack of continuous records to investigate historical collapses.

The Livermore Nevada Network (LNN) was a 4-station seismic network in California, Nevada and Utah that recorded nuclear and tectonic events starting in the 1960s. Here, we present previously unreleased data from LNN between 1979 and 1992 containing over 100 recorded nuclear tests as well as over 50 collapses associated with a nuclear test. We will present the challenges and mitigation efforts we undertook to preserve and correct any errors in the digitization, waveform rotation and metadata.

Revisiting Earth's Inner Core: Historical Data Using Modern Approaches

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Careful analysis of what, at the time, were considered high-quality compressional phase data led Inge Lehmann to interpret the existence of a solid inner core in 1936. Greater understanding of the physical properties of the inner core came through normal mode observations studied by Adam Dziewonski and Freeman Gilbert in 1971. What makes the discovery of the inner core by Inge Lehmann even more remarkable was that it was done by way of analog records before any idea of broadband seismology or digital data existed. Along with identifying the existence of the inner core she was also able to estimate the radius of the inner core to be 1405 km (more modern models, such as ak135 estimate the inner core to be 1218 km).

To identify potential limitations produced by phase identification on historical instruments, which had less accurate timing and potentially higher noise than modern broadband instruments, we compare International Seismological Centre (ISC) archived phase arrivals between 1906 and 1935 to those obtained on modern broadband data. We also revisit Inge Lehmann's observations from a modern perspective by estimating uncertainties in the phase arrival information of the core triplication phases PKPdf, PKPab, and PKPbc. We then look at how these uncertainties propagate into uncertainty in the radius of the inner core by comparing these phase arrivals to those predicted by ray tracing using perturbations of the inner core radius of ak135.

Monitoring Climate Change With Seismology

Oral Session • Tuesday 18 April • 10:00 AM Pacific

Conveners: Michael G. Baker, Sandia National Laboratories (mgbaker@sandia.gov); Siobhan Niklasson, New Mexico Institute of Mining and Technology (sniklasson@lanl.gov); Robert Mellors, University of California, San Diego (rmellors@ucsd.edu); Allison Bent, Natural Resources Canada (allison.bent@nrcan-rncan.gc.ca); Robert Anthony, U.S. Geological Survey, Albuquerque Seismological Laboratory (reanthony@usgs.gov)

Climate Change Seismology

ASTER, R. C., Colorado State University, Colorado, USA, rick.aster@colostate.edu

The ubiquity of elastic wave energy in the solid Earth, oceans, and atmosphere and the growth of well-calibrated and otherwise high-quality global and freely accessible seismic data provide distinctive opportunities to measure and interpret multiscale signatures of climate change in the seismographic record. It was well known by the late 19th century that Earth experiences a continuous seismic excitation between approximately 8 and 30 s period. Corresponding oceanic microseism source and wave propagation processes were observationally and theoretically clarified by the mid 20th century and have appreciably advanced during the past decade. The microseism is a unique integrative proxy for ocean forcing of the solid Earth and the primary microseism in particular displays significant widespread secular changes spanning the past several decades attributed to increased wave energy in coastal regions. Another growing field of climate-associated seismology has evolved with recent general advances in cryoseismology ranging from the global observation of large-scale calving trends to studies of evolving firn, glacial, hydrological, and permafrost cryosystems. Transformative developments in data collection and "noise"-based time-lapse methods facilitate the study of cryosphere and hydrologic change via interpretations of seismic velocity variations driven by temperature, englacial or subglacial hydrology, and other seasonal and secular processes. Recent demonstration of ocean thermometry using near-repeating earthquakes and T phase propagation is further noteworthy given its emergent capability for resolving deep sea temperature change. In association with an ever-growing and globally integrated seismological data archive, and accelerating efforts in water column and seafloor global ocean seismic instrumentation, studies of ocean-sensitive signals offer particular promise for transdisciplinary oceanographic, climate, acoustical, and seismological collaborations and progress in understanding the evolving state of Earth's oceans and atmosphere.

Vertical-Slice Ocean Tomography Using CTBTO Hydrophones

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Monitoring the warming of the global ocean remains a challenging sampling problem because the observational coverage is limited. Seismic ocean thermometry (SOT) uses T waves from repeating earthquakes to infer large-scale averaged ocean temperature changes complementing existing in situ point measurements. We have previously used a T-wave station at the Diego Garcia atoll to demonstrate the merits of SOT. Compared to those land-based seismometers, CTBTO (Comprehensive Nuclear-Test-Ban Treaty Organization) hydrophones can record T waves with much lower noise levels and therefore allow us to use T waves from small repeating earthquakes (magnitude < 4.0) to improve the temporal resolution of the inferred temperature change. In this study, two CTBTO hydrophones in the Indian Ocean are used to capture ocean signals that include decadal warming, seasonal variations, equatorial waves, and mesoscale eddies. Compared to our previous single-frequency measurement scheme, here we also use the relationship between frequency-dependent T-wave travel time changes and depth-dependent temperature changes to conduct depth-slice tomography. The tomography results are consistent with our understanding of ocean dynamics and predictions based on the ECCO (Estimating the Circulation and Climate of the Ocean) state estimate. This application demonstrates the great advantage of hydrophone stations for applying SOT globally, especially in regions with low seismicity levels.

Deciphering Climate Information From Array Ambient Noise in Groningen

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Ocean waves, storing the information of climate change and celestial body movement, contribute significantly to seismic ambient noise. We collected seven-year continuous array seismic data in the Groningen area from 2016 to 2022 to investigate the spatiotemporal variations of offshore ambient noise. The spatial features of ocean waves were tracked through beamforming of seismic ambient noise. The lower-frequency sources, below 1.0 Hz, were tracked from the direction of the North Sea, and the higher-frequency sources were tracked from the direction of bocht van watum, which is a marine channel in Groningen. The frequency dispersion curves were extracted by the frequency-wavenumber analysis. To study the temporal features of seismic ambient noise, we conducted long-term time dependent frequency analysis, that revealed seasonal and annual variations of noise generated by the ocean over the last seven years. The time dependent spectra amplitude showed an obvious period of 29-30 days which related to the moon phase cycle. More interestingly, the relationship between seismic noise and North Atlantic Oscillation (NAO) was revealed. The seismic noise generated by the single frequency wave (SFW) in the band 0.16-0.20Hz and double frequency wave (DFW) in the band 0.30-0.36Hz have a positive correlation with NAO, whose trend is consistent with NAO. However, the seismic noise around 0.07Hz has a negative correlation and the oscillation phase reverse to that of NAO. These analyses show the potential of using existing off-shore seismic monitoring systems for studying global climate change and physical oceanography.

Seasonal Change at Shallow Depth in the Permafrost Region of Alaska From Seismic Noise

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The EarthScope Transportable Array and their succeeding network stations in Alaska have provided an excellent opportunity to monitor temporal shallow structural changes. We report our analysis from a simultaneous examination of (1) temperature, (2) vertical seismic data, (3) horizontal seismic data, and (4) wind data that can provide a unique perspective to the seasonally changing shallow process at each station.

Observations at some stations indicate a rapid, massive melting phenomena in the summer that causes a thousandfold increase in horizontal power spectral density (PSD). This rapid rise in horizontal seismic noise typically occurs in July, lasting about 30 days. The initiation of this major melting period does not happen immediately after the surface temperature exceeds 0^{o}C; instead, there is a delay of about a month. After the peak horizontal amplitude is reached, it gradually returns to the pre-melting level. Many stations show that this return occurs by the end of December; some stations, however, require until March or April to arrive back to their pre-melting level. For all stations, this return occurs well after the surface temperature becomes negative in September or October. These observations suggest that the melt layer remains at depth as temperatures drop below freezing, perhaps sandwiched between the developing ice from the surface and the underlying permafrost ice. However, we noted some caution is required at a few stations because a transient surge in horizontal amplitudes seems to occur in February and November that appears to be correlated with winds. We summarize the temporal characteristics of individual stations and also the seasonal geographic patterns throughout Alaska.

Seismic Network Hardening Against Tropical Systems: A Tale of Two Hurricanes

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In 2017 Hurricanes Irma and Maria impacted seismic monitoring networks across the Caribbean including the Puerto Rico Seismic Network (PRSN). In the wake of Hurricane Maria only 3 stations continued to provide real-time data to PRSN and due to the destruction of critical communications infrastructure data was not exporting to federal partners, particularly the Tsunami Warning Centers and the National Earthquake Information Center. Tropical systems such as Irma and Maria will happen again in the future, so a collaborative project between the PRSN and the USGS was undertaken to not only restore the network but also harden the network against these future events. In the five years since hurricanes Irma and Maria PRSN has undergone significant changes in its network instrumentation, telemetry, and systems. Changes to the network include but are not limited to the implementation of post-hole seismometers, the development of a satellite backbone network, and the implementation of the Advanced National Seismic System Quake Monitoring System (AQMS). In this presentation an overview of these changes and the challenges and lessons learned during implementation will be discussed. The network hardening is already showing benefits as in the network improvements played a critical role in the response to the M6.4 January 6, 2020 earthquake. Additionally in September 2022, the southern and western region of Puerto Rico was hit by Hurricane Fiona. While Fiona was a weaker hurricane than Maria it was a direct hit on Mayaguez where PRSN is located. Critically, data from the PRSN network continued to flow locally as well as to external partners for continuity of operations. While Fiona has provided its own lessons for future operations in tropical systems, the performance of the improved infrastructure demonstrates the benefits of network hardening against tropical systems.

Monitoring Climate Change With Seismology [Poster]

Poster Session • Tuesday 18 April

Conveners: Michael G. Baker, Sandia National Laboratories (mgbaker@sandia.gov); Siobhan Niklasson, New Mexico Institute of Mining and Technology (sniklasson@lanl.gov); Robert Mellors, University of California, San Diego (rmellors@ucsd.edu); Allison Bent, Natural Resources Canada (allison.bent@nrcan-rncan.gc.ca); Robert Anthony, U.S. Geological Survey, Albuquerque Seismological Laboratory (reanthony@usgs.gov)

Changing Climate and Microseismic Noise in Alaska

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Arctic Climate is changing much more rapidly compared to the rest of the world. Numerous studies suggest an increase in the number and strength of extratropical cyclones along with the poleward shift of storm track over the years. These changes in the pattern can be accompanied by severe weather conditions such as winter storms, the build-up of waves and storm surges, or extreme precipitation events. Sea ice extent, on the other hand, has been declining since 1979 continuously in each month of the year. Historical reconstructions and palaeoclimate evidence suggest that Arctic sea ice loss in summer months since 1979 is unprecedented in the past 1000 years. Arctic sea ice decline, coupled with changing extratropical storm patterns, are resulting in rampant coastal erosion and pose severe threats to the arctic communities and ecology. Ocean storms have long been understood to be the primary driver of microseism noise. Sea ice, on the contrary, suppresses the wave action on oceans dampening microseism production. The objective of our study is to identify how these ocean processes are linked to microseismic noise across the Alaska Seismic Network and by doing so obtain the ability to track, monitor, and forecast the impacts of these arctic changes. We find that waves in the Gulf of Alaska tend to create higher amplitude microseisms than waves of equivalent height in the Bering Sea. We trained a machine learning algorithm to predict microseismic power from significant wave height and sea ice concentration data with substantial accuracy. Feature importance from the model suggests that sea ice build-up close to the coast is what plays the major role in dampening microseismic noise. We also provide baseline observations for tracking microseismic noise and quantify the spatial and seasonal variation of the microseismic noise in different bands. Finally, we provide insights into the increasing coastal erosion period over the years. These patterns suggest more rapid coastal erosion in the future.

Estimation of First-Year Sea Ice Thickness With Seafloor Distributed Acoustic Sensing Using Flexural-Gravity Waves From Environmental and Anthropogenic Sources.

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Monitoring programs for sea ice thickness currently rely on estimations of freeboard height collected by satellite-based instrumentation. These methods, however, provide only kilometer-scale resolution and may suffer data blackouts in regions with excessive surface ponding or where high density ice pack prevents measurements of local sea level. Here, we show that distributed acoustic sensing (DAS) on a trenched seafloor telecommunications cable in shallow (<10 m) coastal waters at Oliktok Point, Alaska, can be used to provide estimates of sea ice thickness by inverting for flexural-gravity (FG) wave dispersion curves. We use data from multiple one-week campaigns during the winters of 2021 and 2022, the first such DAS data ever recorded beneath ice-capped waters. We leverage a variety of FG wave sources, including environmentally-driven icequakes, a commuter hovercraft, and ice road traffic. These sources generate short-to-mid period (0.5–20 s) FG wave trains that propagate coherently for several kilometers and are observed by the seafloor DAS via hydrostatic pressure transients. Dispersion curves may be extracted with established array processing techniques, with an assumption of near-field radiation patterns. Using a simple grid search across candidate snow, ice, and water thicknesses, we then estimate ice thickness by minimizing the misfit between observed and predicted FG wave dispersion curves. This method has potential for site-specific monitoring of sea ice at spatial and temporal resolutions greatly exceeding those of satellite-based methods.

SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Ross Ice Shelf Micro-Icequakes and Ocean Swell Induced Seismicity

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Seismological deployments spanning the Ross Ice Shelf (RIS) have provided substantial data to interpret the physical processes taking place across the ice during an era when many Antarctic ice shelves are undergoing mass loss through calving and basal melting processes (Rignot, et al., 2013). Thirty-four broadband seismic stations deployed across the RIS continuously collected data at high-sampling rates (100 and 200 S/s) between 2015-2017 (e.g., Bromirski et al., 2015). Interpretations of these data paired with satellite imagery and other constraints have identified multiple seismogenic phenomena related to rifting, fracture, calving, and flexure of the ice shelf induced by oceanic forcing across tidal, tsunami, infragravity, and ocean swell periods. Wave impacts and fracture near the ice front create micro-icequakes, particularly in the summer when ocean swell (periods of 8 to 30 s) is not attenuated by sea ice in the Ross Sea. For certain three-week periods in the multi-year dataset, stochastically swell-synchronized seismic events are observed to generate swell-harmonic spectral peaks in long-widow-duration spectrograms. Components of this signal have been interpreted as the multistage failure of near-front crevasses that can culminate in calving. We are establishing a catalog of such events spanning the complete RIS/DRIS seismic dataset to further interpret seismogenic phenomena associated with near ice-front fracture and calving, and to better understand temporal and other characteristics using matched filtering, envelope beamforming, and single-station seismic signatures. Additionally, seismicity associated with the cataloged swell-synchronized events will be compared with several ocean state parameters to investigate the hypothesized (Aster et al., 2021) controlling mechanism(s) of the events. The high temporal resolution of these seismic observations may uniquely provide valuable insights into the synchronicity of the compounding inputs which stress the ice shelf and ultimately result in ice mass loss.

Using Distributed Acoustic and Temperature Sensing to Characterize the Rapidly Changing Nearshore Arctic Ocean (PEMDATS)

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The Arctic is outpacing the rest of the world in its response to climate change. Distributed fiber optic sensing (DFOS) data is increasingly being used to characterize nearshore oceanographic processes from the seabed to the sea surface. For the first time we will be demonstrating the use of both distributed acoustic and temperature sensing data to characterize the nearshore Arctic seismic seabed structure. The PEMDATS project will acquire both unconventional and traditional acoustic signals, in addition to seabed temperature, along ~35 km of commercial dark fiber cable that extends offshore from Oliktok Point, Alaska into the Beaufort Sea. Our main goal is to assess the potential for using DFOS to map the evolution of degrading permafrost, associated gas hydrate deposits, and seafloor seeps. Acquiring colocated acoustic and temperature information creates a unique data set that allows us to image the seabed in multi-physical dimensionality across all seasons. Remote operation of this data acquisition system provides a use case that brings together new sensing modalities under climate relevant applications. We will show initial DAS and DTS data and processing results that set the stage for the upcoming characterization of the nearshore submarine permafrost and seabed structure. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

Multi-scale Models for Seismic Hazard Analysis

Oral Session • Thursday 20 April • 02:00 PM Pacific

Conveners: Kim Olsen, San Diego State University (kbolsen@mail.sdsu.edu); Evan Hirakawa, U. S. Geological Survey (ehirakawa@usgs.gov); William Stephenson, U. S. Geological Survey (wstephens@usgs.gov)

Multi-Scale Imaging of the Ridgecrest Area With Full-Wave Inversion of Regional and Dense Seismic Datasets

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There are several regional seismic velocity models for Southern California (e.g., CVMH, CVMS), but validation studies show that they all have poor resolution at the top 1-3 km of the crust, probably due to the lack of high-frequency input data. After the 2019 Ridgecrest mainshock, dense 2D and 1D nodes were deployed in the area with station spacings of ~5 km and ~100 m, respectively. Using data recorded by regional stations and those nodes, we aim to build a multi-scale velocity model via full-wave inversion of waveforms of numerous aftershocks and Green's functions from ambient noise interferometry. The developed model will be self-consistent with detailed structures of rupture zones and the shallow crust embedded in the regional model. The regional model is inverted with a spatial grid of ~200 m from data recorded by regional stations and the 2D array. The rupture zone and shallow crust models are further refined by updating the regional model using local earthquake signals recorded by the dense 1D arrays and local grid size of 25 m. Waveforms from local events can be recorded with high SNR for frequencies of 10 Hz or more, capable of resolving small-scale features with size of ~50 m or less. The developed model can illuminate the multi-scale structure around fault zones and with depth, and it will allow deriving more accurate earthquake locations and source properties. The multi-scale model will also provide an improved framework for simulating dynamic earthquake ruptures and seismic motion.

Fusion of Multi-Resolution Seismic Tomography Maps Using Physics-Informed Probability Graphical Models

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The resolution of velocity models obtained by tomography varies due to the inversion approach, ray coverage, etc. Fusing tomography models with different resolutions are desired in many cases, such as in updates of community models, or to enable more accurate ground motion simulations. Fusion involves the appropriate weighing of the internal velocity structure in each model. Simple combining the velocity model with edge interpolation may bias velocities along the edges of the models that are combined. Here, we propose an approach to fuse multi-resolution seismic tomography models with physics-informed probability graphical models (PIPGMs), which takes the physical information (ray-path density and gradient of the low-velocity zone) into consideration. We present the corresponding relation between subdomains with multiple resolutions, in terms of high-resolution (HR) and low-resolution (LR) component areas. By transferring the distribution information from the HR to the LR parts, the details in the LR areas can be enhanced by solving a maximum likelihood problem with prior knowledge from the HR models. To evaluate the efficacy of the PIPGM fusion method, we employ the fusion method on both synthetic checkerboard models and a fault zone structure imaged from the 2019 Ridgecrest, CA, earthquake sequence area. The Ridgecrest fault zone model consists of high-resolution Rayleigh velocities obtained from ambient noise tomography, which is embedded into the regional Southern California Earthquake Center Community Velocity Model (CVM) version S4.26-M01. The proposed method improves the combined models under multiple evaluation metrics, including travel time residual, compared to those obtained by multiple conventional methods. The proposed fusion method can merge any type of gridded multi-resolution velocity models and may provide a valuable tool for seismic tomography and hazard monitoring.

Fault Damage Zone Effects on Ground Motions During the 2019 Mw7.1 Ridgecrest, CA, Earthquake

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We have simulated 0-3 Hz deterministic wave propagation in the Southern California Earthquake Center Community Velocity Model (CVM) version CVM-S4.26-M01 for the 2019 M7.1 Ridgecrest earthquake. A data-constrained high-resolution fault-zone model is incorporated into the CVM in order to investigate the effects of the near-fault low-velocity zone (LVZ) on the resulting ground motions, constrained by strong motion data recorded at 161 stations.

The finite-fault source used for the simulation of the Ridgecrest event was obtained from kinematic inversion, enriched by noise following a von Karman correlation function above about 1 Hz with an omega-squared high-frequency decay. Our results show that the near-fault LVZ inherent to the fault zone structure significantly perturbs the predicted wave field in the near-source region, in particular by more accurately generating Love waves at its boundaries. Furthermore, the presence of the fault zone structure imbedded in the CVM increases the peak ground velocities in the western Los Angeles Basin (about 200 km from the source). The fault zone structure generally improves modeling of the long-period features in the data and lengthens the coda wave trains, in better agreement with observations. The favorable fit to data was obtained with a model including high-resolution surface topography, a 700 m-thick geotechnical layer (GTL) and frequency-dependent anelastic attenuation in the model domain, with Qs=0.1Vs (Vs in m/s) and a powerlaw exponent of 0.5 for frequencies higher than 1 Hz. We recommend that surface topography, a calibrated GTL and a fault zone velocity structure, where available, be included in ground motion modeling to obtain the least biased fit to observed seismic data.

3-D Broadband Modeling of Near-Field Ground Motions and Deformation in Dynamic Rupture Simulations of the 2019 Ridgecrest Earthquake Including Fault Zone and Fault Roughness Effects

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We present large-scale modeling of near-field broadband (>5 Hz) ground motion parameters and deformation in dynamic rupture simulations of the 2019 Mw 7.1 Ridgecrest earthquake. We include an observationally constrained shallow low-velocity fault zone and band-limited self-similar fractal fault roughness. Fault roughness induces geometric and small-scale stress perturbations, which are effective in generating deterministic high-frequency radiation. The model also incorporates a strong velocity weakening rate-and-state friction law, complex non-vertical fault geometry, 3D velocity structure, high-resolution topography, 3D initial stress distribution, off-fault plasticity, and viscoelastic attenuation (Taufiqurrahman et al., ResearchSquare, 2022).

We examine different ground motion parameters (PSA, PGA, PGV, PGD) and compare them with observed seismograms and GMPEs. We are especially interested in the near-field, closer than 10 km to the rupture, where real observations of strong ground motions are sparse and GMPEs are poorly constrained. The modeled ground motion parameters exceed the empirical predictions close to the rupture zone (< 2 km), which is only partly explained by effects of the low-velocity fault zone. We discuss which (if any) surface observations can constrain the dynamics of earthquakes, in particular for rapidly decaying near-field source effects. For each examined parameter, we show how the values inferred from the surface compare to their equivalents inferred within the volume. We also analyze the distributions of plastic vs. elastic off-fault deformation and their partitioning into volumetric and shear components.

3D Seismic Velocity Model for the Eel River Basin Region and Ground-Motion Simulations for the 2022 Mw6.4 Ferndale, California Earthquake

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We simulate 3D seismic wave propagation from the 2022 Mw 6.4 Ferndale, California earthquake and compare synthetic ground motions (<2 Hz) with recordings. The simulations use a 3D seismic velocity structure obtained by embedding a model of the Eel River Basin into the USGS San Francisco Bay region 3D seismic velocity model – regional domain (SFCVM-R). The basin model consists of a 2D bedrock-depth surface which was originally interpolated by Graves (1994) from cross sections drawn by Ogle (1953). We insert this as a new surface into the regional 3D geologic model and fill the basin with properties appropriate for Quaternary sediments. We model three moderate earthquakes (Mw<4.5) with hypocenters close to the 2022 earthquake as point sources and compare synthetics with recordings in order to test the velocity model.

We model the 2022 Ferndale earthquake source as a left-lateral rupture propagating unilaterally to the east, with our preliminary models using an assumed randomized slip distribution generated using the Graves and Pitarka (2016) approach. Synthetic ground motions are significantly amplified in the low velocity Eel River Basin, where >1g acceleration was recorded and MMI VIII shaking was experienced. We interpret the amplification of ground motions to result from a combination of rupture directivity and basin response effects.

Network Seismology: Recent Developments, Challenges and Lessons Learned

Oral Session • Thursday 20 April • 08:00 AM Pacific

Conveners: William L. Yeck, U.S. Geological Survey (wyeck@usgs.gov); Kris Pankow, University of Utah Seismograph Stations (kris.pankow@utah.edu); Ranate Hartog, PNSN (jrhartog@uw.edu); Dmitry Storchak, ISC (dmitry@isc.ac.uk); William Barnhart, U.S. Geological Survey (wbarnhart@usgs.gov)

An Overview and Update on the Advanced National Seismic System (ANSS)

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The Advanced National Seismic System (ANSS) is a cooperative effort of Federal, State, and academic partners to provide authoritative and actionable earthquake information in the United States and US territories. Partners of the ANSS collect and analyze seismic and geodetic data on earthquakes, issue timely and reliable notifications of earthquake occurrence and impact, and provide foundational data for earthquake research, hazard characterization, and risk assessment. The ANSS consists of national elements including the National Earthquake Information Center, regional seismic networks operated by the USGS and/or State and university partners, and real-time geodetic networks. ANSS delivers a broad suite of earthquake data and information products, including catalogs of earthquake origins, magnitudes, and source characteristics (moment tensors, focal mechanisms, and finite fault models), earthquake waveforms and phase picks, strong motion records, impact products (Did You Feel It?, ShakeMaps, PAGER loss reports, ShakeCast, Ground Failure), operational aftershock forecasts, and origins for earthquake early warning.

Domestically in 2022, the ANSS reported on approximately 120,000 earthquakes, with event M4.5 and larger typically reported within 5 minutes of origin time. ANSS produced ShakeMaps for 969 earthquakes, moment tensor solutions for 260 earthquakes, PAGER loss report for 134 earthquake, and reviewed ShakeAlert origins for 52 earthquakes. This presentation serves to provide an overview of the current contributors and elements of the ANSS, and earthquake monitoring performance in the United States and territories. We will also highlight ongoing development opportunities and activities within ANSS focused on improving regional earthquake response capabilities and earthquake analysis capabilities in high-risk urban areas.

ISC: Collaborating with ~150 Seismic Networks

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The mission of the International Seismological Centre (ISC) is to produce the most long-term and complete Bulletin of instrumentally recorded seismicity on a global scale in collaboration with ~150 seismic networks in ~100 countries. Parametric data collection from these networks has proved challenging during the recent pandemic years. The ISC is also obtaining some useful event source parameters by using station waveforms freely available on-line from a number of dedicated data centres. We also produce several specially designed data products that stem from the ISC Bulletin and allow ISC to assist several different areas of seismological research. These include the ISC-EHB dataset (1964-2020), ISC-GEM catalogue (1904-2019), IASPEI Reference Event List (GT, 1959-2020), ISC Event Bibliography (1904-2023). We also maintain the supplementary datasets: the Electronic Archive of Printed Station/Network bulletins, the ISC Dataset Repository and the International Seismological Contacts.

Error Estimates for Seismic Body Wave Delay Times in the International Seismological Centre's Bulletin

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A cumulative half century of openly accessible global seismic phase arrival time data at the International Seismological Centre (ISC) presents an opportunity to independently asses their errors and how these might vary with epoch, epicentral distance, hypocentral depth, phase identity, and other factors. To separate the effects of Earth structure on the errors from measurement errors we constructed a large tomographic matrix for each of nearly 20 thousand earthquake clusters, using delay time data from the years 1964-2018 in the most recent version of the ISC-EHB bulletin. We applied a singular value decomposition to these matrices and estimated errors from the transformed data vectors belonging to the least significant singular values, i.e. those not related to Earth structure. Using a robust initial estimate of the standard deviation of the clustered delay times, we removed a small fraction of outliers before calculating the ultimate errors. We found that the errors depend on the phase identity, and hypocentral depth (crust or mantle), slowness, as well as on the precision with which the arrival times were reported. The epoch in which the arrival time was reported does not significantly affect the error estimates. Using these parameters, we distinguish 45 different classes of delay times for 11 different types of body waves. The errors for each class generally are normally distributed with means that range from 0.32 s for PKPbc waves from mantle earthquakes to 2.82 s for S waves from shallow earthquakes bottoming in the upper mantle. The uncertainties in the errors themselves are around one third of the estimated error, with two outliers at 10 % and 50 %, rendering the estimated errors representative in formal statistical quantification of the quality of fit in tomographic experiments.

A One-Stop Shop for Network Status? Developing an Application for a Diverse Set of Users

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The Pacific Northwest Seismic Network (PNSN) is responsible for monitoring seismic activity in WA and OR and is also part of the USGS ShakeAlert earthquake early warning system. Fulfilling our role effectively requires monitoring metrics related to state of health, telemetry, waveform quality, site noise, and those specific to ShakeAlert. We store, view, and mine these metrics using SQUAC, the Seismic Quality Assessment Console https://github.com/pnsn/squac/wiki. SQUAC consists of a backend database with an API for interfacing, a user-friendly python client to simplify reading and writing, and a web-based GUI with dashboards and alarms. We currently collect or calculate about fifty metrics internally from thousands of channels from ANSS regional seismic networks. External partners are also contributing to the database. Most metrics are calculated every ten minutes, hourly or daily with little lag from real-time. Millions of measurements are added each day to the database which currently has about two billion rows. Recent updates to improve usability include automatic updating of channel groups, new plot types displaying metrics by hour-of-day or hour-of-week, and a configurable alarm summary to customize notification frequency. SQUAC has been designed with diverse users in mind, from field techs monitoring and troubleshooting station health, to network seismologists data mining the database to investigate questions like ideal station distance from roads, to an easy-to-share and easy-to-modify dashboard showing ShakeAlert station acceptance status.

The Effects of Seismic Network Modernization on Earthquake Detection and Analysis in Southern California

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The growth and modernization of seismic networks is typically assumed to benefit detection and understanding of seismic activity. However, the location and set-up of new seismic stations is very important for making this a reality. Over the past ~17 years, efforts have been made to modernize operations of the Southern California Seismic Network. These efforts have included adding new stations, upgrading equipment, and improving data analysis software and procedures. In this presentation, we evaluate the effects of the modernization efforts on our earthquake detection and analysis capabilities. We examine the magnitude of completeness (Mc) for the earthquake catalog as a whole and for specific regions that have been a focus for improvements, such as the Salton Sea. The overall Mc appears to have had only a small decrease over the study period. We also consider other measures of catalog and detection limitations that depend on the network geometry. The results of these analysis will help guide future improvements and adjustments of the seismic network.

Evaluation of Machine Learning Assisted Earthquake Phase Detection Performance in Different Tectonic Regions and Environmental Noise on the Alaska Seismic Network

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Many available machine learning (ML) phase-detection algorithms promise real-time monitoring applications and to be broadly transferable across different seismic regions when trained on a global dataset. One such algorithm, Earthquake Transformer (EQT), developed by Mousavi et al. 2020, is repeatedly used by the research community to generate localized earthquake catalogs in various tectonic regions. We systematically apply the global pre-trained EQT package to disparate seismogenic regions in Alaska as a first assessment of ML-assisted, phase-picking competency on the Alaska Seismic Network.

We select three regions with varying station azimuthal coverage, environmental noise, and seismicity characteristics to evaluate overall ML performance. We define the minimum performance goal as reproducing the Alaska Earthquake Center's (AEC) existing real-time catalog. The three chosen regions are (1) Purcell Mountain in northwestern Alaska, (2) Andreanof and Fox Islands along the Aleutian Island chain, and (3) Yakutat and Icy Bay in southeastern Alaska. The Purcell Mountain region represents near-ideal ML conditions with moderate magnitude, shallow-crustal events recorded with good azimuthal station coverage and low environmental noise. The Aleutian and Yakutat/Icy Bay regions incorporate poor azimuthal station coverage and varying earthquake source characteristics in addition to volcanic and glacial signals, respectively. Application of EQT in each region produces an alternative earthquake catalog that is directly comparable to both the AEC's augmented STA/LTA monitoring catalog and analyst-reviewed catalog. Leveraging all three catalogs provides insights into the ability of ML to accurately detect seismic arrivals in the wide range of conditions present in Alaska.

Deep Learning-based Detection of Explosions and Earthquakes in South Korea

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The classification of earthquake and explosive signals in seismology is imperative for understanding the physical mechanisms of explosions and for accurately analyzing and interpreting earthquakes. Individual signals can be classified as explosions and earthquakes based on physical factors such as differences in P/S amplitudes, differences between regional and coda magnitudes, and focal depths of earthquakes. However, accurate classification is occasionally not achievable when the data lay on the decision boundary of classifiers. Furthermore, as the magnitude of detectable events decreases due to improvements in networks and sensors, technologies such as machine learning that can automatically process substantial amounts of signals are required, and thus massive volume of label data are naturally needed to improve the performance of supervised machine learning. Located inside the Asian tectonic plate, South Korea has low seismic activity, which makes it easier to discriminate earthquakes and explosions generated from mining operations distributed across the country. In this study, we detect body waves from explosions and earthquakes using machine learning-based phase detection techniques applied to 421 stations in South Korea, which were augmented for early warning after recent two Mw 5 earthquakes. Automatically detected phases are associated into events based on the backpropagation method. We detected and confirmed ~150,000 events in 7 years from 2016 through 2022. Over 180 clusters containing more than 100 events were identified based on differential travel time measurements and clustering algorithms, and each cluster was classified as an earthquake or explosion based on the proximity of the epicenters to mines and consistency in onset times of day. We verified over 100,000 explosions from clustering analysis. They can be used for the discrimination of explosions and earthquakes and analysis of physical mechanisms of explosions. In parallel, the microseismicity is useful for characterizing previously unidentified fine-scale active faults, characterizing intraplate swarms, and analyzing aftershock sequences.

Routine $M_{w,\,coda}$ Calculation for Small Earthquakes in Utah

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Measuring M_w for small earthquakes is desirable in order to have a uniform magnitude catalog to compute accurate catalog statistics, such as *b*-value, and for earthquake hazard analysis. However, M_w is difficult or impossible to compute for events with $M_w < 3.5$ using traditional regional moment tensor analysis. An alternative is the S-wave coda $M_{w,coda}$ method outlined in Mayeda et al. (2003). $M_{w,coda}$ measurements are very stable due to the coda waves' relative insensitivity to source radiation pattern and path heterogeneity. The $M_{w,coda}$ method has been used to measure M_w in diverse regions worldwide, including the entire state of Utah as well as a more focused study of the March 2020 M_{ww} 5.7 Magna, UT earthquake and its aftershocks (Holt et al., 2021). $M_{w,coda}$ is effective for small magnitude earthquakes, down to approximately $M_{w,coda}$ 1.5 in Utah. Currently, no seismic network calculates $M_{w,coda}$ routinely. Here we outline the process for calculating routine $M_{w,coda}$ for Utah earthquakes with $M_L > 2.0$ and depth > 0 km in the UUSS catalog. We calculate $M_{w,coda}$ for such events from 2012 to present, and going forward will routinely calculate $M_{w,coda}$ on a daily or weekly basis. Shallow events are eliminated from the analysis because their $M_{w,coda}$ tend to be unreliable and overestimated due to an Rg-to-S scattering "bump" in the low frequency spectra. While this phenomenon makes measuring $M_{w,coda}$ difficult for shallow events, it could perhaps be used as a depth discriminant. We rely on several quality checks before adding an $M_{w,coda}$ to the catalog, including verification that the corner frequency is within the measured frequency range, and magnitude comparisons to M_L and M_e. Finally we calculate *b*-value using the traditional Gutenberg-Richter method as well as the more recent *b*-positive (van der Elst, 2021) for our new $M_{w,coda}$ catalog and compare to M_L *b*-values for the same events.

Improving the Detection of Microearthquakes Without Prior Events: Application to Large-N Arrays

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In recent years, the development of high-resolution earthquake catalogs has enabled new insights into earthquake source dynamics. These catalogs, which lower the magnitude-of-completeness, have been made possible by new data-dense seismic experiments (e.g., Large-N arrays) and advances in algorithms that include Template Matching (TM) and Machine Learning (ML). However, most TM and ML must be trained using prior events, which may not always be available. In this study, we explore a new approach for the detection of microearthquakes that exploits dense seismic network data to backproject waveform correlations or Local Similarity (LS) waveforms. The Local Similarity-Back Projection method does not require templates or training. Furthermore, it enhances signal-to-noise ratio (SNR) by stacking coherent signals thus enabling us to detect even smaller events. We apply the method to Large-N data including the IRIS Wavefield Experiment in Oklahoma. Continuous ground motion velocity data were processed to compute LS, which were then backprojected through grid-search over a volume of event hypotheses to find the best origin times and hypocenters. We demonstrate that this effort resulted in a 30-fold increase in detection as compared to analyst detection.

The Marsquake Service: Facing Off-World Challenges for Seismic Networks

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For more than four years the Marsquake Service (MQS) has been detecting and cataloguing marsquakes from the near realtime data recorded by SEIS, the seismometer deployed to the surface of Mars by InSight. With only a single station, there are obvious challenges in providing a catalogue for the entire planet. Due to the low SNR of marsquakes and the extreme variability of background noise, impulsive seismic signals are rarely evident and standard automated algorithms cannot be used to identify marsquakes, and manual review is needed. Here, we review the procedures and methods developed by MQS and describe the contents of the catalogue.The MQS tools are based on best practice and standards used in seismic networks on Earth, for example we use a single station interactive analysis GUI based on SeisComP. Consistent procedures were developed to distinguish marsquakes from atmospheric noise or other data anomalies, classify events, pick phases, determine distance using a suite of Martian velocity models which has been updated during the mission, determine back azimuth, and locate events. Mars magnitudes are assigned using calibrated magnitude relations including the use of P and S body phase amplitudes, 2.4 Hz resonance amplitude and spectral fitting. The final catalogue includes 1319 marsquakes. Six events are known meteoroid impacts confirmed from visual imaging, their proximity to the original MQS locations confirms our location methodology. The catalogue contains quakes from within 1 degree of the lander out to 146 degrees distance and moment magnitudes span from 1 to 4.6. Body waves, crustal phases, surface waves, atmospheric shock waves and even core phases have been observed. Future planetary missions or even remote single stations on Earth will benefit from the MQS experience and the catalogue will be the foundation for planetary seismicity studies in the coming decades.

Network Seismology: Recent Developments, Challenges and Lessons Learned [Poster]

Poster Session • Thursday 20 April

Conveners: William L. Yeck, U.S. Geological Survey (wyeck@usgs.gov); Kris Pankow, University of Utah Seismograph Stations (kris.pankow@utah.edu); Ranate Hartog, PNSN (jrhartog@uw.edu); Dmitry Storchak, ISC (dmitry@isc.ac.uk); William Barnhart, U.S. Geological Survey (wbarnhart@usgs.gov)

A Rotational Seismometer for Geohazards and Scientific Monitoring in a Regional Seismic Network (RSN)

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Observing seismic rotations of the ground and structures is a challenge at the advancing forefront of seismological monitoring. Incorporating ground rotations into monitoring at a regional scale fuels research and development of both instrumentation and theory. Combining pure point rotations and translational shaking at a site comprise a "6 degree of freedom" (6DoF) "mini-array". 6DoF observations can be used to infer the velocity profile at the site, help locate off-array events, and refine S-wave arrivals. Moreover, they contain information about inhomogeneity, anisotropy, near-field effects, structural damage, and phase conversions. And because rotations may contaminate translational sensors, they can help correct and reduce noise on traditional sensors. An RSN can use rotations in several settings to assist and enhance their missions. A critical goal currently of the RS effort is to measure pure wide-band rotations at the low-noise spectral model level. We have field-tested a new portable rotational motion sensor, the QRS quartz rotational seismometer. The QRS uses a load-sensitive resonant quartz crystal to measure the rotational torque sensed by a beam-balance angular accelerometer, providing inherently digital broadband observations of pure rotation. The combination provides improved insensitivity to translational motions and a lower noise floor than other similar-sized systems currently employed. During a 3-month long deployment of a QRS alongside a broadband seismometer in a quiet vault, we observed rotational and translational motions from several small (M<3) local and regional earthquakes as well as longer-period waves from large teleseisms. The noise floor was measured to be ~45 pico-radian/$Hz^{-1/2}$ at 1 Hz and ~23 pico-radians/$Hz^{-1/2}$ at 0.1 Hz, the sensor's resonant frequency. Among other similar-sized broadband rotation sensors this represents a lowering of the instrumental noise floor by more than two orders of magnitude.

An Updated Catalog of Seismicity for New Mexico

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Seismic monitoring in New Mexico began in 1962, when Dr. Allan R. Sanford, a professor of seismology at the New Mexico Institute of Mining and Technology, combined data from seismic instruments installed to monitor earthquakes from the Socorro Seismic Anomaly with data collected by the USGS, Los Alamos National Laboratory, the Air Force Technical Applications Center, and several universities in Texas to examine seismicity throughout the state. The first catalog of New Mexico seismicity was published in 2002, and included instrumented data from 1962-1998 as well as information about pre-instrumented earthquakes from felt reports beginning in 1869. The catalog was updated twice to include earthquakes through 2009. Earthquake locations and magnitudes were calculated using a program called SEISMOS that was developed to study earthquakes in the Socorro area, and magnitudes were calculated using duration magnitude.

In recent years, seismicity in New Mexico and the methods used to study it have changed significantly. Increasing numbers of induced earthquakes have occurred in the northeastern and southeastern parts of the state, and stations have been added in those regions to better study those events. TexNet began operating in Texas in 2017, and both Arizona and Colorado have built networks starting with stations from the Transportable Array that provide additional data that can be used to locate earthquakes in New Mexico. However, New Mexico still experiences naturally occurring seismicity in other parts of the state that are not fully instrumented, and there is a need to improve the overall level of seismic monitoring throughout the state. Despite the limited network, improved processing methods including using machine learning detection (using EasyQuake) have allowed us to detect events throughout the state and compute local magnitudes using Seiscomp. Here we present our updated catalog, assess the current magnitude of completeness in various parts of the state, and suggest improvements for the future.

Coordinating Access to Seismic Waveform Data in the Euro-Mediterranean Region: Orfeus Actions, Data Services and Products

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ORFEUS (Observatories and Research Facilities for European Seismology, orfeus-eu.org) is a non-profit foundation that coordinates and promotes seismology in the Euro-Mediterranean area and beyond, via harmonized collection, archival and distribution of seismic waveform (meta)data, services and products. ORFEUS is one of the founding members of EPOS Seismology (www.epos-eu.org/tcs/seismology) and ORFEUS services are largely integrated in the EPOS Data Access Portal (www.ics-c.epos-eu.org). ORFEUS comprises: (i) the European Integrated waveform Data Archive (EIDA; orfeus-eu.org/data/eida); (ii) the European Strong-Motion databases (orfeus-eu.org/data/strong); and iii) the recently established group representing the community of European mobile pools, including amphibian instrumentation (orfeus-eu.org/data/mobile). Selected products and services for computational seismology are also considered for integration. Currently, ORFEUS services provide access to the waveforms acquired by ~18,000 stations in the Euro-Mediterranean region, including dense temporary experiments (e.g., AlpArray, AdriaArray), with strong emphasis on open, high-quality data. Access to data and products is based on state-of-the-art technologies, with strong emphasis on federated web services, clear policies & licenses, and acknowledging the crucial role played by data providers. Significant efforts are underway, by ORFEUS participating institutions, to enhance the existing services to tackle the challenges posed by the Big Data Era, and to actively encourage interoperability and integration of multidisciplinary datasets in seismological and Earth Science workflows. ORFEUS implements community services that include software and travel grants, webinars, workshops and editorial initiatives. ORFEUS activities are routinely assessed and improved through the technical and scientific input of a User Advisory Group of European Earth scientists with expertise on a wide range of seismological disciplines.

Earthquake Monitoring Capabilities in Ohio: The Evolution of a Modern State Seismic Network in the Midwest USA

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Ohio has a long history of earthquake activity with historical records dating back to the founding of the United States. However, continuous instrumental recording of earthquakes did not begin until 1999. Since then, the Ohio Seismic Network (OhioSeis) has undergone several eras of configuration. Ohio sits between the Grenville Front Tectonic Zone, Rome Trough, and the New Madrid Seismic Zone, both regions with historical damaging earthquakes that have affected and still do affect the state. Naturally occurring earthquakes in Ohio are frequent (5–10 per month) but typically of lower magnitude. However, several M4–M5+ earthquakes have struck Ohio in the past several decades, causing damage. Future earthquakes in the region pose threats to transportation corridors, communications infrastructure, and nuclear power plants. More recently, oil-and-gas production, fracking, and wastewater injection within the state have increased demand for high-quality and timely seismic monitoring for public safety and operator regulation. Historically, Ohio was not considered an area in need of real-time seismic monitoring. However, increasing requirements for rapid post-earthquake solutions present challenges to efficient monitoring of these events. Currently, OhioSeis employs a small number of staff (3) that manages a statewide, complex network. Developing and fostering relationships with outside organizations not normally familiar to state geological surveys in the eastern U.S., such as IRIS, USGS, ASL, ISTI, LDEO, and others, has been critical to our success. Ohio has increased its seismic monitoring capability dramatically in the past seven years. OhioSeis transitioned from an educational seismic network to a research-quality network in 2016 using AQMS for managing 30-plus stations of 3-component broadband seismometers in surface and posthole vaults. Data are sent in real-time to the IRIS DMC and metadata are tracked with the Station Information System (SIS). Owing to the hard work of a small but dedicated staff, more research on Midwest seismicity is being published using data from OhioSeis stations.

Exploring Local Seismic Detection Capabilities Using Earthquake Triggered and Continuous Dataset Recorded by the Los Alamos Seismic Network

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Operated by Los Alamos National Laboratory located in Northern New Mexico, the Los Alamos Seismic Network (LASN) has monitored seismicity in the area since 1973. Local seismic monitoring by LASN remains a pertinent resource in understanding the seismic behavior and activity along the Pajarito fault system and Valles Caldera. Starting in 2019, LASN transitioned to recording continuous seismic data across the network. Prior to 2019 the network operated as a triggered system (recording only 10-minute segments of triggered events). As a result, LASN data mostly consists of discontinuous waveform segments across the network.

Since 2010, we have detected and located ~300 local earthquakes and added 11 stations to the LASN network (18 stations total) to extend its monitoring capability. To improve the magnitude of completeness in the LASN earthquake catalog and gain an understanding of the spatial-temporal behavior of seismicity in the local region, we apply a correlation detector to the continuous data. We utilize previously documented seismicity to extract earthquake templates and improve the detection of small magnitude events not previously catalogued. We present the results from the correlation detector and comparisons of detection capabilities between the triggered and continuous data.

Monitoring Volcano Hazards in the Cascades of Washington and Oregon: Recent and Ongoing Network Diversification and Advances

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The U.S. Geological Survey's Cascades Volcano Observatory (CVO) operates a geophysical network (CC) for monitoring hazards associated with the Cascades Volcanoes throughout Washington and Oregon. CVO's monitoring goals are to detect and interpret geophysical and geochemical phenomena to provide the public with early and accurate warnings of volcanic unrest and eruptions. Nine of these volcanoes are classified as high- or very-high-threat by the National Volcano Early Warning System [Ewert and others, 2018] due to their eruptive history, types of hazards, and potential impact to populations and infrastructure. In coordination with the Pacific Northwest Seismic Network (PNSN) and support from the UNAVCO GAGE facility, CVO has significantly expanded its regional volcano monitoring network and monitoring capabilities by adding more than 66 stations over the last 20 years. The CVO regional network of real-time stations includes a broad spectrum of stand-alone and co-located monitoring instrumentation (seismic, infrasound, deformation, gas, and cameras) with metadata and continuous data shared publicly in near-real-time at IRIS (ds.iris.edu/mda/CC) and daily GNSS data and metadata available from UNAVCO (https://www.unavco.org/data/gps-gnss/gps-gnss.html). CVO is continuously designing and developing more reliable and robust station design and infrastructure capable of operating in extreme environments, while also focusing on expansion of the network to under-monitored volcanoes. This multiyear coordinated effort has improved CVO's hazard detection ability and knowledge of individual volcanos background activity to better assess volcanic hazards in near-real time throughout Washington and Oregon.

Network Analysis of the University of Utah Seismograph Stations Regional Seismic Network

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The University of Utah Seismograph Stations (UUSS) operates a regional seismic network (RSN) and is authoritative for seismic monitoring in the Utah region. This network has grown from a sparse, analog, statewide network in the 1960s to the current network composed of 51 modern digital stations and 71 legacy analog and short period stations. Geographically, the focus of the RSN is concentrated in the region of highest seismicity along the Intermountain Seismic Belt for earthquake location and characterization. The goal of this study is to use a data-driven approach to assess the current combined digital and analog seismic network and provide a prioritized list of analog stations needing upgrade, removal, or re-location. Problematic noisy stations may prove to be ineffective and are strong candidates for upgrades or removal when considered within the overall network geometry. These decisions can be performed objectively, and without bias using network detection modeling that uses both station noise characteristics and network geometry. Here, we extend previous network detection modeling work to the UUSS RSN using a subset of the UUSS earthquake catalog. Specifically, we combine source, magnitude, and distance information from analyst-located events in the UUSS catalog from 2011-2021 with noise characteristics from individual stations. The algorithm used in this study was originally designed for the central and eastern U.S. and in applying it to the Utah region, we derive a new distance-magnitude relationship for this RSN. This study provides a means to improve the UUSS regional seismic network based on a data-driven approach.

Network of the Americas Borehole Strainmeter and Seismic Network: Network Highlights at 15 years plus of Continuous Operation

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The Network of the Americas (NOTA) Borehole Strainmeter and Seismic (BSM) Network was installed between 2005 to 2009 as part of the NSF-funded Earthscope MREFC Plate Boundary Observatory (PBO). The network has continuous data collection for up to 18 years consisting of 73 sites, with 6 additional seismic only borehole sites, clustered around areas of geophysical interest such as observing slow slip along the Cascadia Subduction Zone from Vancouver Island through Northern California, the Mendocino Triple Junction, sections of the San Andreas Fault that observe creeping to locked zones as well as transition zones, the Eastern CA Shear Zone, Yellowstone Caldera, and St Helens Volcano. Subsequent to the original PBO network, 4 stations from the CALIPSO network in Montserrat, 6 strainmeters from the GONAF network in Turkey, and 6 strainmeters from the TABOO-STAR network in Italy are also maintained by NOTA and provide data to the archive. Throughout the NOTA BSM network, the Gladwin Tensor Strainmeter (GTSM) is grouted near the bottom of the borehole with a Malin 3-component 2 Hz Geophone Borehole Seismometer above. Instrument depths range from 76 to 243 meters, determined by the downhole geology. 10 volcano sites include Lily Borehole Tiltmeters and 27 sites include pore pressure sensors.

In celebration of the BSM network at 15 years of operations we will share network highlights, such as observing the 2019 Ridgecrest and other plate boundary geophysical events. Strain data has been used to create Peak Dynamic Strain models, which give an event magnitude estimate from the Gladwin strainmeters. With an aging network there is the constant assessment of replacing old technology with newer technologies and will share our direction for the future of the BSM network. All NOTA BSM data is available at the EarthScope Consortium DMC as the PBO Borehole Seismic Network (FDSN code PB) and has near-real-time data flow capabilities. Strain data is also available as network code GF (Geophysical Borehole Observatory at the North Anatolian Fault) and IV (Italian Seismic Network).

Portable Volcano Monitoring Station for Rapid Response

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The U.S. Geological Survey Cascades Volcano Observatory (CVO) monitors very-high-threat and high-threat volcanoes in the Cascade Range of Oregon and Washington. CVO's mission is to detect and monitor signs of volcanic unrest and communicate hazards to the public in order to mitigate risk. Often, a critical need during a volcanic emergency is to improve seismic monitoring. Installations of CVO's permanent and temporary volcano hazard monitoring stations are limited due to their size and weight and require road access or helicopter support for any remote installation. To enable the rapid deployment of seismic stations in remote areas and increase the number of stations that can be deployed in a day, CVO has developed a prototype for a portable real-time seismic station by paring down a temporary seismic station to the essentials and making it as light and transportable as possible. In this design, weight and bulk were reduced by using lithium iron phosphate batteries, a carbon fiber mast, a lightweight waterproof enclosure, and a foldable solar panel. The design allows for establishing real-time telemetry utilizing cellular technology, digital radios, or a combination of both. At roughly 160 lbs, a complete station can be packed into a remote area by a team of four. The ability to rapidly hike in and deploy new stations is an invaluable addition and significant improvement over CVO's existing temporary seismic cache. This cache of portable stations will increase CVO's ability to rapidly densify a seismic monitoring network during a period of unrest, using fewer resources.

Science Communication, Outreach, and Community Engagement in Harmony With Real-Time Network Operations

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Prior to 2010, Oklahoma experienced approximately 2 M3.0 or greater earthquakes per year. That background rate of earthquakes rapidly increased so that 579 and 903 M3.0 or greater earthquakes occurred in 2014 and 2015, respectively. A broad consensus in the scientific community of the causal link between deep wastewater disposal near the Precambrian basement led to regulatory actions, which, in combination with a market decline, drastically reduced seismicity. In the last several years, some earthquakes (sometimes M3.0+) have been triggered by hydraulic fracturing. Though out of greater than 3,000 completions we found only a small percentage (<5%) of well stimulations produced an earthquake on the state network. Subsequent to mitigating actions taken by regulators and industry, the seismicity rate was down to 15 earthquakes of M3.0 or greater in calendar year 2022. While we continually improve the technology behind the scientific products, such as with implementation of machine-learning, we have strived to address and continually improve public education and community outreach to all Oklahomans. These efforts include informational literature that is distributed during public events and available online. We have made a concerted effort to get professionals into classrooms and public libraries for dynamic demonstrations, showcasing pathways for academic careers and engaging the public with accessible and relevant science. The demonstrations are often coupled with an installation of a Raspberry Shake in both rural and urban schools and other educational institutions such as libraries and museums. In addition, we have produced four professional-grade public service announcements targeted at different grade levels that highlight preferred safety procedures: "Drop, Cover, Hold On." We plan to discuss lessons-learned and best-practices from our experience and perspective as the state agency responsible for the public dissemination of earthquake alerts and information. A real-time network coupled with effective science communication showcases a roadmap, where stakeholders can work quickly to mitigate earthquake activity.

Seismic Background Noise of Italian Strong Motion Network

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Italian strong motion network monitors Italian territory and its surrounding with more than 700 seismic stations. Recent development of the strong motion network, now it is possible to determine the noise level of the network. In this study, background noise of the network has been processed in three different time ranges that are 2019, covid-19 lockdown period, and 2022. To do that, power spectrum density is calculated for the continuous stations. Due to the nature of the seismic instrument and the periods that are significant for the purpose of the network, periods lower than 5s are analyzed. Since the Italian strong motion network is deployed in order to detect the effects of the seismic events in urban areas, stations are mostly installed in towns and cities. Hence, the background noise is dominated by the human activity. This effect can be seen up to 14 decibel noise level changed between day time and night time. It is found that stations located in the city centers are suffered from the anthropogenic sources. During the covid-19 lockdown, background noise levels are dropped up to 6.5 decibels in day time and overall noise are reduced significantly. Due to the deployment of the stations in urban areas, stations are also affected by the vehicles. Their effect can be seen in several distinctive period ranges.

Seismic Network Expansion in the Caucasus and Central Asia (SNECCA)

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With support from the U.S. Department of Energy (DOE), Lawrence Livermore National Laboratory (LLNL) and the Incorporated Research Institutions for Seismology (IRIS) are collaborating with seismic monitoring centers in the Caucasus and Central Asia to expand national seismic networks through the installation of permanent broadband seismic stations. The main goal of the project is to improve regional network coverage by making high-quality data from new stations openly available to the global scientific community. The multi-year project involves deployment of more than fifty posthole broad-band sensors across six participating countries: Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, and Tajikistan. Additionally semi broad-band stations will be deployed for local monitoring of volcano and mud-volcano sites in Armenia and Azerbaijan; and standalone urban type strong motion sensors will be deployed in large cities. To facilitate data exchange and incorporate diverse sources of real-time data into national monitoring solutions, the project also supports the installation of high-capacity servers for participating monitoring centers. LLNL and IRIS collaborate with participants to develop technical training and incorporate best practices in seismic network operation and management. Station deployments began in the summer of 2021 and are planned to be completed in 2023. The project is implemented through the Seismic Targeted Initiative of the International Science and Technology Center and the Science and Technology Center in Ukraine.

The Colorado Geological Survey Seismic Network, Colorado Seismicity, and Non-Earthquake Seismic Signals.

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The Colorado Geological Survey Seismic Network (CGSSN) consists of nine permanent broadband stations in the state of Colorado. To date, the primary focus of the CGSSN is to assist in the monitoring and locating of small magnitude natural and induced earthquakes. We will be presenting on the status of the CGSSN, general seismicity of Colorado, and our goals for the future of the network. One of our goals is to identify, characterize, and classify non-earthquake signals on our seismic stations. This is part of a larger objective to find novel ways to use our seismic network to serve the people of Colorado. We are interested in examining anthropogenic signals as well as those from geologic hazards such as surficial mass movements including landslides and debris flows. We will present on our experience and plans to use seismic stations to compliment other studies at the Colorado Geological Survey including those on landslide and debris flow hazards.

New Methods and Models for More Informative Earthquake Forecasting

Oral Session • Wednesday 19 April • 08:00 AM Pacific

Conveners: Jose A. Bayona, University of Bristol (jose.bayona@bristol.ac.uk); William H. Savran, Southern California Earthquake Center (wsavran@usc.edu); Max Schneider, U.S. Geological Survey (mschneider@usgs.gov); Leila Mizrahi, ETH Zurich (leila.mizrahi@sed.ethz.ch); Nicholas J. van der Elst, U.S. Geological Survey (nvanderelst@usgs.gov)

The Roles of Coseismic Slip and Afterslip in Driving On-fault Aftershock Distributions: An Analysis of Behaviourally-varied Continental Case Studies

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Spatio-temporal complexity is a common characteristic of aftershock sequences and may require explanation beyond the role of coseismic Coulomb static stress change. Aseismic afterslip has long-been proposed as a driver of aftershock sequences, generally based on observations of spatial co-migration and a shared decay. However, observational evidence is limited to case studies, and efforts to test systematically have not indicated that afterslip is the outright driver of aftershocks. To investigate the role that afterslip may play in specifically driving the spatial distributions of near/on-fault aftershocks, we investigate seven behaviourally varied Mw6.0-7.6 continental earthquakes (in terms of relative afterslip moment and relative aftershock productivity), using high resolution coseismic and afterslip models and regional seismic catalogs. We project slip models and aftershock data onto a best-fitting plane, and statistically test whether coseismic slip, afterslip or total cumulative slip (and each of their respective gradients) best explains near/on-fault aftershock density. In six out of seven cases, we show that total cumulative slip correlates with near/on-fault aftershock density moderately-strongly, and fairly stably through time (up to ~1000 days). However, to explain why we see aftershocks occurring in regions which have: 1) apparently already ruptured (having gone coseismic slip), and 2) theoretically velocity-strengthening regions (having undergone afterslip), we propose that abundant fine scale rheological heterogeneity and/or significant amounts of conditional stability/instability must be present in fault zones. We discuss the role that uncertainty may have on our results, but confidently conclude that near/on-fault aftershock density is well-predicted by total cumulative slip, for analyses at these (2x2 km) resolutions. Pragmatically, this may be used to update our understanding of likely aftershock distributions in real-time.

A-Positive: An Improved Estimator of the Earthquake Rate That Is Robust Against Catalog Incompleteness

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Earthquake rate and magnitude distribution are the fundamental quantities of statistical seismology. Long term rate models inform our hazard and building codes, and short-term models provide situational awareness during aftershock sequences. There is even hope that the temporal evolution of the rate may provide some information about larger earthquakes to come. Earthquake catalogs are at the core of these estimates, but catalogs are imperfect due to both sparse network coverage and to saturation of the network during periods of high activity. Traditional attempts to address incompleteness center on modeling the time-varying magnitude of completeness, but such models are non-unique and introduce additional uncertainty.

Here I present a method for estimating the earthquake rate that is insensitive to catalog incompleteness and does not depend on a completeness model. This method is rooted in the assumption that catalogs improve monotonically in time between any two earthquakes and that small earthquakes do not obscure larger ones. I define an estimate for the earthquake rate, 'a-positive,' that is based on interevent times between successive earthquakes where the second earthquake is larger than the first. I show how to use this approach to generate a non-parametric estimate of the earthquake rate and magnitude frequency distribution, as well as a parametric rate estimate using a modified definition of the Epidemic Type Aftershock Sequence model that considers only the time between successive earthquakes. When applied to aftershock data, the improved rate estimate finds essentially no evidence for a plateau in the early aftershock rate, even at the times of the earliest detected aftershocks in a sequence. The early time plateau modeled by the c-value in the modified Omori's law is most likely a statistical feature of the earthquake catalog and is unlikely to encode anything about the aftershock nucleation process.

A Decade of Prospective Evaluations of 1-Day Seismicity Forecasts for California: First Results

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Since 2007, the Collaboratory for the Study of Earthquake Predictability (CSEP) has been prospectively evaluating 24-hour seismicity forecasting models for California to address seismological questions with important implications for time-dependent earthquake hazards. Among others, the pool of 24 models includes various flavors of ETAS, STEP, non-parametric models, and ensemble models. Using statistical methods developed by CSEP, we assess the consistency of these models against observed M3.95+ earthquakes, and compare their long-term performance with that of an early standard ETAS model. Our prospective dataset contains nearly 600 target events, including the 2010 M7.2 el Mayor-Cucapah, 2014 M6.9 Cape Mendocino, and 2014 M6 South Napa earthquakes. Here, we present preliminary test results that may be helpful in improving our ability to forecast earthquake clustering, and advancing Operational Earthquake Forecasting in California.

Question-driven Ensembles of Flexible ETAS Models

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The development of new earthquake forecasting models is often motivated by one of the following complementary goals: to gain new insights into the governing physics and to produce improved forecasts quantified by objective metrics. Often, one comes at the cost of the other. Here, we propose a question-driven ensemble (QDE) modeling approach to address both goals. We first describe flexible ETAS models in which we relax the assumptions of parametrically defined aftershock productivity and background earthquake rates during model calibration. Instead, both productivity and background rates are calibrated with data such that their variability is optimally represented by the model. Then we consider 64 QDE models in pseudo-prospective forecasting experiments for Southern California and Italy. QDE models are constructed by combining model parameters of different ingredient models, where the rules for how to combine parameters are defined by questions about the future seismicity. The QDE models can be interpreted as models which address different questions with different ingredient models. We find that certain models best address the same issues in both regions, and that QDE models can substantially outperform the standard ETAS and all ingredient models. The best performing QDE model is obtained through the combination of models allowing flexible background seismicity and flexible aftershock productivity, respectively, where the former parameterizes the spatial distribution of background earthquakes and the partitioning of seismicity into background events and aftershocks, and the latter is used to parameterize the spatio-temporal occurrence of aftershocks.

Overcoming the Achilles' Heel of the Foreshock Traffic Light System

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After the occurrence of a moderate to large earthquake, the question shared between Civil Protection, scientists, the population, and all decision makers is only one: *Was it the mainshock or a bigger event has yet to come?* According to standard earthquake statistics, the chance that after a moderate earthquake an even larger event will occur within five days and 10 km is typically 5% (Reasenberg and Jones, 1990). Recently, a more specific answer to this question has been given by the Foreshock Traffic Light System (FTLS, Gulia and Wiemer, 2019). The method allows the real-time discrimination between foreshocks and aftershocks in well-monitored regions. However, some expert judgements are required in order to overcome local peculiarities (Brodsky, 2019) such as magnitude of completeness and the duration of the short-term aftershock incompleteness (STAI, Kagan, 2004). We here introduce the new version of the code that, using the b-positive estimator (van der Elst, 2021), successfully overcomes the above-mentioned limits, allowing the implementation of the FTLS already in few hours after a M36 event without any specific expert judgements.

Earthquake Magnitude Prediction Using a Machine Learning Model

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Standard approaches to earthquake forecasting - both statistics-based models, e.g. the epidemic type aftershock (ETAS), and physics-based models, e.g. models based on the Coulomb failure stress (CFS) criteria, estimate the probability of an earthquake occurring at a certain time and location. In both modeling approaches the time and location of an earthquake are commonly assumed to be distributed independently of their magnitude. That is, the magnitude of a given earthquake is taken to be the marginal magnitude distribution, the Gutenberg-Richter (GR) distribution, typically constant in time,or fitted to recent seismic history. Such model construction implies an assumption that the underlying process determining where and when an earthquake occurs is decoupled from the process that determines its magnitude. In this work we address the question of magnitude independence directly. We build a machine learning model that predicts earthquake magnitudes based on their location, region history, and other geophysical properties. We use neural networks to encode these properties and output a conditional magnitude probability distribution, maximizing on the log-likelihood of the model's prediction. We discuss the model architecture, performance, and evaluate this model against the GR distribution.

Are Earthquake Sizes Correlated? Insight From Neural Temporal Point Process Models

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Seismology is witnessing an explosive growth in the diversity and scale of earthquake catalogs owing to improved seismic networks and increasingly automated data augmentation techniques. Hopefully, this community effort to produce more detailed observations should translate into improved earthquake forecasts. Current operational earthquake forecasts build on seminal work designed for sparse earthquake records that combine the canonical statistical laws of seismology. Here, we explore the potential of a neural-network based earthquake forecasting model that leverages the new data in an adaptable forecasting framework: the Recurrent Earthquake foreCAST (RECAST). Our previous research shows that RECAST achieves robust improved forecasting skill against the standard benchmark model (ETAS). Here, we test the capabilities of RECAST beyond the standard earthquake-rate forecasting task. Whether or not the ultimate size of an earthquake is influenced by patterns of the event history is a fundamental question in seismology. A standard assumption is that the size of an earthquake is independent of the event history yielding the well-known Gutenberg-Richter model. Some attempts to move beyond this assumption include reference to previous event magnitudes with moving windows. How to translate the characteristics of timing in an event sequence into a magnitude forecasting model is less clear. RECAST enables an exploration of this relationship without ascribing or exhaustively searching for the appropriate parametric model. Preliminary results indicate that even without the inclusion of event timing a non-parametric and time-varying magnitude forecast is an improvement over a single regional Gutenberg-Righter model. Importantly, improvements also arise when including the timing of events indicating that the magnitude and timing are not independent.

Modelling and Model Performance Assessment of the Spatiotemporal Development of Event Rates and Event Clustering for Induced Seismicity in the Groningen Gas Field

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Induced seismicity due to natural gas production from the Groningen field has been steadily on the rise from the first instrumental recording in 1991 into the first half of the 2010s. In a societal context of accelerating damage rates, safety concerns and public outrage, the national government ultimately decided to reduce production as much as possible. A minimal level of production is currently maintained as required for the security of supply within the national energy budget. Hazard and risk forecasts for the seismicity in the Groningen field rely to a large extent on a source model that relates production to seismicity rates. The state-of-the-art model combines pressure diffusion and reservoir geometry into a spatiotemporal stress proxy that predicts seismicity rates with an exponential trend and includes ETAS clustering. For the last half decade both the model forecast and the observations show a decline in seismicity. The last couple of years however, it seems that the model is underpredicting the number of events. This may be due to an underestimation of the expected rates, and/or an underestimation of the annual variability. The former may be caused by, e.g., unaccounted delays, the latter, by, e.g., unaccounted trends in clustering intensity. We assess the performance of the state-of-the art model in terms of the spatiotemporal seismicity distribution according to CSEP testing criteria and variations thereupon, and explore directions of model improvement for enhanced forecasting performance.

A Test of the Earthquake Gap Hypothesis in Mexico: The Case of the Guerrero Gap

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The seismic gap hypothesis has been widely cited in Mexico to predict the location of future earthquakes. However, no analysis of the outcome of any predictions of the hypothesis in Mexico has been done to-date. This work analyzes the outcome of the prediction by Nishenko and Singh (1987a), which is based on probability distribution functions over time in defined segments that allow for a formal evaluation. Specific probabilities were given for 5 years, 10 years, and 20 years after 1986, using the cumulative distribution function. The prediction relies on the precise repeat times of characteristic earthquakes to define segments, but we show that the catalog that the authors use relies on an imprecise definition of characteristic earthquakes. We discuss some of their decisions in building their catalog to explain how we analyze the outcome of the prediction. An unexpected result is that the very catalog the authors use to create the gap hypothesis prediction does not seem to support a narrow recurrence interval, and instead seems to suggest large variability in earthquake recurrence intervals along the Mexican subduction zone We generate null model earthquake catalogs using the average number of earthquakes that occur in the subduction zone, and randomly distribute these along the segments according to their relative lengths. We find that the null model performs better than the seismic gap hypothesis prediction. No earthquakes occur in segments with a 70% or higher probability according to NS1987 (there were 4 such segments in the 20-year timeframe), but a Mw 8.0 earthquake occurs in a segment with a less than 16% probability of an earthquake. We conclude that the gap hypothesis performed poorly at predicting earthquakes in Mexico and, in fact, its predictions were worse than predicting earthquakes by chance.

Using Multi-Resolution Grids and MCC-F1 Curve to Improve Aftershock Forecast Testability

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Testing a forecast model is key to further improving it. Aftershock forecasts are usually provided for each cell of a gridded region, and the spatial forecasts are often evaluated by using the Receiver Operating Characteristic (ROC) curve. It draws a binary comparison of earthquake occurrences or non-occurrence for each grid cell. Previous tests suggested that Coulomb stress is not a good predictor of aftershocks despite its large use in literature. However, the results of the ROC tests were questioned because data imbalance can largely bias the results.We analyze the feasibility of ROC for evaluating aftershock forecast models. We conduct a synthetic experiment by creating a perfect Coulomb model, in which all earthquakes are made to occur in the positive stress change regions, and compare it with simpler distance-based all-positive forecasts. The experiment shows that ROC favors the models that only tend to forecast the active regions, while the models trying to forecast the quiet regions are at a disadvantage, thereby highlighting flaws in using ROC for aftershock forecast ranking.

We suggest a two-fold improvement in the testing strategy. We propose Matthews Correlation Coefficient (MCC) and F1 curve as a replacement for the ROC curve. Furthermore, we suggest using a multi-resolution test grid adapted to the earthquake density. We conduct the same synthetic experiment to evaluate forecast models using MCC-F1 and a radial grid (a simple example of a multi-resolution grid). With this strategy, we can better differentiate between the Coulomb forecast model and the non-informative model, particularly in the case of existing outliers. We also use this strategy to test forecast models for Chi-Chi and Landers aftershocks. For evaluating those real scenarios, we use the recently introduced Quadtree approach to generate multi-resolution grids. Despite the improved tests, we find that the simple distance-based model outperforms the Coulomb model in both cases, indicating that MCC-F1 and multi-resolution grids do not alter the ranking of the models as long as the Coulomb model is not adjusted to local conditions.

New Methods and Models for More Informative Earthquake Forecasting [Poster]

Poster Session • Wednesday 19 April

Conveners: Jose A. Bayona, University of Bristol (jose.bayona@bristol.ac.uk); William H. Savran, Southern California Earthquake Center (wsavran@usc.edu); Max Schneider, U.S. Geological Survey (mschneider@usgs.gov); Leila Mizrahi, ETH Zurich (leila.mizrahi@sed.ethz.ch); Nicholas J. van der Elst, U.S. Geological Survey (nvanderelst@usgs.gov)

Investigating the Fault Slip Behavior of an Extensional Faults System Through the Use of a Novel 3D Stochastic Declustering Algorithm: The Alto Tiberina Fault Case Study

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The Alto Tiberina Fault system is a seismic structure located in Central Italy, composed of a principal low-angle normal fault and other minor synthetic/antithetic higher-angle normal faults located in the hanging wall of the principal fault. In the last years, in this zone a dense seismic network has been deployed, making available a high-definition seismic catalog with a low magnitude of completeness. In this work, we applied a novel 3D stochastic declustering algorithm based on the ETAS model to such a catalog, in order to study the clustering properties of the seismicity by considering the earthquakes' depth. We found two distinct behaviors for the seismicity in the principal fault and the synthetic/antithetic faults respectively, both in terms of clustering

properties and magnitude frequency distribution. The principal fault shows a high *b*-value and low clustering (i.e. a majority of spontaneous events), while the synthetic/antithetic faults show a low *b*-value and high clustering (i.e. a majority of triggered events). Consequently, these results also imply a different b-value of the magnitude frequency distribution for spontaneous and triggered events, despite a similar rake of the focal mechanisms (normal faulting). Such a complex fault structure, therefore, shows peculiar and unusual seismic properties.

Real Time Gutenberg-Richter b-Value Estimation for an Ongoing Seismic Sequence: An Application to the 2022 Marche Offshore Earthquake Sequence (Ml 5.7 Central Italy)

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The real-time estimation of the *b-value* parameter in the Gutenberg-Richter law for earthquake magnitudes is essential in short-term forecasting of ongoing seismic sequences. The spatiotemporal variability of this parameter is indeed often interpreted in terms of physical processes, and therefore as a precursor of upcoming strong events.

Nonetheless, the *b-value* estimation is known to be susceptible to several sources of bias, such as the completeness magnitude, and this may lead to a wrong interpretation of the estimates obtained. Still, the global increase of the coverage of seismic stations, as well as the development of new algorithms for detecting earthquakes in the last decades, allowed us to enormously expand the number of events in instrumental seismic catalogs, thus reducing some potential biases. This led to increase the interest in studying the spatial and temporal variations of the *b-value*, with particular focus on real-time estimation.

In line with this promising research branch, here we present the results of an analysis we performed in the early stage of the Costa Marchigiana (Italy) seismic sequence. In particular, we estimated both the completeness magnitude M_c and the *b-value* within the first 4 and 7 days after the initial strong event, and interpret the results in terms of "forecasting avail". We highlighted some critical issues to consider in the real-time evaluation of both M_c and the *b-value*. These are ascribed to the roughness of the data recorded at an early-stage, an unreliable evaluation of M_c with statistical approach, the short-term aftershock incompleteness entailed after the initial strong event, and the magnitude binning.

Time Series Analysis From a High-Definition Italian Catalog: Seismicity Rates and Gutenberg-Richter b-Value Evaluation

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The high-resolution earthquake catalog related to the seismic activity of the Alto Tiberina fault system (Northern Apennine, Central Italy), constructed from the seismic network of the Alto Tiberina Near Fault Observatory (TABOO), was analysed by statistical methods from a seismological perspective.

To bring new information on the study of earthquakes preparatory phases and to identify possible tectonic stress indicators, we focused on the reliable time series computation of the seismicity rates and of the Gutenberg-Richter *b*-value.

In this work, the time series were evaluated starting from the generation of the stochastic declustered catalog obtained using the 2D ETAS Model.

The capability of the algorithm based on the ETAS model to recognize and distinguish the triggered seismicity from the background allowed evaluating the daily seismicity rates and *b*-value variations for both the spontaneous and triggered earthquakes.

Moreover, to overcome the problems due to building *b*-value time series for a non-uniform temporal distribution of seismicity, we considered the weighted likelihood approach for a more robust *b*-value estimation and we implemented the weighted likelihood algorithm using weights obtained by 2D ETAS declustering, in order to evaluate changes in b-values both for background and triggered seismicity.

The obtained time series, in particular the b-value time series, are different from the ones obtained using the classical rolling window approach for the b-value computation, indicating that some of the b-value fluctuations are related to the natural statistical variability of the parameter.

New Observations and Modeling of Triggered Seismicity

Oral Session • Wednesday 19 April • 04:30 PM Pacific

Conveners: Hector Gonzalez-Huizar, CICESE (hgonzalez@cicese.mx); Esteban J. Chaves, OVSICORI, Universidad Nacional, Costa Rica (estevan.j.chaves@una.cr); Abhijit Ghosh, University of California, Riverside (aghosh@ucr.edu); Debi Kilb, University of California, San Diego (dkilb@ucsd.edu)

Observations of Triggering of Earthquakes and Tremor in Mexico by Remote Earthquakes

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After a large magnitude earthquake occurs some areas near its epicenter experience an increase in seismic activity. However, increases in seismicity have also been observed in places very distant from large earthquakes the moments after they occur. This phenomenon is known as dynamic or remote triggering of seismicity. This is explained as the result of physical changes caused by the passing of the seismic waves that bring faults closer to failure. Besides regular earthquakes, other types of seismic events can be dynamically triggered, including tectonic tremor and slow slip events. In this work, we present observations of dynamic triggering in Mexico caused by global earthquakes, as well as observations of dynamic triggering in other parts of the world caused by Mexican earthquakes, including the large 2017 M8.2 Tehuantepec, Mexico earthquake.

Earthquake Triggering in the Context of 2019 Ridgecrest Earthquake Sequence

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2019 Mw 7.1 Ridgecrest earthquake sequence provides an interesting case to study different modes of earthquake triggering. The mainshock is preceded by a Mw 6.4 foreshock that occurred 34 hours earlier. It is unclear what role it plays, if any, in triggering the mainshock. Why did it not trigger the mainshock immediately? If it is a case of delayed triggering, what causes the delay? The mainshock is followed by prolific aftershock activity. The aftershock activity is, however, far from uniform in space and time. It still remains enigmatic how afterslip may have triggered aftershocks and contributed to this heterogeneous distribution. Intriguingly, Coso geothermal area, situated just northwest of the main ruptured fault, appears to be indifferent from stress triggering with little change in seismic activity. On the other hand, Garlock fault, immediately south of the mainshock, appears to be triggered by the mainshock with increased seismic activity and slow slip occurring in a segment close to the mainshock (Ross et al., 2019). In addition, we are investigating the pre-seismic time period (before 2019) spanning several decades. We have built an earthquake catalog based on machine learning (Zhou et al., 2019) that has captured a more complete picture of seismic activity leading to the 2019 Ridgecrest earthquake sequence. We show that a large part of the fault that ruptured in 2019 can be discernable via microseismic activity. It may also indicate stress build-up along this fault before the sequence starts. Interestingly, we found several doublet repeaters in this are including some on or very close to the fault that ruptured in 2019. It is interesting to note that repeaters are reported during the 2019 Ridgecrest sequence (Huang et al., 2020). Overall, this area shows evidence of a variety of triggering phenomena – from potentially delayed triggering to triggered slow slip – making it an interesting case to study. Our new long-term earthquake catalog based

on machine learning is providing new insights into the processes of triggering and underlying physics.

Sea level Changes Affect Seismicity Rates in a Hydrothermal System Near Istanbul

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Small stress changes such as those from sea level fluctuations can be large enough to trigger earthquakes. If small and large earthquakes initiate similarly, high-resolution catalogs with low detection thresholds are best suited to illuminate such processes. Below the Sea of Marmara section of the North Anatolian Fault, a segment of 150 km is late in its seismic cycle. We generated high-resolution seismicity catalogs for a hydrothermal region in the eastern Sea of Marmara employing AI-based and template matching techniques to investigate the link between sea level fluctuations and seismicity over six months. Local seismicity rates are larger during time periods shortly after local minima on sea level, when it is already rising. Local strainmeters indicate that seismicity is promoted when the ratio of differential to areal strain is the largest. The strain changes from sea level variations, on the order of 30-300 nstrain, are sufficient to promote seismicity.

New Insights From Two 2022 Large Magnitude Earthquake Events Occurring Closely in Space and Time in Abra, Northern Philippines

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In the second half of 2022, the province of Abra in the island of Luzon, Northern Philippines was struck by two large magnitude earthquakes in a span of less than three months and within a 20-kilometer radius. On July 27, 2022, at 8:43 am (Philippine Standard Time), the area was struck by a magnitude Mw 7.0 earthquake that caused intense ground shaking. The epicenter was located at 17.64° N latitude, 120.63° E longitude, at a focal depth of 15 km. On October. 25, 2022, at 10:59 p.m. (PST), a magnitude Mw 6.4 earthquake struck the same area, at an epicenter located only about 18 kilometers northeast of the July earthquake epicenter, at the same focal depth of 15 km. Destruction in both earthquakes included collapsed residential and commercial buildings, structural damage in century-old heritage churches, government buildings, bridges and roads. Ground deformation included numerous landslides in the mountainous regions, and liquefaction in riverbeds and coastal areas. While infrastructure damage was significant, surface ground rupture was not evident after both earthquakes. The epicentral areas are known to be prone to earthquakes due to the presence of the Philippine Fault System (PFS) there. However, the focal mechanism solutions of the main shocks suggest gently-dipping fault planes which are not consistent with the known geometry of the PFS and its branches in the area. Instead the distribution of the aftershocks, nodal plane geometries, Coulomb Stress Transfer (CST) modeling and analysis by radar interferometry suggest that the earthquake-generating faults project surface ruptures located further west, following the location and trend of other PFS fault branches. These temporally and spatially closely-spaced July and October earthquakes pose new questions on the current knowledge about the PFS in northern Luzon, but also provide new insights that contribute in understanding the nature and earthquake behavior of complex fault systems, including fault asperities, post-earthquake stress transfer, seismic rate changes, aftershock evolution and earthquake triggering.

Earthquakes in the Shadows: Why Aftershocks Occur in Surprising Locations

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For decades there has been a debate about the relative effects of dynamic versus static stress triggering of aftershocks. According to the static Coulomb stress change hypothesis, aftershocks should not occur in stress shadows, regions where static Coulomb stress has been reduced. We show that static stress shadows substantially influence aftershock occurrence following three M≥7 California mainshocks. Within the modeled static Coulomb stress shadows the aftershock rate is an order of magnitude lower than in the modeled increase regions. However, the earthquake rate in the stress shadows does not decrease below the background rate as predicted by Coulomb stress change models. Aftershocks in the stress shadows exhibit different spatial-temporal characteristics from aftershocks in the stress increase regions. The aftershock rate in the stress shadows decays as a power law with distance from the mainshock, consistent with a simple model of dynamic stress triggering. These aftershocks begin with a burst of activity during the first few days after the mainshock, also consistent with dynamic stress triggering. Our interpretation is that aftershock sequences are the combined result of static and dynamic stress triggering, with an estimated ~34% of aftershocks due to dynamic triggering and ~66% due to static triggering.

New Observations and Modeling of Triggered Seismicity [Poster]

Poster Session • Wednesday 19 April

Conveners: Hector Gonzalez-Huizar, CICESE (hgonzalez@cicese.mx); Esteban J. Chaves, OVSICORI, Universidad Nacional, Costa Rica (estevan.j.chaves@una.cr); Abhijit Ghosh, University of California, Riverside (aghosh@ucr.edu); Debi Kilb, University of California, San Diego (dkilb@ucsd.edu)

Instantaneous and Delayed Triggering of Tremor Along the Parkfield-Cholame Section of San Andreas Fault

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Surface waves of large distant earthquakes are capable of triggering deep tectonic tremor along the Parkfield-Cholame section of the San Andreas Fault. However, only in a few documented cases a major tremor episode lasted for a few days to weeks following a distant mainshock. Here we systematically examine how major tremor episodes near Cholame respond to dynamic stress changes from 115 M>5.5 earthquakes between 2001 and 2021 that are at least 200 km away from the broadband station BK.PKD. We first identify 99 major tremor sequences from a 20-year low-frequency earthquake tremor catalog and select 115 distant mainshocks with predicted peak dynamic stresses larger than 1 kPa. Next, for 57 selected mainshocks, we examine both the relative timing of tremor episodes and the tremor rate changes with respect to the last distant mainshock before the next major tremor episode. We find that the peak ground velocities of distant mainshocks do not determine whether a major tremor episode will likely follow. Instead, major tremor episodes near Cholame need to wait for a certain time before they are susceptible to dynamic triggering by distant mainshocks. This result is similar to previous findings for episodic tremor and slip events in Cascadia, suggesting that major tremor episodes near Cholame likely released most of the built-up tectonic stress, and a certain 're-charge' time is needed before they can be remotely triggered. Our next step is to examine under what conditions distant earthquakes can trigger tremor instantaneously during their surface waves, and other factors that determine whether a major tremor episode is delayed triggered or not. In addition, we plan to use data-driven clustering methods to better define the start and end times of major tremor episodes, in order to better understand how they respond to distant earthquakes.

Remote Dynamic Triggering of Intermediate-Depth Earthquakes in the Mariana Subduction Zone Following the 2012 Indian Ocean Earthquakes

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Although dynamic triggering can provide important insights into earthquake faulting mechanisms, there have been no previous reports of remote dynamic

triggering of intermediate-depth earthquakes. The 2012 Indian Ocean M_w 8.6 and M_w 8.2 earthquakes were unusually prolific in triggering remote shallow earthquakes worldwide. Analysis of data from a temporary, amphibious array deployed over the Mariana subduction zone reveals a dynamically triggered sequence of intermediate-depth earthquakes following the M_w 8.2 aftershock. The first event occurs immediately after the long-period Rayleigh wave arrival. The intermediate-depth seismicity rate increases to 6 times the background seismicity rate in the hour immediately following and continues at twice the background seismicity rate for the subsequent 24 hours, with the triggered events occurring at depths of 160 to 240 km beneath the Northern Mariana Islands. Using synthetic seismograms and a finite difference technique, we calculate displacement and strain as a function of depth at the event locations. Unlike most shallow triggered seismicity from the 2012 events, the triggered intermediate-depth events show Rayleigh wave amplitudes larger than Love wave amplitudes, since the event azimuth lies along a Love wave node. These results suggest that intermediate depth faults are critically stressed, such that extremely small strains can cause seismicity. We suggest that the association of intermediate-depth triggering during the passage of the Rayleigh wave indicates that slight changes in density associated with the wave passage may trigger dehydration reactions that are proposed as a mechanism of intermediate-depth events.

Step-Like Motion Associated With Near-Source ScS Phase From the 2011 Tohoku-Oki Earthquake: Potential Triggering by ScS

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The Mw 9.0 2011 Tohoku-Oki earthquake generated a strong ScS phase with the peak-to-peak amplitude larger than 1 cm in Japan. This near-source ScS phase was recorded at nearly all sites of GEONET, a network of more than 1000 GPS instruments that are densely covering Japan. Even though the individual GPS timeseries data are noisy, stacking 30+ records at adjacent sites results in clean signals of the ScS phase. In addition to the conventional ScS waveforms, the stacked data exhibit an eastward step-like displacement with an amplitude up to about 5 mm, superposed on top of the ScS wave. We show that the observation is robust despite the noise in GPS data and may be supported by seismic data as well. We find that the likely mechanism for our observation is slip triggered by ScS phase which arrives nearly simultaneously throughout Japan. We could rule out other mechanisms such as the near-field term and long moment rate function of the source.

Strong-Motion Records of the M6.4 Ferndale Earthquake on 20 December 2022 and Its Aftershocks

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The M6.4 Ferndale, California earthquake on December 20, 2022, and its aftershocks generated valuable strong-motion data sets at several California Integrated Seismic Network stations of CSMIP, NSMP, NCSN and BDSN regional seismic networks. The epicenter of the mainshock was located offshore, 15 km southwest of Ferndale, at a focal depth of about 18 km. The largest ground acceleration of 1.46g was recorded at the CSMIP station Rio Dell – 101/Painter St Overpass Grounds, located about 27 km northeast of the epicenter. The closest ground station to the epicenter was the NCSN-KCT Station in Cape Town that recorded 0.12g. The maximum ground displacement of 14 cm was calculated using the strong motion record from the BDSN station DMOR in Dinsmore located about 64 km from the epicenter. Stronger ground shaking was observed in the east and northeast of the epicenter. Spatial variation of ground acceleration fits well with the ground motion predictions when the finite fault model is taken into consideration for the earthquake.

A M5.3 aftershock occurred on January 1, 2023. The aftershock was located onshore at about 15 km southeast of Rio Dell, at a deeper depth of 30km. It generated strong shaking in the area. The Rio Dell – 101/Painter St Overpass Grounds station recorded 0.70g acceleration at about 15 km from the epicenter. Also, the mainshock and some aftershocks were recorded at the CSMIP and NSMP structural stations in the area. The M6.4 and M5.3 earthquakes generated the largest structural acceleration at two bridges in Rio Dell area with recorded accelerations over 2 g. The strong-motion records for the mainshock (>160 records) and some aftershocks are available for view and download at the Center for Engineering Strong Motion Data (CESMD) (strongmotioncenter.org), a jointly operated center of the California and United States Geological Surveys.

Normal Faults: From Source to Surface [Poster]

Poster Session • Tuesday 18 April

Conveners: Lucia Andreuttiova, University College London (lucia.andreuttiova.16@ucl.ac.uk); Thomas M. Mitchell, University College London (tom.mitchell@ucl.ac.uk); Alice-Agnes Gabriel, University of California San Diego, LMU Munich (alice-agnes.gabriel@geophysik.uni-muenchen.de); Zachary E. Ross, California Institute of Technology (zross@caltech.edu)

A Semi-Automated Algorithm for Fault Displacement Profile Extraction

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Faults grow over time through incremental slip events. The finite distribution of displacements on faults, and the ratio of the maximum displacement at the surface to the fault length are frequently sought after in fault mechanics, as these metrics reflect the physics of fault growth and the host material. Traditional methods are time-consuming and often spatially sparse which limits the potential of high resolution topographic datasets. We developed a semi-automated MATLAB algorithm to measure throw from high-resolution lidar topography. Our inputs are the lidar DEM for the region and a fault map. We first collect fault-perpendicular topographic profiles evenly spaced along each fault. We then train a Support Vector Machine to detect scarps based on spatial slope characteristics in a manually curated subset. Finally, we use the second derivative of elevation to fit each scarp in the profile and calculate throw. The algorithm outputs the displacement profile for every fault mapped, and the maximum displacement vs length relationship for the network of faults. This approach enables rapid and standardized collection of fault throw and length metrics for large datasets. We tested our algorithm on normal faults in the Volcanic Tableland in Bishop, California. Going forward, we will validate our method on other landscapes dominated by normal faulting where high-resolution topography is available.

Across-Scales Co-Seismic Deformation and Fault Scarp Morphology From the 1954 Dixie Valley-Fairview Peak Earthquake Sequence

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The 1954 Dixie Valley -Fairview Peak earthquake sequence ruptured along a series of normal and strike-slip faults, creating a complex pattern of surface deformation. The displacement created during large-magnitude earthquakes is often used as an input into hazard forecast models and as a proxy to estimate the earthquake magnitude. Therefore, to verify its accuracy we compare the measurements of surface displacement collected from several sources.In this work, we use data from optical image correlation (OIC), high-resolution digital elevation models (DEM) constructed using images from an unmanned aerial vehicle (UAV), and field measurements published in previous work. The results of this study show that the displacement estimated from the high-resolution UAV DEM exceeds the measurements from the other two data sets. Furthermore, the measurements collected in the field are slightly higher than the offset determined from optical image correlation. Such results are inconsistent with previously published work. The displacement measurements from optical image correlation span across a long aperture and include the deformation distributed away from the main fault. Therefore, the data collected from OIC typically exceed the measurements collected in the field.We believe that there are several mechanisms responsible for this discrepancy. Firstly, the fault scarp in the unconsolidated material reaches the angle of repose through erosion and deposition while simultaneously cutting into the steeply dipping topography. Secondly, the change in the fault's subsurface geometry causes higher subsidence close to the fault scarp. Therefore, the results of this study suggest that field data should be carefully evaluated.

The Rocks That Did Not Fall: A Multidisciplinary Analysis of Near-Source Ground Motions From an Active Normal Fault

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On July 08, 2021 a M6.0 normal faulting event rocked Little Antelope Valley near the California-Nevada border, the latest major earthquake to occur in the central Walker Lane. Earthquake hazard along the eastern Sierra south of Reno is dominated by range-bounding normal faults like the ones playing host to this earthquake sequence, motivating our effort to better characterize it. In the 1990s, a series of field surveys in this region identified numerous fragile geologic features that were deemed unlikely to remain standing in the event of strong shaking. This included several sites in Meadowcliff Canyon, on the hanging wall of the 2021 event and only 6 km from the rupture surface. Despite this proximity, the fragile geologic features in the canyon remain intact today. In this work, we endeavor to unravel this mystery by combining advanced source characterization techniques with detailed analyses of strong ground motion. High-precision hypocentral locations reveal a clear mainshock fault plane striking north-north-west and dipping down to the east. The mainshock nucleated near the base of this structure, which did not break the surface but triggered aftershocks updip and to the north and south. Application of Bayesian source spectral analyses indicate that the mainshock event had a relatively high-stress drop (~ 20 MPa), and that within the aftershock sequence, there is a clear trend of increasing stress drop with hypocentral depth along the fault plane. Peak ground acceleration and velocity recordings at regional stations agree well with the NGA-West2 suite of active crustal ground motion models, and would predict PGA of ~0.3g at the Meadowcliff site, an amplitude likely sufficient to topple fragile geologic features. However, our preliminary analyses indicate that while the level of ground motion may be high, the pulse duration for this high stress-drop event at the Meadowcliff site may be too short to supply the impulse necessary to damage these features. This study provides a unique vantage point from which to interpret rarely observed strong motion recording from close to an active normal fault.

Numerical Modeling in Seismology: Developments and Applications

Oral Session • Thursday 20 April • 02:00 PM Pacific

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Modeling Intermittent Rupture in Fault Gouge Using Velocity-Strengthening Rate-and-State Friction with Flash Heating

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Earthquake ruptures on natural faults occur as dynamic slip in layers of a fine granular material known as the fault gouge. An experimental study of earthquake ruptures within a Homalite-100 interface with rock gouge material has revealed the occurrence of complicated slip events, during which the dynamic slip initially arrests when it enters the fault gouge, then spontaneously and repeatedly re-nucleates and arrests within the gouge region (Rubino et al., Nature, 2022). The repeated strengthening and dramatic weakening of the fault gouge inferred by these experiments suggests that this behavior is due to velocity-strengthening properties at lower slip rates and dynamic weakening, reminiscent of flash heating, at higher slip rates. To verify the conjectures based on the experiments and to better understand the friction behavior within the fault gouge, we conduct 3-D finite-element simulations motivated by the lab experiments. In the experimental setup, dynamic ruptures are nucleated within the Homalite-100 interface and propagate there for a while before entering the fault gouge region. We find that such a simulated gouge region with initially rate-strengthening friction is indeed able to first arrest the dynamic slip upon its arrival, and to subsequently re-nucleate another slip event within this region due to flash-heating-like dynamic weakening, although at a different location. The simulation results indicate that whether the dynamic weakening in gouge can occur within the observing window strongly depends on the initial value of state variable. The simulations also reveal complex interactions between rupture on the Homalite-100 interface and the initially barrier-like gouge region, with the slip arrest in the gouge region propagating backward into the Homalite-100 interface, before the rupture elsewhere overtakes the rupture arrest and propagates forward into the gouge region again. Our findings support the developing concept that co-seismic weakening may enable earthquake rupture to break through initially stable fault regions, with significant implications for seismic hazard.

A Fundamental View on Implementation of the Material Interface in the Finite-Difference Modeling

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Capability of a numerical modeling of seismic wave propagation and earthquake ground motion to faithfully represent material interfaces in realistic models of the Earth's interior is of key importance. A sharp sediment-bedrock interface can be a key factor causing an anomalous earthquake ground motion and strong site effects. A sharp interface, e.g., a seabed, is an important structural feature in seismic exploration.We address fundamental implications of presence of the material interface and spatial discretization for the finite-difference modeling by analyzing the equations of motion and constitutive relations in the wavenumber domain.We present heterogeneous formulations of the equations of motion and constitutive relations for several basic configurations of a wavefield in an elastic isotropic medium. We Fourier-transform the entire equations to the wavenumber domain. Subsequently, we apply the band-limited inverse Fourier transform back to the space domain.The heterogeneity of the medium, spatial discretization and the Nyquist-wavenumber band limitation of the entire equations have important implications for a FD modeling. The grid representation of the heterogeneous medium must be limited by the Nyquist wavenumber. The wavenumber band limitation replaces spatial derivatives both in the homogeneous medium and across a material interface by continuous spatial convolutions. The latter means that the wavenumber band limitation removes discontinuities of the spatial derivatives of the particle velocity and stress at the material interface. This allows to apply proper FD operators across material interfaces. A wavenumber band-limited heterogeneous formulation of the equations of motion and constitutive relations is the general condition for a heterogeneous FD scheme.

Interactions Between Shallow Slow Slip Events and Megathrust Earthquakes Based on 3D Dynamic Earthquake-Cycle Modeling

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Recent observations reveal that shallow slow slip events (SSEs) contribute to strain release at shallow subduction zone and may contribute to promoting

shallow megathrust earthquakes. However, physics-based understanding of possible interactions between seismic and aseismic activities at shallow subduction zone is very limited. In this study, we use a 3D dynamic earthquake simulator, which captures both quasi-static (for SSEs) and dynamic (for megathrust earthquakes) slip on shallowly dipping subduction interfaces, to explore their interactions and implications for seismic and tsunami hazards. We construct a 3D subduction-zone model with two asperities of different strengths, including Z1 asperity of high normal stress and Z2 of low normal stress, embed within a conditionally stable zone on the subduction interface. We find that both SSEs and earthquakes can occur on this interface. SSEs occur mainly on the conditionally stable zone and dynamic ruptures can nucleate on asperities and propagate into the conditionally stable zone at slow speeds, generating tsunami earthquakes. There is a clear correlation between the size of an earthquake and SSE activities preceding it. Small earthquakes rupture only the low-strength asperity and stop near the boundary of the high-strength asperity, while large earthquakes rupture both asperities cascadingly. Before a large earthquake, multiple periodic SSEs occur near the high strength asperity Z1 during the interseismic period, which gradually load stress on Z1 to make it critically stressed until Z1 gets ruptured in a large earthquake. Before a small earthquake, the preceding interseismic period is quiet with very few SSEs. An SSE may or may not directly lead to nucleation of an earthquake, depending on whether a nearby asperity is ready for spontaneously dynamic failure. In addition, because of different SSE activities before small and large earthquakes, the coupling degree may change dramatically between different interseismic periods, so that coupling degree estimation based on a short period of observation (e.g. 20 years) may be biased.

Three-Dimensional Distributional Finite-Difference Modelling of Elastic Wave Propagation in a Heterogeneous Earth

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We present a 3D distributional finite-difference algorithm (DFDM) for modeling the propagation of seismic waves in heterogeneous media. Our algorithm relies on the classic staggered finite-difference algorithm and is obtained by substituting the standard finite-difference operators with distributional finite-difference operators. The distributional finite-difference operators lead to improved accuracy while maintaining the structure of the former algorithm. The proposed approach allows for arbitrary Poisson's ratio, and a unique scheme handles wave propagation in both elastic and acoustic domains. The shear modulus is set to zero in the acoustic case. The proposed algorithm accurately and naturally accounts for the free surface and a solid-fluid interface with topography. We compare seismograms obtained using DFDM and the spectral-element method (SEM). For a given polynomial order, DFDM requires fewer points per wavelength than SEM to achieve similar accuracy. DFDM is thus memory efficient and offers a promising alternative to SEM for wave propagation modeling. We demonstrate the proposed algorithm's accuracy through numerical examples and discuss global seismology applications.

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Effect of Asymmetric Topography on Rupture Propagation Along Fault Stepovers

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Complex fault systems are often located in regions with asymmetric topography, and these systems are very common in Southern California. As an example, the eastern portion of the left-lateral Garlock fault system, which is composed of two segments separated by an extensional stepover width of 3-4 km, has high mountain ranges on its northern side and almost a flat topography on the southern side. Previous rupture dynamic studies have investigated the effect of stepover widths on throughgoing rupture but these stepover studies assumed a flat topography and didn't examine the influence of topography on the rupture behavior. Therefore, in this study, to investigate the effect of topography, I consider three cases: a flat topography, a positive (mountain) and a negative (basin) topography on only one side of the fault system outside of the stepover. In each case, I consider a suite of geometries with two 30 km long vertical planar segments with 5 km overlap and stepover widths of 2 to 8 km. I create a three-dimensional finite element mesh for each of those geometries and use FaultMod to compute the rupture dynamics. The results show a significant time dependent variation of the normal stress for the topography cases as opposed to the flat surface case. For a positive topography on the right of the rupture propagation for a left-lateral fault, there is a clamping effect behind the rupture front that prevents the rupture to jump a wider extensional stepover. The opposite is observed for a negative topography or positive topography on the left side of the rupture propagation, where the rupture can jump over a wider stepover than the flat case. These results suggest that topography seems to have significant impact on throughgoing rupture and should be considered in dynamic studies with geometric complexities such as stepovers, bends and branch fault systems.

Seismic Wave Propagation Finite Difference Simulation Based on Adaptive Mesh Refinement (AMR) Grid

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Finite-difference method (FD) is widely used for seismic wave propagation simulate because its efficiency and easy-usage. But low velocity basins cause smaller grid spacing to suppress the numerical errors below the required level and cause severe spatial and temporal oversampling, which is one well-known drawback of FD to simulate strong ground motion in complex basin structures. In this work, we adapt adaptive mesh refinement (AMR) grid to acoustic and elastic wave FD simulations. Unlike mesh refinement at shock waves in computational fluid dynamics, we implement mesh refinement according to velocity values of the velocity model: the mesh is adaptive refined in such a way that the grid spacing everywhere satisfies the minimal points per wavelength requirement of the FD scheme. To speed up the development, we did not create the AMR code from scratch but developed the code based on an existing AMR framework AMReX (https://amrex-codes.github.io/amrex/). We successfully implemented AMR with the staggered-grid finite-difference method to simulate 2D acoustic wave propagation and with the collocated-grid finite-difference method to simulate 2D and 3D elastic wave propagation. We used several numerical tests to demonstrate the stability, accuracy and efficiency of the proposed method in strong heterogeneous models. AMR data structure management and overlapping multi-level grid structures also introduce computational overheads. We discussed the factors influencing the computational efficiency.

Seismic Response of Nenana Basin, Central Alaska, From 3D Seismic Wavefield Simulations of Local and Regional Earthquakes

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The geometry and low wavespeeds of sedimentary basins trap seismic waves, leading to amplification and long-duration shaking. This seismic response of a sedimentary basin can be relevant both for understanding active tectonics and for assessing seismic hazards relevant to society. Using 3D seismic wavefield simulations, we can explore complex seismic wavefield propagation in the basins, wiggle by wiggle and frame by frame. Nenana basin in central Alaska is a promising region for studying basin wave propagation because its basement surface has been estimated from detailed active-source imaging and because there are about 15 broadband seismic stations in the region, enabling comparisons between simulations results (synthetics) and observations (data). We have created three Nenana basin region models in different mesh sizes: 1) the Berg et al. (2020) 3D tomographic model, 2) the Berg model with an embedded basin model, 3) a simplified model of an elliptical basin embedded in a background layered (1D) model. By comparing and analyzing the seismic simulation results in both time and frequency domain from these models, together with the real data collected in this region, we can investigate the detailed mechanism of basin amplification for a variety of different incoming waves and frequencies. We have also compared the basin seismic response from realistic models with recordings from seismic stations in the region, and, using these differences, we have generated sensitivity kernels that could potentially be used for a future tomographic inversion that accounts for regional and basin structures.

Modeling and Simulation of Response Spectra at Regional Distances for the September 19, 2022 (Mw 7.7) and September 22, 2022 (Mw 6.9) Michoacan, Mexico Earthquakes and Comparison With Observed Data

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On September 19, 2022 a 7.7 Mw subduction earthquake occurred in the coast of Michoacan, Mexico, along the tectonic interface between the Cocos and the North American plates. Various broadband and accelerometric seismological stations of the National Seismological Service of Mexico (SSN), recorded the ground motions produced by this earthquake. The closest station that recorded these motions was the MMIG-Maruata, observing maximum accelerations of Ans=1.09g in the North-South component and Aew=0.72g in the East-West component. The vertical acceleration observed had a maximum value of Az=0.68g. The largest aftershock occurred on September 22, 2022 with a magnitude 6.9 Mw and depth of 12.0km, located 23.0km SE from the mainshock. The closest station with available data for this earthquake was Zihuatanejo (ZIIG) showing a maximum acceleration of Ans=0.56g in the North-South component. In this work, we generated different theoretical ground motion scenarios and compared them with observations. To do this, on the one hand we performed a simulation of these two earthquakes by modelling the rupture of both seismic events, taking into account their locations, focal mechanisms and assuming different GMPEs for the interplate subduction tectonic regime; then we obtained the corresponding theoretical response spectra. On the other hand, an analysis of the seismic recordings obtained by the seismological stations was carried out to obtain the corresponding response spectra from the recorded accelerograms. After this, we compared the theoretical spectra obtained from the simulations of the different proposed scenarios with the observed spectra. From the modeled scenarios, our results show that depending on the GMPE assumed, spectral amplitudes are mostly underestimated at close distances from the source, and overestimated beyond a given distance to the source. An important observation results for the different central Mexico recording sites, where in most cases, the observation at large periods are allways underestimated by models. From these results, different explanations for the observed regional amplifications are proposed

Towards "Box Tomography" of Ultra-Low Velocity Zones at the Earth's Core-Mantle Boundary

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The earth's core-mantle boundary (CMB) is a significant boundary for the exchange of energy and material between the liquid outer core and the silicate mantle. Ultralow-velocity zones (ULVZ) with extreme material properties have been detected at the base of Earth's mantle through waveform modeling. The fine imaging of these small-scale objects requires seismic wave data with a period of 10 s or less and illumination from different directions. However, the computational time of global seismic simulations which increases as the 4th power of frequency makes the global waveform inversion of ULVZs challenging. Thus, "Box tomography" is being developed to improve image resolution of such kinds of target small-scale objects buried in the deep mantle. The computation of the wavefield consists of three parts: 1) from the sources to the boundary of the target region including the CMB, then inside the target region, and then from the boundary to the remote stations. The first and last parts are calculated using a global solver once and for all (here SPECFEM3D_globe), while the propagation inside the box is computed using a regional solver. At each iteration of the box tomography, the forward simulation is repeatedly performed only within the box, and the computational cost is proportional to the 3rd power of the size ratio between the box and the global Earth, making the higher resolution imaging possible (Adourian et al., 2022). In this study, after the implementation of the hybrid simulation, both for elastic and acoustic wave equations, and the absorbing boundary condition, we have designed a flexible way to combine two distinct solvers with different spatial meshes, including solid-fluid coupling across the CMB. Details of our approach and initial steps towards the imaging of the ULVZ at the root of the Iceland Plume are presented.

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Crossfade Markov Chain Monte Carlo Simulation for Fault Slip Modeling

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There are many underdetermined geophysical inverse problems. For example, when we try to infer earthquake fault slip, we find that there are many potential slip models that are consistent with our observations and our understanding of earthquake physics. One way to approach these problems is to use Bayesian analysis to infer the ensemble of all potential models that satisfy the observations and our prior knowledge.

Simulating a posterior PDF can be computationally expensive. Typical earthquake rupture models with 10 km spatial resolution can require using Markov Chain Monte Carlo (MCMC) to draw tens of billions of random realizations of fault slip. And now new technological advancements like LiDAR provide enormous numbers of laser point returns that image surface deformation at submeter scale, exponentially increasing computational cost. How can we make MCMC sampling efficient enough to simulate fault slip distributions at sub-meter scale using Big Data?

Here we describe a new MCMC approach called crossfading in which we transition from an analytical posterior PDF to the desired target posterior PDF. This approach has two key efficiencies. First, the starting PDF is by construction close to the target posterior PDF, requiring very little MCMC to update the samples to match the target. Second, all PDFs are defined in model space, not data space. The forward model and data misfit are never evaluated during sampling, allowing models to be fit to Big Data with zero computational cost. It is even possible, without additional computational cost, to incorporate model prediction errors for Big Data, that is, to quantify the effects on data prediction of uncertainties in the model design. While we present earthquake models, this approach is flexible and can be applied to many geophysical problems. This approach is suitable for many hardware architectures, and our algorithm has been run on large-scale clusters, with GPU acceleration, and using vector machines.

Numerical Modeling in Seismology: Developments and Applications [Poster]

Poster Session • Thursday 20 April

Conveners: Peter Moczo, Comenius University Bratislava (moczo@fmph.uniba.sk); Alice-Agnes Gabriel, University of California, San Diego (algabriel@ucsd.edu); Jozef Kristek, Comenius University in Bratislava (kristek@fmph.uniba.sk); Wei Zhang, Southern University of Science and Technology (zhangwei@sustech.edu.cn); Martin Galis, Comenius University in Bratislava (martin.galis@uniba.sk); Emmanuel Chaljub, Université Grenoble Alpes (emmanuel.chaljub@univ-grenoble-alpes.fr)

A New Method for Dissipating Energy in Dynamic Earthquake Rupture Simulations: Non-Linear Radiation Damping

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We introduce 'non-linear radiation damping', a new mechanism that dissipates energy in elastic dynamic rupture simulations and results in more realistic ground motions and slip velocities, while not requiring the large number of assumed variables in viscoplastic methods. Computational simulations of dynamic earthquake rupture help us learn about earthquake source behavior and the resulting ground motions. A challenge with these types of simulations is that they require many assumptions, including the fault geometry, the fault friction constitutive laws, the rock properties, and the initial stress conditions. Although we have some information about these parameters, much of the information is unknown. This requires modelers to make many assumptions, with one of the most common assumptions being that rocks respond elasti-

cally to sudden changes in stress and strain. An elastic rock response is helpful in that it allows for a simplification of the initial stress conditions. However, an elastic rock response can also lead to simulated on-fault slip rates and off-fault ground motions that are faster than those inferred from earthquake observations. Our work provides a solution to this problem. We propose a new method, which we call 'non-linear radiation damping'. The implementation is simple, and just requires adding the non-linear radiation damping term to the friction formulation. The result is slower on-fault peak slip rates and ground motions, similar to what might be achieved by incorporating a complex viscoplastic framework, but without the need to assume values for a variety of unknown features such as the initial stress conditions and rock yielding parameters at all locations in an earthquake region.

Reference: Barall, M., and R.A. Harris, Non-linear radiation damping: A new method for dissipating energy in dynamic earthquake rupture simulations, manuscript submitted to The Seismic Record, January 2023.

Adjoint-Based Synthetic Inversions for Recovering 3D Anisotropic Structures

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Laboratory measurements confirm the presence of complex (low-symmetry) elasticity in a wide range of minerals. The presence of anisotropy in the uppermost mantle is well established. In subduction settings, anisotropy is complex, with different elements—the subducting plate, the mantle wedge, and the crust—potentially having different forms of anisotropy. Seismic imaging problems have non-unique solutions, and the addition of parameters due to the consideration of anisotropy makes the problem even more challenging. Seismic inversion techniques can be tested with the help of synthetic tests, whereby a synthetic target model is used to generate synthetic observed data, for a given source station geometry, which in turn is used to test the recovery of the target model using the technique in consideration. For this, we set up target model blocks, each with a central sub-block of homogenous anisotropy, while the remainder of the model block is homogeneous isotropic. The source station geometry is designed such that we have good, yet feasibly realistic, coverage of the medium. We test several factors that influence the retrieved model: different anisotropic symmetry classes, the source-station coverage, and added noise in the synthetic data. Our study prepares us for realistic synthetic inversions for complex anisotropic structures, which, in turn, will guide efforts for performing adjoint tomography in the Alaska subduction zone.

adjTomo: An Open-Source, Python Toolkit for Adjoint Tomography and Full Waveform Inversion

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Adjoint tomography is a seismic imaging technique that minimizes differences between observed and synthetic waveforms to generate high-resolution images of Earth structure. It is computationally and algorithmically complex, and often requires substantial programming investment to reduce the amount of redundant human effort required during a workflow. Tasks such as wavefield simulations, seismic data processing and interactions with high performance computers may be repeated hundreds to thousands of times during a tomographic inversion. Currently, closed-source software, lack of documentation or loss of active code maintainers make it difficult to leverage existing workflow tools. In an effort to provide a unified set of tools for the entire adjoint tomography community, we present adjTomo: open-source, Python-based tools for adjoint tomography. adjTomo tools tackle the tasks of seismic data manipulation, compute-system interaction, and workflow automation, working alongside existing 2D and 3D numerical solvers (e.g., SPECFEM). The software emphasizes documentation, tutorials and unit testing, which ensure the software can be used, understood and modified by future users and developers. The aim is to foster community research codes which can be adopted and improved by the seismological community. adjTomo packages have been used for published studies, including a real data inversion of an active subduction zone, and numerous synthetic inversion experiments. Here we showcase the software, their supporting material, and associated ongoing research projects.

An Equivalent Point-Source Stochastic Simulation of the NGA-East Ground-Motion Models

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In this study, a point-source stochastic ground-motion model (GMM) is developed by utilizing a particle swarm optimization (PSO) genetic algorithm (GA) to invert a weighted average of the median 5%-damped spectral acceleration predicted from the Next Generation Attenuation-East (NGA-East) ground-motion models (GMMs), yielding a well-constrained set of ground-motion parameters. First, algorithmic differentiation is used to ensure a broad range of magnitudes and distances are used in the inversion, and that each parameter has unique influence on the model. Then, the inversion is performed separately for magnitudes ranging M = 4.0-8.0. Each inversion includes rupture distances R_{rup} = 1-1000 km and periods T = 0.01-10s, and National Earthquake Hazard Reduction Program (NEHRP) Site Class A. This study is the first to perform a formal inversion using the GMMs developed for the NGA-East project. The approach has been validated by using simulated small-to-moderate magnitude and large-magnitude data derived from the NGA-West2 GMMs (Zandieh et al., 2016, 2018; Pezeshk et al., 2015).

Computational Study of Foreshocks in the Burridge-Knopoff Earthquake Model Using Machine Learning

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The study of mechanical models of earthquake faults are important to understand the different behaviors observed in real earthquakes. The model we consider for this work was introduced by Burridge and Knopoff [Bull. Seismol. Soc. Am. 57, 341 (1967)], which, consists of blocks connected by linear springs in contact with a moving rough surface. It was implemented a numerical simulation of the model founding a wide variety in the events size which have a power law distribution. As the next step, it was made a data base of artificial earthquakes with the purpose of training an artificial neural networks (ANN) model that are able to predict the events generated by the simulation. The ANN models have an acceptable prediction to calculate the event magnitude, but it was found that they have difficulty to predict the time when they occurred.

Earthquake Ground Motion Selection for Time History Analysis of Structures Using an Evolutionary Algorithm

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This study proposes a biogeography-based algorithm (BBO) for selection of a set of seismic ground motions (GM). Uniform hazard spectrum (UHS) can be selected as the target spectrum. We considered two sites from two different geographical areas in the United States, first site is in Memphis, and second site is in San Francisco. Selected ground motions are subjected to scaling factors that are scalar values within the user-specified range. As a result, there is no alteration to the phase or shape of the response spectra of earthquake ground motions. The proposed method can search a set made up of thousands of earthquake records and recommend a desired subset of records that match the target design spectrum. BBO, which considers the union of 7 or 11 records and appropriate scaling factors, is employed to complete this task. The process is quick and reliable, producing recordings that closely match the target spectrum with the least amount of manipulation and variation from the target spectrum. In Addition, we provided some error measures between target spectrum and the predicted spectrum that is obtained by mean of selected records (7, or 11 records) for both sites. Results indicate that the suggested solution model can be viewed effective for acquiring suitable GM record sets to be used for time history analysis within a probabilistic seismic design.

Earthquake Rupture Simulations on Faults with Different Degrees of Cementation

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Earthquakes are usually modeled as a frictional instability propagating along a preexisting weakness plane. The evolution of shear stress with fault slip is described by failure parameterizations obtained from frictional experiments e.g., slip-weakening or rate-and-state friction. While this modeling approach is appropriate for some tectonic faults, induced earthquakes and earthquakes happening on faults with significant degrees of interseismic healing might require different failure parameterizations taking fault cementation into account.

Here we investigate how the cementation degree of fault gouge affects fault failure parameterization and earthquake rupture properties. Previously, Casas et al. (2022) performed direct shear discrete element simulations with different percentages of cementation prescribed within the fault gouge (i.e. different contact laws between particles) and found that increasing cementation enhances the maximum shear strength and gouge brittleness, increases the fracture energy magnitude, and changes the shape of the failure parameterization from smooth curves with pronounced strengthening and single weakening to sharper double weakening curves. To understand how these failure parameterizations affect macroscopic earthquake observables, we derive analytical equations that approximate the numerically obtained curves and use them in finite element simulations of earthquake ruptures. We model earthquake nucleation quasi-statically and the coseismic phase of the earthquake rupture dynamically. We find that surfaces with lower degrees of cementation accumulate substantial magnitudes of slip of significant lateral extent during earthquake nucleation, unlike higher cementation surfaces that produce negligible preseimic slip. Dynamic models of coseismic phase show differences in cumulative slip, maximum slip rate, and earthquake spectra which are related to the differences in stress drop and fracture energy of the different failure parameterizations.

Effects of Random Small-Scale Heterogeneities in 1D, 2D and 3D Modeling of Earthquake Ground Motion in a Halfspace and in a Local Sedimentary Basin

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The effect of random small-scale heterogeneities in lithosphere and crust has been well recognized for more than a half of century. There is an increasing number of indications that random heterogeneities can play an important role also in modelling earthquake ground motion especially in local surface sedimentary and topographic structures. The problem is being addressed recently in observational and numerical-modeling studies.We present results of comparison of effects of Random Small-scale Heterogeneities in 1D, 2D and 3D Modeling of Earthquake Ground Motion in two very different macroscopic models - a halfspace and a local sedimentary basin in Colfiorito, Italy.The main reason for the analysis of results of extensive finite-difference simulations of seismic motion was to look at differences in seismic motions due to reduced dimensionality of the 3D problem. While it is obvious that 3D modeling would be a prime wish and approach, the real practice often restricts numerical-modeling approach to 2D or, even worse, to 1D case due to a variety of reasons, e.g., high computational demands, practical limitations in data and/or knowledge of a local structure.Our analysis is thus related also to a practical aspect/question in earthquake ground motion analysis and prediction – the possibility to estimate 3D effects of random small-scale heterogeneities based on 2D or even 1D numerical simulations.

Higher-order Finite-difference Spatial Operators Across a Material Interface

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Recently, we have analyzed consequences of the heterogeneity of the medium, spatial discretization and the Nyquist-wavenumber band limitation for a finite-difference (FD) modeling of seismic wave propagation and earthquake ground motion. We have found that: 1) The grid representation of the material interface must be limited by the Nyquist wavenumber. 2) The wavenumber band limitation replaces spatial derivatives both in the homogeneous medium and across a material interface by continuous spatial convolutions. 3) The convolution of an infinite spatial extent must be replaced by a finite-extent discrete convolution, that is, by a proper FD spatial operator.It is obvious that higher-order FD schemes significantly reduce grid dispersion in smoothly and weakly heterogeneous medium. Higher-order schemes involve relatively spatially-long FD operators. Can a long FD operator be applied across a material interface? Are the higher-order FD operators more accurate in evaluating spatial derivatives across a material interface?We compare errors of spatial derivatives obtained using the spatial FD operators of the 4th, 6th, 8th, 10th and 12th orders across the material interface for two interface representations. In the first one, a sharp material discontinuity is represented using an exact Heaviside step function. In the second one, the same material discontinuity is represented using a wavenumber band-limited Heaviside step function.Based on the numerical investigations, we formulate implications for the FD modeling of seismic waves and earthquake ground motion in media with material interfaces.

Nonlinear Pseudostatic Analysis of Seismic Responses to Differentially Interconnected Structures in Aggregate Masonry Structures in a High-Seismic-Risk

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In seismic risk studies, the vulnerability of dwellings is analyzed by the behavior of isolated buildings, although in densely populated cities buildings are usually displayed in aggregate form. Previous studies in historical centers of unreinforced masonry dwellings, show the importance of considering interconnected behavior of aggregate structures to analyze the damage caused by dynamic loads acting on complexes. Costa Rica is located in a high seismic hazard area where there are often clustered partially grouted reinforced concrete block masonry buildings. The purpose of this work is to analyze the seismic behavior of the most common types found in San José, Costa Rica, especially when comparing the different inter-dwelling connections that usually exist in structural aggregates with respect to the response of isolated structures.

Nonlinear pseudostatic analysis was performed using macroelement modelling. This approach enables us to investigate the seismic behavior of aggregate masonry structures at a very low computational cost. To study the applicability of the proposed model for partially grouted reinforced concrete block masonry, studies are carried out considering an isolated structure. Then, identical structures will be added in a row using four approaches in the connections between adjacent buildings. Each of these modelled connections represents a constructive reality in the urban area. The results show that the responses to these typologies differ considerably when considered isolated or aggregate. In addition, the seismic capacity of the structure within the aggregate is different depending on its position. Furthermore, important differences in resistance and failure mechanisms are observed when diverse types of connections between dwellings are considered. This study enables the establishment of the importance of connections in aggregate buildings in areas with high seismic risk.

Using Dynamic Rupture Simulations to Investigate the Effects of Topography on Rupture Propagation Along Branch Faults: Implications for the San Andreas and Garlock Faults

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The San Andreas (SAF) and Garlock (GAF) fault intersection in Southern California represents the juncture of California's two longest faults. Paleoseismic studies suggest this section of the SAF has hosted some of the largest earthquakes in California (M 7.9 1857 Fort Tejon Earthquake) with an estimated recurrence interval of 100-150 yrs for M > 7 events. Therefore, determining whether rupture will stop or propagate through this juncture is vital to the estimation of seismic hazard. Numerical models of branch faults have described many factors that affect the ability of rupture to propagate through discontinuities. Many branch fault systems are located in regions with asymmetric topography. Previous dynamic studies investigating the effect of asymmetric topography on a single fault have demonstrated that topography causes normal stress perturbations during rupture. Thus, considering the irregular topography at the SAF-GAR junction, it is worth investigating whether this topography has any effect in influencing rupture to propagate or not past the branch intersection. In this work we first run simple planar models with 5 different synthetic topographies to isolate the effects of topography on the rupture process on branch faults. Our results indicate that topography can introduce dynamic clamping and unclamping phases during the rupture which can lead to different rupture behavior at the branch intersection. We then consider a more realistic fault model of the SAF-GAR intersection with the actual topography. In this simulation, consistent with the simple models, our result shows that incorporating real topography leads to different rupture behavior in comparison to a model with no topography. This suggests that although dynamic phases are smaller in magnitude than static stress changes, they could be sufficient to cause failure if the branch is weak. We plan to further investigate this by considering a variety of on fault stresses as well as nucleation location.

Opportunities and Challenges for Machine Learning Applications in Seismology

Oral Session • Wednesday 19 April • 10:30 AM Pacific

Conveners: Nishtha Srivastava, Frankfurt Institute for Advanced Studies (srivastava@fias.uni-frankfurt.de); Filippo Gatti, CentraleSupélec, Université Paris-Saclay (filippo.gatti@centralesupelec.fr); Quentin Brissaud, Norwegian Seismic Array (quentin@norsar.no); Claudia Q. Cartaya, Frankfurt Institute for Advanced Studies (quinteros@fias.uni-frankfurt.de); Florent Aden, GNS Science (f.aden@gns.cri.nz); Kiran K. Thingbaijam, GNS Science (k.thingbaijam@gns.cri.nz)

Pickblue: Seismic Phase Picking for Ocean Bottom Seismometers With Deep Learning

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Detecting phase arrivals and pinpointing the arrival times of seismic phases in seismo- grams is crucial for many seismological analysis workflows. For land station data ma- chine learning methods have already found widespread adoption. However, deep learning approaches are not yet commonly applied to ocean bottom data due to a lack of ap- propriate training data and models. Here, we compiled a large and labeled ocean bottom seismometer dataset from 15 deployments in different tectonic settings, comprising ~90,000 P and ~63,000 S manual picks from 13,190 events and 355 stations. We adapted two popular deep learning networks, EQTransformer and PhaseNet, to include hydrophone recordings, either in isolation or in combination with the three seismometer components, and trained them with the waveforms in the new database. The performance is enhanced by employing transfer learning, where initial weights are derived from models trained with land earthquake data. Our final model, PickBlue, significantly outperforms neural networks trained with land stations and models trained without hydrophone data. The model achieves a mean absolute deviation (MAD) of 0.06 s for P waves and 0.10 s for S waves. We integrate our dataset and trained models into SeisBench to enable an easy and direct application in future deployments.

Phasehunter: Seismic Wave Onset Time Determination Through Probabilistic Deep Learning Regression

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Seismic phase picking is the process of identifying the onset time of seismic waves in a seismogram. The onset time is one of the most important measurements in seismology because it is used in a wide range of applications such as earthquake location, seismic tomography, source discrimination, and earthquake early warning. The detection and picking of seismic phases is a difficult and labor-intensive task when performed manually, and it becomes particularly challenging during times of high seismic activity. We have developed a deep learning method that measures the onset time of seismic waves through probabilistic deep regression. Previous deep learning methods that have been developed for this purpose treat onset time determination as a classification problem operating on discretely sampled time series. Instead, we treat it as a regression problem, which enables - at least in principle - sub-sample accuracy. Our method also estimates onset time uncertainty, which can be used to increase the reliability of phase association and location accuracy.

Calibrated Uncertainty Estimates for Deep Learning-Based Phase Arrival Time Estimates

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Few techniques exist for estimating the prediction uncertainty of deep learning models. Nominally, estimates of prediction uncertainty are obtained by sampling from the predictive distribution, but this task is computationally intractable for deep learning models with millions of parameters. Consequently, a Bayesian approximation method must be used. Dropout at inference time is a common approach but generally fails to approximate the true posterior effectively. Here, we use a method called Stochastic Weight Averaging with Gaussian posterior (SWAG). This method explores a mode of the model posterior during training using stochastic gradient descent with a large learning rate. It computes and stores a mean for each model parameter and approximates a low-rank covariance matrix. At inference time, many model realizations can efficiently be sampled from the distribution of model parameters. We produce an ensemble of SWAG models, known as MultiSWAG, to compute phase arrival times and their uncertainties. We then compare the uncertainty estimates to those from dropout. We find the two methods are comparable when an appropriate dropout rate is selected. MultiSWAG produces a broader range of predicted pick distributions than dropout without overly restricting the minimum potential width. Additionally, MultiSWAG uncertainties show a stronger correlation with signal-to-noise ratio. However, MultiSWAG requires more hyperparameter tuning and is ~6-7 times slower. Both methods produce broader prediction distributions when shown noise examples. In either case, deep learning models are often over-confident, so we utilize an efficient, model-agnostic method of empirically calibrating the uncertainties to produce meaningful credible intervals. Before calibration, only 47% of the predicted MultiSWAG standard deviations for a test set contain the analyst pick. Afterward, 66% of analyst picks are within the predicted 68% credible interval bounds.

Ditingtools and Ditingbox: Seismic Big Data Processing via Edge and Cloud Computing

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In the era of seismic big data, traditional “centralized” data processing methods are increasingly facing bottlenecks in data transmission, data storage, and peak data processing capabilities. We suggest that “decentralized” data processing via edge and cloud computing will be a solution to that dilemma and would become the next-generation tool in observational seismology. To achieve this goal, two major points should be considered in practical applications: (i) sufficiently robust data processing algorithms that can handle the variety of big seismic data recorded in different regions; (ii) edge devices that can deploy these algorithms for real-time data processing on the instrument side.

Based on a large-scale Chinese seismic benchmark dataset (the so-called “DiTing” dataset) and several other big datasets such as STEAD and INSTANCE, we have developed and trained several deep learning neural networks for seismic analysis, which are collectively referred to as

"DiTingTools": the U-net architecture "DiTingPicker" for earthquake detection and P and S arrival-time picking, the Holistically-Nested Edge Detection architecture "DiTingMotion" for further P first polarity determination, and the Convolutional Network "DiTingAzi" for single station azimuth estimation. These models have good generalization ability, and more importantly, they can be deployed on edge devices with limited computing resources. We also designed an edge device named "DiTingBox" to deploy "DiTingTools", which can predict earthquake phases, azimuths, and magnitudes in less than 5 seconds after receiving an earthquake signal with a power consumption of only 1 watt. Finally, we can build a big data processing system by combining "DiTingBox" with cloud computing, which gathers outputs from individual stations and conducts multiple-station analysis on the cloud including phase association, earthquake location, and focal mechanism inversion. This system could be used in rapid earthquake cataloging, earthquake nowcasting, as well as aftershock monitoring.

Neural Mixture Model Association of Seismic Phases

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Seismic phase association is the task of grouping phase arrival picks across a seismic network into subsets with common origins. Building on recent successes in this area with machine learning tools, we introduce a neural mixture model association algorithm (Neuma), which incorporates physics-informed neural networks and mixture models to address this challenging problem. Our formulation assumes explicitly that a dataset contains real phase picks from earthquakes and noise picks resulting from phase picking mistakes and fake picks. The problem statement is then to assign each observation to either an earthquake or noise. We iteratively update a set of hypocenters and magnitudes while determining the optimal class assignment for each pick. We show that by using a physics-informed Eikonal solver as the forward model, we can impose stringent quality control on surviving picks while maintaining high recall. We evaluate the performance of Neuma against several baseline algorithms on a series of challenging synthetic datasets and the 2019 Ridgecrest, California sequence. Neuma outperforms the baselines in precision and recall for each of the synthetic datasets. Furthermore, it detects an additional 3285 more earthquakes than the best baseline on the Ridgecrest dataset (13.5%), while substantially improving the hypocenters.

Semiai Seismic Detection and Picking: An Application to Active and Passive Seismic Data for the Tomography of the Stromboli Volcano Island.

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In several seismic applications, including seismic location and tomography, the detection and selection of seismic waves is essential. The application of artificial intelligence to earthquake analysis is a relatively recent development which attempts to tackle these objectives. Today's machine learning methods greatly benefit from the availability of large earthquake datasets that can be employed throughout the training process. However, data related to active seismic experiments is still limited. At Stromboli, a large seismic database combining active seismicity data (air-gun shots) and local earthquakes was created as a result of two active seismic experiments conducted at the end of 2006 and during 2014, as well as a greater number of earthquakes acquired across a wider temporal range. Therefore, an automated and extremely accurate phase arrival picking is required to analyze this large amount of data and execute a seismic velocity tomography to examine the internal structure of the volcano. In this work, we developed an automatic SEMI Artificial Intelligence (SEMIAI) method for the detection and the picking of seismic events. The shortage of active seismic data is circumvented by employing a polarization and spectral analysis for the detection, while the picking relies on a deep neural network. This in order to distinguish the active seismic events from earthquakes and volcanic events. As first step, the SEMIAI methodology has been applied to the Stromboli's 2006 active seismic dataset. We focused on this dataset because it had a large number of active seismic sources and stations (1500 shots recorded at 42 stations), both on land and offshore (ocean bottom seismometer), as well as about 300 local earthquakes. The tomography of the Stromboli Volcano island provided by the automatic dataset is practically the same as the one previously obtained by using manually picked phases, demonstrating the effectiveness and efficiency of the SEMIAI method.

Developing a Seismicity Catalog at Mayotte With Deep-Learning-Based Picking and Phase Association

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The active seismic sequence off the coast of Mayotte island, in the Mozambique channel, that began in 2018 has drawn much attention, due to the high seismic activity which was strongly felt by the local population. The detected seismic events have been made primarily with either human analyst assistance (Saurel et al., 2022) or a combination of deep-learning-based (DL) picking and traditional phase association methods (Retailleau et al., 2022). These catalogs have detected 1000s of earthquakes and concentrated seismic activity at ~35 km depth, within ~30 km of the newly developing volcanic vent. Nonetheless, the high density of events in time apparent from visual inspection (>1000 events per day during the highest activity) indicates a large fraction may still be missed, such as for small events and those occurring close to one another in time and space. Similarly, false positives may result from using traditional associators (e.g., Earthworm) on such high pick rate sequences, since such associators were designed before the era of DL-based pickers.

In this work, we revisit the Mayotte seismic sequence and process the local ocean bottom seismometer (OBS) data using both PhaseNet picking, and the recently developed graph neural network associator, GENIE (McBrearty and Beroza, 2022), initially trained for regional scales in northern California. We compare our developed catalog using GENIE with the existing automated approach (Retailleau et al., 2022). We measure the rate of matched and distinct events obtained in either catalog, for a range of different threshold and hyper-parameter choices. On average, we find ~70% matched events. The non-overlapping seismic events appear to be the smallest events, and we look for additional systematic trends that can explain differences in the catalogs. Our findings reveal new insights into the Mayotte seismic sequence and demonstrate the generalizability of GENIE to local networks.

Magma Movement Revealed by Unsupervised Spectral Feature Characterization of Seismicity at Axial Seamount

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Axial Seamount is an active submarine volcano on the Juan de Fuca Ridge which last erupted in April 2015. The eruption was captured by the OOI cabled, 7-station OBS array that started operation 5 months before the eruption. The array records signals from a variety of sources, providing crucial constraints on the dynamics of Axial's magma system and its complex ring faults. We used supervised machine learning and double-differences to compute a 7-year long, high-precision earthquake catalog of over 160,000 events. Here, we explore this catalog with an unsupervised spectral feature extraction method (SpecUFEx) to characterize time-dependent variations in the event spectrograms. We condensed the spectrograms with nonnegative matrix factorization and hidden Markov model to reduce dimensionality and built fingerprints that best represent the events' time-variant spectral features. These fingerprints were then clustered by a k-means algorithm to form groupings of events based on their spectral characteristics. Among the groupings we find clusters corresponding to signals of earthquakes, impulsive events generated by hot lava reaching the sea floor, and fin whale calls. Another cluster includes characteristic waveforms with a rich low frequency train following the first arrival. These low-frequency events (LFEs) first appeared in the northern part of the caldera a few hours before the 2015 eruption at depths near the top of the magma chamber (1.5-2 km), in an area of large seafloor deformation. The LFEs then migrated south along the eastern ring fault and intensified and moved upward near where fresh lava first reached the sea floor in the central part of the caldera, consistent with the onset of small deformation recorded at the tilt sensors. We interpret the LFEs as localized brittle failure in response to

magma movement prior to the eruption. We show that by combining supervised and unsupervised machine learning we can efficiently discriminate between various types of seismic sources at high spatial and temporal resolution, which in our particular case may help forecast the timing of Axial's next eruption.

Medium Changes and Source Diversity Revealed by Unsupervised Machine Learning.

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The description of the evolution of seismic signals is most often relying on discontinuous catalogues of events, and by temporal evolution of elastic parameters deduced from extensive signal processing. We will present two examples where machine learning, namely a scattering network combined with independent component analysis, is used to monitor medium changes or the dynamic evolution of seismic activity from continuous records.First, we investigated the signature of a thin centimetric layer of ground freezing at the surface, inducing known subtle changes in the medium. With ICA we reduce the dimension of the scattering network output and use a hierarchical clustering to identify clusters associated with freezing despite despite the extreme variability of urban-induced noise sources surrounding the station. We found that actually one the components of the ICA is precisely describing the temperature, meaning that the surface freezing is directly encoded in the seismograms and can be extracted automatically with our approach. This suggests that slight changes could be detected without relying on difficult measurements of physical parameters such as seismic speed temporal change. Second, we studied volcanic tremors that cover a wide range of different signal characteristics. Despite their complex signal characteristics and their different source mechanism, volcanic tremors are either treated as one seismic signal class or as a set of seismic signal classes. We apply blind source separation methods and manifold learning techniques to continuous seismograms and reveal the underlying patterns in the time series data dominated by volcanic tremors. During a year period, the data-driven descriptors of the seismogram recorded at the active Klyuchevkoy volcano reveal an ever-changing tremor signal, challenging the division of the observed volcanic tremors into a few distinct classes. The results highlight the complexity and non-stationarity of the volcanic tremors, revealing a non-stationary volcanic system.

Mutual Information Between Seismic and Geodetic Data Revealed with Machine Learning in Mexico

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Slow-slip events are typically seen in geodetic measurements and can occur during "slow earthquakes" recorded in seismic data. The connection between these two phenomena is still being discussed nowadays, primarily due to the difficulty in identifying the specific seismic signatures of slow earthquakes. Detecting the seismic signatures associated with slow-slip events would be a crucial step toward understanding these phenomena and their role in the seismic cycle. This study explores how utilizing machine learning can aid in understanding the relationship between geodetic and seismic data. Through analyzing a decade of continuous seismograms from a station in Guerrero, Mexico, using a deep scattering network and independant component analsyis, we identify the seismic features that correspond to geodetic movements, suggesting that the seismic signals of slow-slip events can be (empirically) defined. Additionally, we investigate the properties of the associated seismic wavefield to gain insight into how these events contribute to overall displacement seen in geodetic measurements.

Pisgan: Physics-Informed Seismic Waveform Generator Trained With a Large-Scale Seismic Benchmark Dataset of China

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Every year, millions of earthquakes occur around the world. Some of the large ones can cause serious hazard to constructions and facilities. The prediction of ground motion in specific locations can help mitigate the seismic risk. Traditional physics-based ground motion modeling methods suffer the problems of model misspecification, high computational cost, and uncertainty quantification. In this study, we introduced PISGAN – Physics-informed Seismic Generative Adversarial Networks – as an alternative simulator to generate realistic seismic waveform. The PISGAN was implemented with the architecture of conditional deep convolutional GAN. We embedded physical information, such as epicenter distance, azimuth angle, and velocity model, as conditions to both the generator and the discriminator of our PISGAN. The ability of the PISGAN was first validated by synthetic tests. Then, the PISGAN was trained with data from DiTing, a large-scale Chinese seismic benchmark dataset. The trained PISGAN can generate realistic seismic waveforms with "Chinese characteristics" that can fool human experts and models, including traditional models and neural networks.

Rapid 3D Seismic Waveform Modeling using U-Shaped Neural Operators (U-NO)

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Recent development of Neural Operators such as the Fourier neural operator enables accurate approximation of the various operators used in scientific research. Within seismology, successful application of Fourier neural operators on solving the acoustic wave equation and the 2D elastic wave equation and apply them to full waveform inversion build the basis for further development of the methods. In this presentation, we extend prior efforts to use U-NO for solving the 3D elastic wave equation in seismic waveform modeling. Using the high-performance computing facilities, a general solution operator to the 3D elastic wave equation can be learned from an ensemble of numerical simulations generated by using random velocity models as well as the source locations. We will show the initial results as well as the difficulties we encountered to train the U-NO model.

Ground Motion Models: Comparison Between Traditional Regression-based Techniques and Machine Learning Approaches

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This study aims at a comparison between traditional methods for predicting ground motion Intensity Measures (IMs), usually based on linear regression, and machine learning techniques, which are widely used today for different purposes thanks to the increasing availability of data and computing performance. Typically, Ground Motion Models (GMMs) are empirical equations to estimate IMs as a function of several variables, generally related to the seismic source (e.g. magnitude), source-to-site distance (e.g. Joyner-Boore distance), and local site conditions (e.g. site categories or VS30). An alternative could be the use of machine learning (ML) algorithms, non-parametric models that are fully trained by data. We investigate the efficiency of different ML algorithms to identify the most suitable for predicting ground-motion using the data set used by Lanzano et al (2019) to derive the most recent ground-motion model for Italy. We explore different Matlab© ML algorithms and we split the dataset randomly into two parts, 70% as training data and 30% as test data, such that each class is correctly represented in the resulting subsets. We find out that the Gaussian Process Regression (GPR) significantly reduces the standard deviation associated with the predictions. The predictions by the GPR are compared with the Lanzano et al. (2019) model, in order to quantify the differences in terms of standard deviation, which is broken down into between-event, between-station, and event- and site-corrected components, implemented as random effects.

The differences between the two approaches are maximized when the variable sampling is poor since the ML approach tends to reproduce, with small uncertainty, the few observations available, which could be extremes.

Reliable predictions can be obtained when the combination of all predictor variables is well sampled by high volumes of data (e.g. 1000 observations or more). At present times this goal can be achieved with worldwide data sets.

Applications of Machine Learning to Earthquake Early Warning and Ground Motion Prediction Equations

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In this study, we applied machine learning approaches to predict possible strong ground motions for earthquake early warning (EEW) and ground motion prediction equations (GMPEs). Regarding EEW, many AI-based algorithms have been proposed for on-site warning. In contrast, the waveforms' spatial characteristics are seldom implemented into the algorithm, with one exception being Münchmeyer et al.'s Transformer Earthquake Alert Model (TEAM) (2021). In our study, we applied the TEAM model to the Taiwan region by implementing the strong-motion waveforms obtained by the Taiwan Strong Motion Instrumentation Program (TSMIP) network. We trained the TEAM model using features of the traces within three seconds after P-wave arrivals that the convolution neural network had extracted and the transformer model linked to station locations. We further expanded our model to predict not only peak ground acceleration (PGA) but also peak ground velocity (PGV) to provide a wider application to end users.

To establish a set of AI-based GMPEs, we compared the performance of the models considering Support Vector Regression, Random Forest Regression, Gradient Boosting Regression, and XGBoost Regression and reduced the prediction error by taking advantage of ensemble learning. We applied this approach to build GMPEs for crustal earthquakes in Taiwan by implementing the strong-motion records from the TSMIP network. Comparing our results with observations, we found our GMPEs underestimated the ground shakings for large events due to insufficient observations. To solve the imbalanced numbers of events for some parameters (e.g., magnitudes, rupture distance, and site amplification factor), we implemented GAN, SMOTR, and Gaussian noise methods to synthesize artificial data for training to improve model performance. Furthermore, we used the grid search method to find the best solution for the hyperparameters and collect total combinations into MySQL to identify differences. We presented the GMPEs in the forms of not only PGA and PGV, but also various periods of spectral acceleration (SA).

Fully Automated DAS Signal Denoising Using Weakly Supervised Machine Learning and Spliced Optical Fibers

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We present a weakly supervised machine learning method for suppressing strong random noise in distributed acoustic sensing (DAS) data. The method aims to map random noise processes to a chosen summary statistic, such as the distribution mean, median or mode, whilst retaining the true underlying signal. This is achieved by splicing (joining together) two fibers hosted within a single optical cable, recording two noisy copies of the same underlying signal corrupted by different realizations of random observational noise. A deep learning model can then be trained using only these two noisy copies of the data to produce a completely denoised copy. We use a dataset from a DAS array deployed on the surface of the Rutford Ice Stream in Antarctica. Despite being a very low anthropogenic noise environment, strong random noise processes heavily dominate the signal from microseismic icequake events. We demonstrate that the proposed method greatly suppresses incoherent noise and enhances the signal-to-noise ratios (SNR) of these microseismic events, enhancing the performance of subsequent processing steps, such as event detection. We further demonstrate that, following training, this approach is more efficient and effective than standard frequency filter routines and a comparable self-supervised learning method, known as jDAS. Our preferred model for this task is extremely lightweight (three hidden layers, 47,330 model parameters), processing 30 secs data recorded at a sample frequency of 1000 Hz over 985 channels (~ 1 km of fiber) in < 1 sec. The model is trained in a 'weakly supervised' manner, such that it requires no manually-produced labels (i.e., pre-determined examples of clean event signals or sections of noise) for training, and doesn't require prior assumptions on the distribution of the noise or event signals, other than that they are independent. Due to the inherently high noise levels in DAS recordings, efficient data-driven denoising methods, such as the one presented, will prove essential to time-critical DAS detection and early warning processing workflows, particularly in the case of microseismic monitoring.

Opportunities and Challenges for Machine Learning Applications in Seismology [Poster]

Poster Session • Wednesday 19 April

Conveners: Nishtha Srivastava, Frankfurt Institute for Advanced Studies (srivastava@fias.uni-frankfurt.de); Filippo Gatti, CentraleSupélec, Université Paris-Saclay (filippo.gatti@centralesupelec.fr); Quentin Brissaud, Norwegian Seismic Array (quentin@norsar.no); Claudia Q. Cartaya, Frankfurt Institute for Advanced Studies (quinteros@fias.uni-frankfurt.de); Florent Aden, GNS Science (f.aden@gns.cri.nz); Kiran K. Thingbaijam, GNS Science (k.thingbaijam@gns.cri.nz)

A Curated Pacific Northwest Seismic Dataset

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The Pacific Northwest (PNW) region of the United States is a dynamic tectonic plate boundary between the North American continental plate and the Juan de Fuca oceanic plate. The active margin between the two plates is a subduction zone that hosts a wide range of earthquake, near surface, and volcanic behaviors.

The curation of seismic data and metadata sets is the cornerstone of seismological research and the starting point of machine-learning applications in seismology. We present a 21-year-long diverse data set of seismic events, their metadata, and their waveforms, as curated by the Pacific Northwest Seismic Network (PNSN) and ourselves. We describe the earthquake catalog, the temporal evolution of the data attributes (e.g., event magnitude type, channel type, waveform polarity and signal-to-noise ratio, phase picks) as the network cataloging system evolved through time. We also pick additional waveforms for the recent 20 December 2022 Northern California earthquake sequence, which was the largest event recorded recently in proximity to the PNSN authoritative boundaries. We propose this AI-ready data set as a new open-source benchmark data set.

A Dataset of Regional Earthquake Waveforms

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We present an extensive quality-controlled dataset of waveforms of earthquakes recorded at regional distances. These waveforms are 5 minutes long and contain arrivals for the P, Pg, Pn, S, Sn and Sg phases, as well as event and station metadata. Each one of the examples in the dataset is required to have at least one of {P, Pg, Pn} arrivals and at least one of {S, Sg, Sn} arrivals. Arrivals in the dataset are recorded at a source-receiver distance between 1 and 20 degrees in three component instruments. After initially collecting over 3 million waveforms, we quality controlled the data using an ensemble of Machine Learning Models. First, we trained a Recurrent Neural Network that distinguishes between earthquake signals and synthetic noise. This model allows us to flag examples in the dataset for which there are labeled arrivals, but the waveforms do not show any distinguishable earthquake signal. On the other hand, given that 5 minutes is a long window, and many earthquakes can be recorded in such time, we used a fine-tuned version of our RNN to flag those examples for which there are multiple earthquakes, because only one of them is labeled. We show preliminary ML models trained on the dataset for seismic phase picking.

Automatic Seismic Monitoring Using Regional and Local Temporary Networks in Colombia

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Seismological networks, whether global, regional, or local, have the objective of monitoring seismic activity. This implies the detection of seismic events and determination of their location (latitude, longitude, depth and origin time) with an acceptable level of uncertainty. We apply these steps in three seismic networks to get an automatic catalog that shows the seismicity in the Colombian territory for 6 years (2016-2021). A regional seismic network (the Colombian national seismic network, with station separation of about 100 km), and two local and temporary networks (station separation 10-30 km approx.) in northern South America: the Middle Magdalena Valley Array, and the Caribbean-Mérida Andes seismic array.

To achieve this, continuous data of multiple stations needs to be processed to detect and pick seismic phases. We used the EQTransformer, a pre-trained Supervised Deep Learning model, to detect and pick seismic phases at each station. Then, we used GaMMA, an unsupervised machine learning method to associate phase detections originated by a common source. Then, we used the NonLinLoc algorithm to locate sources with a reliable hypocentral location. Finally, we estimated the local magnitude for each event. This process was fully automated, allowing it to be rolled out to other networks around the world.

The results show that this implementation is reliable enough to generate automatic seismic catalogs with the appropriate quality in terms of the event location errors, it is capable to define major tectonic structures and highlight regional crustal faults. Better yet, it can improve earthquake processing times and complement manual catalogs due to its good performance to detect small earthquakes and aftershocks.

Classifying Central and Eastern U.S. Seismic Events in the Earthscope Database Using Machine Learning and Lg-Wave Spectral Ratios.

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Historical earthquake catalogs allow for the characterization of natural seismicity prior to subsurface fluid injection, which can induce earthquakes. To facilitate large-scale seismicity characterization in the central and eastern United States (CEUS), our team applied a machine-learning-based waveform classifier (WC) to events in the EarthScope database to augment existing earthquake catalogs. We selected EarthScope's Transportable Array because it transected the contiguous United States from west to east with uniform station coverage in the otherwise nonuniformly—and, in some regions, sparsely—monitored CEUS. EarthScope's Array Network Facility (ANF) detected seismic events that occurred within the array but did not classify them as earthquakes or mining-related events. The WC was employed to calculate the probabilities that waveforms were produced by earthquakes or mining activities such as blasts and mining-induced collapses (MIC). Using a subset of 502 manually classified events, we determined the WC reliably classified earthquakes at probabilities ≥ 0.7 and blasts at probabilities ≥ 0.5. Events with lower probabilities, with waveforms from fewer than four stations, or with standard deviations of the individual-station probabilities ≥ 0.40 were manually classified. Of the 6,634 events, 14% required manual review. Because some events falsely classified as earthquakes occurred in mining areas, and some events in those areas classified as blasts occurred during the nighttime, when blasting is typically restricted, we also calculated Lg spectral ratios to assist with discriminating between MICs, blasts, and earthquakes. Preliminary results using 1-2 to 2-4 Hz Lg-wave spectral ratios on a subset of known events shows that MICs have higher Lg spectral ratios relative to blasts and to earthquakes. In total, we found that 61 earthquakes were uniquely detected by the ANF.

Comparative Study of the Performance of Seismic Waveform Denoising Methods

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Seismic waveform data are generally contaminated by noise from various sources, which interfere with the signals of interest. In this study, we implemented and applied several noise suppression methods. The denoising methods, consisting of approaches based on nonlinear thresholding of continuous wavelet transforms (CWTs), convolutional neural network (CNN) denoising and frequency filtering, were all subjected to the same analyses and level of scrutiny. We found that for frequency filtering, the improvement in signal-to-noise ratio (SNR) decreases quickly with decreasing SNR of the input waveform and that below an input SNR of about 32 dB the improvement is relatively marginal and nearly constant. In contrast, for CWT and CNN denoising, the SNR gains are low at high input SNR and increase with decreasing input SNR to reach the top of the plateaus corresponding to gains of about 18 and 23 dB, respectively. The low gains at high input SNRs for these methods can be explained by the fact that for an input waveform with already high SNR (low noise), only very little improvement can be achieved by denoising, if at all. Results involving 4780 constructed waveforms suggest that in terms of degree of fidelity for the denoised waveforms with respect to the ground truth seismograms, CNN denoising outperforms both CWT denoising and frequency filtering. Onset-time picking analyses by an experienced expert-analyst suggest that CNN denoising allows more picks to be made compared with frequency filtering or CWT denoising, and is on par with the expert-analyst's processing that follows current operational procedure. The CWT techniques are more likely to introduce artifacts that made the waveforms unusable.

Earthquake Detection in Subduction Zones: Transfer Learning With Amphibious Data From the Alaska Amphibious Community Seismic Experiment

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We train the machine-learning (ML) earthquake detection and picking algorithms EarthquakeTransformer (EQT) and PhaseNet for use with amphibious or offshore seismic networks in subduction zones, and we apply them to data from the Alaska margin. ML is revolutionizing earthquake detection, with trained models sometimes finding an order of magnitude more events than traditional methods. With better detection, an enhanced picture of small seismicity emerges, yielding better understanding of fault zone processes and seismic hazard. Yet, ML methods are under-utilized in high-hazard subduction zones. We contribute two new subduction-zone oriented training datasets generated from earthquakes recorded by the Alaska Amphibious Community Seismic Experiment (AACSE), 2018-2019, and we use these datasets to train EQT and PhaseNet for subduction zones. One dataset (~52k waveforms) contains ocean-bottom data from 66 sites crossing the trench, and the other (~123k waveforms) contains data from 129 neighboring land sites. We use these datasets to train EQT and PhaseNet, testing various dataset and waveform filtering approaches to generate best models for ocean-bottom and land data separately. We then apply the two models to continuous AACSE data to find more small seismicity.

We provide two important products for earthquake detection in high-hazard subduction zones: large on- and offshore training datasets, and picking models trained on them. These products provide a foundation for future subduction-zone-oriented dataset generation and training, important for SZ4D and similar initiatives. In addition, detection and picking improvement over pre-trained models suggests that transfer learning with known regional earthquakes may be important to customize ML models to regional variability. Last, the improved catalog is a snapshot of Alaska margin seismicity late in the seismic cycle, just prior to the 2020 M7.8 Simeonof, 2020 M7.6 Sand Point, and 2021 M8.2 Chignik sequence of earthquakes.

Effective U.S. Event Classification Through Model Ensembling

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Event type discrimination models built with deep learning have proven to be highly effective for identifying known nuisance signals in earthquake catalogs at local scales. We know that deep learning models can also often outperform traditional methods in local-regional discrimination in low signal-to-noise cases. However, models trained in one geographic region on this task typically do not generalize well to new areas. Transfer learning, taking a model trained on data from one area and retraining it on data from a new area is one way to achieve high performance across regions when catalogs from new regions exist. Instead of transfer learning for each new region, in this work we utilize historic phase data available through the NEIC for non-earthquake events, as well as non-earthquake events from the high density Transportable Array, and regional event catalogs across the US to assess the viability of building ensemble models from catalog subsets to achieve high performance on known non-earthquake events and decision abstention when a model is likely to make poor decisions on new signals.

Employing Machine Learning Pickers for Routine Global Earthquake Monitoring With SeisComP: What are the Benefits and How Can We Quantify the Uncertainty of Picks?

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Recent years have seen the development of several very powerful machine learning pickers for P and S waves. The recent development of the *SeisBench* platform (https://github.com/seisbench/seisbench) in combination with mixed regional teleseismic benchmark datasets published by the NEIC (USGS) and GEOFON (GFZ Potsdam) enabled the retraining of the most popular picker neural network models (*PhaseNet* and *EQTransformer*) optimised for global monitoring applications in the benchmark study of Münchmeyer et al (2021, J. Geophys. Res.). In this contribution we introduce a module *scdlpicker*, which connects SeisBench to SeisComP (https://www.seiscomp.de/) through a client submodule, which listens to new event detections from the regular *SeisComP* automatic detection system and triggers repicking of those events with any picker implemented in SeisBench, using the improved picks to trigger a relocation. The machine learning picks are subsequently available within the SeisComP GUI in case further manual refinement or checking is desired.We demonstrate application of this system with the GEOFON global earthquake monitoring service (https://geofon.gfz-potsdam.de/eqexplorer), evaluating the benefits of using the machine learning picker with respect to the conventional workflow relying on traditional pickers with respect to timeliness of reporting earthquakes and reduction of manual work load, and improvement in the number of high quality picks available for each event.The quantification of the uncertainty of machine learning picks is important when weighing the contribution of different picks in many location algorithms, yet this information is not readily available from machine learning pickers. They do return, however, a characteristic function (nominally the confidence in the pick), whose properties might correlate with the uncertainty of the pick. We will show whether and how the picking uncertainty correlates with properties of the characteristic function.

Ensemble Learning for Earthquake Detection and Phase Picking: Methodology and Application

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Seismic detection and picking is the first step toward earthquake catalog building, earthquake monitoring, and seismic hazard management. Recent advances in deep learning have leveraged the amount of labeled seismic data to improve the capability of detecting and picking earthquake signals. While these deep learning methods have shown great promise, they remain challenged by low generalizability and sensitivity to low signal-to-noise ratios (SNRs). Here, we propose a new processing workflow, which integrates conventional deep learning models, multi-frequency band predictions, and ensemble estimations including coherence-based and learning-based ensemble algorithms, in order to enhance the prediction performance. Our primary test on INSTANCE, STEAD, and PNW datasets to demonstrate our multiband and ensemble estimation strategies can significantly improve detection and picking rate and accuracy, especially for low SNR signals. We further show the effectiveness of this workflow for characterizing volcanic seismicity in Mount St. Helens region. Available detection or picking models can be easily assembled into our workflow without further training costs.

Expanding Wavelet-Transform-Based Neural Network Denoiser Performance Using Utah Regional Data

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Seismic waveform data can be interpreted as a superposition of some target signal defined as being from a unique source of interest and noise generated from all other sources. Previous projects focused on the development of convolutional neural network (CNN) based denoisers have shown the viability of incorporating discrete wavelet transforms (DWTs) to improve performance on both constructed test and real-world data. The advantages of utilizing the DWT in the U-Net style architecture are that, when compared to conventional pooling functions, the wavelet transform functions allow for a higher degree of information retention between model layers. Evaluation of both models on test data showed that the MWCNN model (average cross-correlation, CC, value of 0.85) outperformed the CNN model (average CC value of 0.75) in its ability to recover the ground truth signal component with little amplitude distortion. Ultimately, the Multi-level Wavelet-based Convolutional Neural Network (MWCNN) denoiser outperformed conventional CNN-based denoisers when trained on the same single-station based training data set. Here, we utilize a data set of over 300,000 constructed seismograms using recordings from three-component stations spanning the entirety of the University of Utah Seismograph Stations network to improve the transferability of the MWCNN denoiser to broader regions of seismicity. Additionally, we seek to improve the performance of the MWCNN denoiser on real-world datasets by expanding the real-world data evaluation set beyond its prior single-station single-channel extent. Lastly, we demonstrate the ability of the MWCNN denoiser to both improve detection rates and increase signal-to-noise ratio (SNR) values for those detected events, while not distorting the target signal amplitude values, on continuous segments of data.

Exploring Generalized Relationships Between Rockfalls and Seismograms

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Rockfall event parameters are typically estimated using field surveys or satellite imagery. These methods have poor temporal resolution, and potentially poor spatial resolution depending on the data and have uncertainties in the measurements that may be challenging for hazard characterization. The seismic waves generated by these rockfalls carry information about their source. Therefore, seismic monitoring of rockfalls provides an excellent opportunity to monitor rockfalls. By understanding the relationships between the time-frequency representation of the seismograms and the rockfall dynamics, one can estimate event parameters for the small to moderate sized slope movements for which event parameters cannot be estimated using traditional methods. We explore the relationship between over 300 features extracted from seismograms and three rockfall event parameters - volume, runout distance and drop height - for the rockfall events in IRIS Exotic Seismic Event Catalog (ESEC). IRIS ESEC contains a database of 52 rockfalls (as of 10 January 2023) compiled from published studies. These rockfalls have occurred in a wide range of geographical locations, and range in size from less than 100 m3 to more than 1,00,000 cubic meters.

Our primary motivation is to find features that show high correlation with rockfall event parameters. We use correlations and a random forest algorithm. Our preliminary results indicate that certain features characterizing the spectral content of the seismograms show high correlation with all the event parameters. Some of these features show even better correlation compared to some of the features previously chosen by other studies (Dammeier et al. 2014, Manconi et al. 2016, Hibert et al. (2017a, b)).

Implementation and Testing of EQTransformer to Detect Microseismicity Near the Alpine Fault, South Island, New Zealand

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The Alpine Fault in South Island, New Zealand poses a significant hazard to people and infrastructure in New Zealand. The likelihood of a large earthquake in the next 50 years is approximately 75%. Hazard analyses typically assume that the seismogenic thickness measured interseismicaly corresponds to the maximum depth of rupture of moderate and large earthquakes. Having reliable information on background microseismicity, and therefore of the seismogenic thickness, is important to accurately determine potential rupture areas through the Alpine Fault. More than 80 permanent and temporary seismic stations are currently operating near the Alpine Fault. This large volume of data provides the basis for a new generation of earthquake catalogs. However, processing all data manually would be very time-consuming, and would likely result in a biased and inconsistent catalog. EQTransformer, a deep learning model used for earthquake signal detection and seismic phase picking, has proven effective and efficient at detecting microseismicity in diverse locations worldwide, so we use this model to process all data from the Alpine Fault. To ensure that we develop a robust and highly-complete catalog using EQTransformer, we have performed a quantitative analysis of EQTransformer's parameters and overall performance by comparing its output against a high-quality, long-duration microseismicity catalog from the Alpine Fault. We find that due to the prevalence in the training data set of P-arrivals occurring within 5–15s of each seismogram's start-time, it is important to use large overlap lengths when applying EQTransformer to continuous data. We also find that the majority (92%) of EQTransformer picks are within 0.25s of the manual picks. EQTransformer is a recent advancement, and testing the effects of different parameters against existing high-quality picks will be key for obtaining high-quality microseismicity catalogs.

Latent Representations of Seismic Waves With Self-Supervised Learning

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Fully-supervised deep learning models and large, labeled earthquake datasets have revolutionized earthquake detection in the past five years, but the reasons why these models either perform well or do not generalize to other datasets remain opaque. In this work, we propose a latent, or internal vector space, representation of seismic waves learned from self-supervised training on a large corpus of unlabeled continuous seismic waveform data. We take inspiration from the field of speech recognition, where latent representations have become the basis of nearly all natural language processing, such as transcription or translation. Our approach differs from previous fully-supervised earthquake detection methods in that we encode a time window of recorded ground acceleration as a feature vector in a latent space, rather than as a single label, such as "P-wave", "S-wave", or "noise". Our approach allows for a more nuanced encoding of complex waveform data, such as during early aftershock sequences. Using years of continuous waveform data from the Southern California Earthquake Data Center (SCEDC) AWS Public Dataset as an unlabeled training set, we train a transformer model to learn latent representations of continuous seismic waveforms using a contrastive loss function. We compare our learned representations to seismic phases identified by conventional earthquake pickers, human analysts, and deep learning-based earthquake detection models. As demonstrated recently in speech recognition, we suggest that latent representations can be used as a pre-trained encoder in a diverse set of seismological tasks requiring continuous seismic data such as earthquake detection, earthquake early warning, and ground-motion forecasting.

Machine Learning Models for Urban Image Analysis: Building Height Estimation

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Artificial intelligence (AI) is triggering major advances in construction engineering in the era of the generalization of Building Information Modelling (BIM). One of the main areas of AI development is the determination of building attributes from street view images. Building height is an essential factor for the assessment of structural vulnerability that is often missing, although sometimes available in cadastral databases. The goal of this research is to help the KUK_AHPAN project (RTI2018-094827-B-C21/C22) in the collection of building attributes for seismic exposure assessment in Central American cities. The techniques presented on this paper are being applied to datasets from San José (Costa Rica). This work presents the framework and the development of machine learning techniques for urban image analysis and an application to the estimation of building heights.Building heights were calculated from street view imagery based on a semantic segmentation machine learning model. The model has a fully convolutional architecture, and it is based on the HRNet encoder and on ResNexts depth separable convolutions, achieving fast runtime and state of the art results on standard semantic segmentation tasks. Average building heights on a pilot German street were satisfactorily estimated with a maximum error of 3 meters. Further research alternatives are commented, as well as the difficulties of obtaining valuable training data to apply these models in countries with no training datasets and different urbanism conditions. This line of research contributes to the characterization of buildings and the estimation of attributes essential for the assessment of seismic risk using automatically processed street view imagery.

Reconstructing Seismograms via Self-Supervised Learning: Methodology and Applications

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Seismograms are studied to decipher earthquake mechanisms, resolve Earth's structures, and assess seismic hazards. However, fully exploiting them remains challenging for their imbalanced and contaminated spectral contents. Typical earthquakes of moderate size (M2-4) are usually deficient in clean low-frequency signal (< 1 Hz) , but have sufficient signal at high-frequency (> 1 Hz). Conversely, some earthquake signals may be depleted in high-frequency information, such those recorded in the past at low sampling rates or those looking at attenuated signals. Additionally, current numerical methods and knowledge of the Earth's structure generally limit accurate simulations of seismograms to low frequencies. These limitations prevent seismologists from discovering detailed earthquake source physics and structural information. Therefore, decontaminating low frequencies from seismic noise and recovering high frequencies in seismograms are critical for better utilizing seismic signals. Here, we use a deep neural network to investigate the relationship between low- and high-frequency seismograms. After self-supervised learning of a small volume of high-quality broadband seismograms, our deep-learning model can reconstruct high-quality relative amplitudes and phases of waveforms with high similarity to the true ones for either low-frequency or high-frequency seismograms. In particular, our model can reconstruct high-quality low-frequency signals from high-frequency ones; it can also reconstruct high-quality high-frequency signals from low-frequency ones. Our seismogram reconstruction method can improve the utility of seismic data and hence allow for resolving the source mechanism of noisy earthquakes, enhancing structural imaging, and evaluating earthquake ground motions.

Seismicity Behavior Within Rock Valley Illuminated by a Dense Nodal Deployment and Machine-Learning Methods

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A dense 48-node array was deployed within Rock Valley in Nevada and crosses a number of faults that are within the valley. The nodal array has been deployed for roughly a whole year providing an extensive view of the current seismicity. The primary goals of the deployment were to detect microseismic events and to allow for the detailed mapping of the spatiotemporal evolution of seismicity on these fault structures. We expand the number of events in this catalog by using Earthquake Transformer (Mousavi et al., 2020) and alternatively PhaseNet (Zhu and Beroza, 2019), a machine-learning based event detector and phase picker. We improve the model used in the detection of events via Transfer-Learning to update the model using analyst picks made on the nodal deployment. For the detected phases we associate them with the REAL (Rapid Earthquake Association and Location) (Zhang et al., 2019). We initially use Hypoinverse to locate the events, and later relocate them with GrowClust (Trugman and Shearer, 2017). The refined locations illuminate many fault structures. We also use the machine-learning based method of Ross et al. (2018) to determine the first motion polarity of the P-wave arrivals, which we use to compute focal mechanisms. The dense nodal array's density provides the azimuthal coverage needed to obtain accurate focal mechanisms even for microseismicity. Using the expanded catalog of earthquakes and focal mechanisms, we examine the spatiotemporal variability in focal mechanisms for different fault strands for the array. With this level of detail, we can determine, which fault strands are active currently.This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Opportunities and Challenges in Source Modeling for Seismic Hazard Analysis

Oral Session • Thursday 20 April • 08:00 AM Pacific

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A New Earthquake Recurrence Model That Better Reflects the Strain Accumulation and Release Processes That Produce Earthquakes

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Current earthquake recurrence models have two major limitations. First, they predict that the probability of a large earthquake stays constant or even decreases after it is "overdue" (past the expected average recurrence interval), so additional accumulated strain does not make an earthquake more likely. Second, the models assume that large earthquakes release all accumulated strain, despite evidence of partial strain release in earthquake histories showing clusters and gaps. These limitations arise because the models are purely statistical, assuming that future earthquakes will satisfy a probability distribution that describes the times between past large earthquakes. These models describe average earthquake behavior, but not deviations from it, because they do not incorporate fundamental aspects of the strain accumulation and release processes that cause earthquakes.

Here we calculate earthquake probabilities using our Generalized Long-Term Fault Memory (GLTFM) model, which better reflects the strain accumulation and release processes. Our model assumes that earthquake probability always increases with time between earthquakes and allows the possibility of partial strain release. We apply this model to different faults including the southern San Andreas fault. By allowing partial strain release, GLTFM incorporates the specific timing of past earthquakes, which commonly used probability models cannot do, so it better forecasts the short inter-event time preceding the 1857 Ft. Tejon earthquake. Looking to the future, current models estimate the earthquake probability on the southern SAF will be essentially unchanged in the next 80 years, but GLTFM predicts that the probability will continue to grow, resulting in a 30-year earthquake probability approximately 60% higher than the other models. These forecast differences could have major implications for hazard assessment.

Towards Objective Models of Locking on Partially Creeping Faults and Subduction Zones

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Accurate modeling of earthquake scenarios and assessment of seismic hazards requires accurate estimates of the dimensions of likely earthquake sources. In cases where faults are partially creeping, as in most continental creeping faults and most subduction interfaces, dimensions of the fault area that is fully locked can be much smaller than the total fault area. Inverse models based on inversion of geodetic data are one way to estimate locking, but tend to be underdetermined and need strong regularization which can reduce resolution. In addition, most geodetic data are land-based, and provide weak constraints on locking models.Boundary element models offer a means of adding additional constraints to such models through introducing additional physics. Elements on the fault surface can be 'locked' (backslipped or stationary with respect to a driving dislocation) or 'creeping' (freely sliding to accommodate stress). Stress shielding – the phenomenon where creep rates are reduced due to proximity of locked areas – adds some sensitivity to the location of locked elements, even where resolution of inverse models may be low.I present a method for determining objectively the distribution of such locked elements, employing a modified Metropolis-Hastings algorithm with no intervention from the user. I will show two examples – the partially creeping Hayward fault in California, constrained by InSAR and GNSS data, and the Kamchatka subduction zone, constrained by GNSS velocities. In both cases I run the algorithm for 1 million iterations. After a short 'burn-in' period, each iteration produces an alternative plausible model of fault locking. The ensembles of models obtained for each case reveal details of fault behavior – including robust determination of areas where locking does not occur (<2% of models show locking) and the locations of likely asperities (locked in >70% of models), as well as areas where some locking may occur, but with poor constraints on location (locked in 20-50% of models). I identify additional structure in the model ensemble by applying hierarchical clustering based on Jaccard dissimilarity.

Augmenting Near-Source Probabilistic Seismic Hazard Analysis (PSHA) With North American Crustal Stress Field Data

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Probabilistic seismic hazard assessment (PSHA) provides an assessment of the annual frequency of exceeding various levels of ground shaking at a location. In locations without detailed characterization of the seismic hazard associated with individual faults, significant epistemic uncertainties relate to source characterizations, including the identification of potential rupture characteristics and their likelihoods. As we show, knowing the state of stress in the Earth's crust can reduce epistemic uncertainties for PSHA by providing information about the likelihood of a given fault or fault segment to fail, and the expected sense of fault slip. The orientation of the maximum horizontal principal stress (S_Hmax) and the style of faulting (relative principal stress magnitudes) determine which orientations of pre-existing faults are more and less likely to fail seismically. The probability that faults of any orientation may be potentially active may be estimated from stress, fault, and rock property parameters and their corresponding uncertainty distributions. Stress maps for North America have been developed that provide both S_Hmax orientations and quantify the style of faulting, together with uncertainties. We focused on a case study that evaluated the Meers Fault repeated large magnitude earthquake (RLME) to allow us to assess the potential impact of the stress information on a well characterized RLME. Stress information was applied to a simplified 2012 CEUS-SSC base model with real and fictional stress scenarios. We observed that stress-informed epicenter localization and near-fault directivity effects resulted in significant differences in near-fault ground motion exceedance frequencies. The use of crustal stress data during the development of fault source parameters for a PSHA may improve ground motion estimates, particularly in near-source locations, sites sensitive to ground shaking, or where fault orientations are well characterized but paleoseismic data or other fault hazard indicators are not.

Accuracy of Finite Fault Slip Estimates in Subduction Zones with Topographic Green's Functions and Seafloor Geodesy

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Until recently, the lack of seafloor geodetic instrumentation and the use of unrealistically simple, half-space based forward models have resulted in poor resolution of near-trench slip in subduction zone settings. Here, we use a synthetic framework to investigate the impact of topography and geodetic data distribution on coseismic slip estimates in various subduction zone settings. We attempt to recover target slip distributions by using a Bayesian method to invert for slip with two sets of Green's functions -- one that accounts for topography and one that does not -- and five sets of 50 or more observation points, three that are entirely onland and two that include 5-10 seafloor geodetic sites. We find that failure to account for topography in Green's functions results in ensembles of recovered slip distributions that often do not include the target model, while the use of both topographic Green's functions and seafloor geodetic data enables an almost perfect recovery of a target slip model, even in the near-trench region.

Dynamic Rupture Simulations on the Alpine Fault: Investigating the Role of Fault Geometry on Rupture Size and Behavior

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The right-lateral transpressional Alpine Fault is the primary plate boundary fault on the South Island of New Zealand. At a broad scale, its onshore surface trace between Milford Sound in the southwest, and the branching Marlborough Fault System in the northeast consists of two planar sections connected by a major geometrical boundary at Martyr River. This boundary is characterized by both a dip change of as much as 40° over an along-strike length of only ~5 km (e.g., Warren-Smith et al. [2022]) and by two small (8–13 km) subparallel strands near a ~6° restraining bend. Several previous studies suggest that changes in dip along a strike-slip fault (e.g., Lozos [2021]) as well as smaller fault features can both affect rupture dynamics (e.g., Lozos et al. [2012]); we therefore hypothesize that these geometrical features affect conditional earthquake segmentation behavior on the Alpine Fault, as documented by the extensive paleoseismic record (e.g., Howarth et al. [2001]).

We use the 3D finite element method to simulate dynamic ruptures on four idealized parameterizations of the onshore Alpine Fault geometry: 1. a single vertical plane, 2. a vertical plane with two smaller parallel vertical planes at the restraining bend, 3. a single dipping plane, and 4. a dipping plane with two smaller dipping planes at the bend. We embed the faults in a 1D velocity structure and impose heterogeneous initial tractions computed using seismologically estimated local principal stress orientations and magnitudes computed using a critically-stressed crust model. We compare the modelled rupture lengths and surface slip values to geologic and paleoseismic studies to ensure that we are producing physically-plausible simulations consistent with observations. These simulations may be helpful not only in assessing the hazard associated with the Alpine Fault, but also in constraining the geometry of the fault and implications for rupture directivity.

Frequency-size Parameters as a Function of Dynamic Range - The Gutenberg-Richter b-Value for Earthquakes

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The Gutenberg-Richter *b*-value represents the relative proportion of small to large earthquakes in a scale-free population and is an important parameter used in earthquake hazard assessment. Discussion of the amount of data required to obtain a robust *b*-value has been extensive and is ongoing. To complement these analyses, we show the effect of the *b*-value with changes to the dynamic range – the difference between minimum magnitude (or magnitude of completeness) and maximum magnitude, which is inherently linked to the sample size, but not proportionately correlated. Additionally, we show that biases in high *b*-values are due to the bias in the mean magnitude of a catalogue, which asymptotically converges from below.

We derive and analytic expression for the bias that arises in the maximum likelihood estimate of b as a function of dynamic range r. Our theory predicts the observed evolution of the modal value of the mean magnitude in multiple random samples of synthetic catalogues at different r, including the bias to high b at low r and the observed trend to an asymptotic limit with no bias. In the case of a single sample in real catalogues, the situation is substantially more complicated due to the heterogeneity, magnitude uncertainty and lack of knowledge of the true *b*-value. We summarise that these results explain why the likelihood of large events and the associated hazard is often underestimated in small catalogues with low r, for example in some studies of volcanic and induced seismicity.

Investigation of Spatiotemporal Variations in the Magnitude Distribution of Induced Seismicity Due to Natural Gas Production in the Groningen Field

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Production of natural gas from the Groningen gas field in the Netherlands causes induced earthquakes that have already led to many cases of building damage and also pose a personal safety threat to the local population. To enhance public safety and mitigate damage claims, the gas production has recently been strongly reduced to a minimal level that is still required for (meteorological/geopolitical) security of supply. Also, even after production stop, seismicity is expected to continue, for example due to pressure equilibration. As a result, seismic hazard and risk assessment remains relevant for the near future . As a part of our efforts to improve hazard and risk forecasts, we perform statistical analyses on spatiotemporal patterns in the magnitude distribution of the Groningen earthquake catalogue, which contains 336 earthquakes with above M=1.45, observed in the period between 1 January 1995 and 1 January 2022. An exploratory moving-window analysis of maximum-likelihood b-values exposes significant variations in space, but not in time. In search for improved understanding of the observed spatial variations in physical terms we test a number of physical reservoir properties as possible b-value predictors. The predictors include static (spatial, time-independent) properties such as the reservoir thickness and the topographic gradient (a measure of the degree of faulting intensity in the reservoir) as well as dynamic (spatiotemporal, time-dependent) properties such as the pressure drop due to gas extraction, the reservoir compaction, and a measure for the induced stress development. We assess the predictive capabilities of the static and dynamic predictors by statistical evaluation of both moving window analysis, and maximum-likelihood parameter estimation for a number of simple functional forms that express the b-value as a function of the predictor. We find significant trends of the b-value for topographic gradient and induced stress, but even more pronouncedly for reservoir thickness.

Virtual Faults for PSHA

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Seismic source-to-site distance metrics are the primary influences on ground motion amplitude models (GMMs) for probabilistic seismic hazard analysis (PSHA). For well-characterized crustal fault sources, 2-d surficial "line" sources have evolved into 3-d, often multi-segment planar features, with geometric uncertainties treated in a logic tree format. On the other hand, seismic activity in areal zones, where unidentified faults often comprise significant if not dominant contributions to the hazard, has been modeled as either uniformly distributed, or heterogeneously distributed based on spatial patterns of historic seismicity. A simple, commonly used method of distributing seismicity in an areal zone is to first create a grid of points within the boundaries of the area zone. Each point is then assigned a seismicity rate based on an independent analysis, scaled to the area the point represents. Crustal GMMs in use today generally use two distance metrics: "Rjb", the nearest distance to the horizontal projection of the fault plane, and/or "Rrup", the nearest distance to the fault plane. It was recognized that because earthquakes occur on 3-d planar structures, using a point as the source gave incorrect distance metrics. Attempts have therefore been made to adjust the point source distance to these two metrics. However, seismic source models (SSMs) have become more explicit as to the strikes, dips, and depth distributions of rectangular ruptures specified for a given zone. In addition, GMMs now include geometrically sensitive parameters such as hanging-wall and depth-to-top-of-rupture corrections. Therefore, modeling each rupture associated with a gridpoint as a planar rupture, in accordance with the SSM specifications, has become necessary. A method for doing so is presented, in the context of the CEUS-SSC source model for the central and eastern U.S.

PSHA for Lebanon Relying on an Interconnected Fault System

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We aim at estimating probabilistic seismic hazard levels for Lebanon, a country prone to a high seismic hazard since it is located along the Levant fault system (~5mm/year deformation). As a first step, we develop a source model that includes major faults in the area, with earthquake recurrence models for each fault based on the available geomorphology, paleoseismology and geodetic studies. This moment-balanced fault model is combined with a catalog-based smoothed-seismicity model to also forecast earthquakes off the main fault segments. Uncertainties are tracked and propagated up to the final hazard calculations to understand which parameters' uncertainties control hazard estimates. A set of seismic hazard maps at the scale of Lebanon is obtained, representative of uncertainties in the source model. As second step, another class of fault models is explored for application to the Levant fault system, algorithms that propose to include information on the segmentation of the faults, and permit that sub-fault segments freely break together, as in nature (SHERIF from Chartier et al. 2019; OpenSHA Fault System tool from Milner and Field 2021). These algorithms take into account more detailed information along the fault system. Again, uncertainties are tracked at the different steps required for building the source model, to understand the impact on hazard of the uncertainties associated to the input data, as well as the impact of the hypothesis and decisions that these algorithms require. We test the feasibility of such approaches for the Levant fault system, which is unevenly characterized along its 1000km length. We show how the hazard levels are modified within Lebanon if applying these methods, with respect to our previous hazard results relying on more classical fault models.

Revisiting Seismic Hazard in Iran: Role of Stress Drop in Peak Ground Acceleration in a Zone of Immature Faulting

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The continental collision between the Arabian shield and Eurasia has resulted in an average of ~15,000 earthquakes in Iran every year, having led to more than $3 billion of economic loss over the past decade. The existing seismic hazard models for the country do not consider rupture kinematics on the complex, immature fault zones in the region. Here, we use the source slowness parameter, Θ, obtained from teleseismic data, to evaluate the frequency content of dip-slip CMT events during 1999-2022 in Iran for which strong motion data is available from the Iranian network. The advantage of Θ algorithm is its robustness with sparse network coverage and the use of only the first several seconds of body waves train. We then compare the anomalies in rupture velocity and consequently the stress drop to the locally recorded PGA values by the Iranian strong motion network, as well as to spectral variations predicted by attenuation equations between 2–5 Hz, considering various site properties. Our results reveal a strong correlation between earthquake source slowness parameter (with ~0.2 logarithmic unit standard deviation) and the anomalies in the observed PGA. This result reaffirms the notion that slowness parameter is a good measure of observed ground shaking and as such can be used as an identifier for the seismic hazard in the near-field. We also find that our spectral dataset deviates from existing seismotectonic zonings of Iran and thus we propose modifications to the current hazard models for the country.

Opportunities and Challenges in Source Modeling for Seismic Hazard Analysis [Poster]

Poster Session • Thursday 20 April

Conveners: Kiran Kumar S. Thingbaijam, GNS Science (k.thingbaijam@gns.cri.nz); Chris Rollins, GNS Science (c.rollins@gns.cri.nz); Matt C. Gerstenberger, GNS Science (m.gerstenberger@gns.cri.nz); Andrea L. Llenos, U.S. Geological Survey (allenos@usgs.gov); Marco Pagani, GEM Foundation (marco.pagani@globalquakemodel.org); Delphine Fitzenz, Risk Management Solutions, Inc (delphine.fitzenz@rms.com); Andrew J. Michael, U.S. Geological Survey (ajmichael@usgs.gov); Andy Nicol, University of Canterbury (andy.nicol@canterbury.ac.nz)

Advancing the SRCMOD Database

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The SRCMOD database provides an openly accessible and consistent repository of finite-fault earthquake rupture models (http://equake-rc.info/srcmod/). These source models were inferred from kinematic modeling using a variety of source-inversion techniques. They are based on either seismic recordings, geodetic measurements or both, sometimes augmented with tsunami data. As a community-based database, SRCMOD is a platform for scientific authors to share their models for further research and teaching purposes. Over the last 10 years, the SRCMOD database has emerged as a significant resource and has been extensively used for seismological research. Topics of follow-up studies based on the SRCMOD database include earthquake rupture dynamics, source-scaling relations, stress-change calculations, intra-event variability of source models, and scenario earthquakes for seismic and tsunami hazard analysis.<CR>In the near future, we aim to further develop the database and solicit input from the community. We also envision complementary repositories for dynamic rupture models and afterslip models. Fundamentally, our plan includes support for a number of data formats, software tools, interactive online visualization, and web services. These core functionalities will be implemented through *eqsrcpy*, a python package, currently being updated. The upgrade will not only be a paradigm shift for the database, but also will significantly improve its usefulness.

Capturing the Uncertainty of Seismicity Observations in Earthquake Rate Logic Tree Branches

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Earthquake rate models based on seismicity are a key element in probabilistic seismic hazard analysis. For the 2023 update of the USGS National Seismic Hazard Model, we split these seismicity rate models into two elements: a spatial kernel that gives the relative distribution of seismicity in a region and an absolute rate model. The absolute rate model gives the distribution of the Poisson rate of earthquakes with magnitudes above the minimum level used to calculate hazard (Mmin), along with a distribution of Gutenberg-Richter b-values that controls the extrapolation to other magnitudes. Poisson is a valid assumption for declustered catalogs or full catalogs when determining low probabilities of a single exceedance. To include uncertainty in the hazard logic tree we use the mean and +-2s (s=1 standard deviation) rate branches. The b-value distribution is determined with the b-positive method (van der Elst, JGR, 2021). The distribution of earthquake rates at the magnitude of completeness (Mc) is determined by considering the likelihood of rates given the number of observed earthquakes with M>=Mc. To get the distribution of rates for M>=Mmin, and other thresholds, we project the distribution of rates from Mc to Mmin using the full distribution of b-values. The mean and +-2s rates of earthquakes with M>=Mmin gives us the first part of the information needed for the three branches. These three rates are each associated with a range of b-values. But we wish to choose a single b-value for each branch. A simple approach is to use the mean b-value with the mean rate, the -2s b-value with the high-rate branch, and the +2s b-value with the low-rate branch. However, that approach can overestimate the uncertainty in earthquake rates for magnitude thresholds higher than Mmin. A second choice is to choose b-values that connect the +-2s rate quantiles at Mmin and the highest magnitude of interest (Mmax). We are exploring the implications of these options.

Complex Ruptures for Hazard and Risk: Case Studies for El Salvador and Ecuador

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We know that complex ruptures happen in nature. Why then are they often missing in hazard and risk models? Fault mapping and characterization throughout much of Latin America and the Caribbean has made great strides in the past decade and hazard models like the Global Earthquake Model's CCA (Styron et al., 2020) and SARA (Garcia et al., 2017) projects along with consensus models like RESIS II (Benito et al., 2012) and Alvarado et al. (2017) have helped to bring this work together for use in seismic hazard modeling. How then can we make better use of this information when it comes to modeling complex ruptures?

Complex ruptures involving multiple segments of faults or multiple faults can have a two-fold impact on hazard: (1) they can increase the maximum magnitude in a region, and (2) they push the impact of the faults involved to longer return periods as rate is distributed to these complex ruptures. The associated impact on risk is three-fold, involving both (1) and (2) from hazard as well as (3) correlating exposure that otherwise might not be correlated. Here we present examples of the impact of modeling these ruptures in El Salvador and Ecuador. We show that it is important to consider these ruptures, particularly for long return period hazard and risk, especially in areas where the fault database indicates a system of faults (e.g., El Salvador) and areas where only surficial fault information is available (e.g., Ecuador).

Estimation of Seismic Hazard in Northern Argentina, Combining Faults and Zones Hazard Estimations (PSHA). Validation of Proximity Factors to Active Faults of the Argentine Seismic Code Inpres-Cirsoc 103

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The general objective of the study presented here is to characterize and estimate the seismic hazard in the northern zone of the Argentine Republic, using a methodology that combines zones and faults as seismic sources, and to analyze, in light of the results, the impact of modeling faults as independent sources in hazard assessment. The results provide criteria to validate the amplification factors due to the proximity of faults proposed by the Argentine Regulation for Seismic Resistant Constructions INPRES-CIRSOC 103 -2018 Part I, "Constructions in General". With this general objective, a complete seismic hazard study was carried out in zone N 3 according to the map of the INPRES building code, classified as highly hazardous zone, following a classical zoned methodology (MCZ) and another hybrid method that combines zones and faults (MH). Thus, maps of the expected motion for return periods of 475 and 975 years have been generated, as well as hazard curves and uniform hazard spectra (UHS) in the capitals of the provinces of Salta and Jujuy. The main results include: 1) considerable increase in accelerations in the fault environment when applying the MH, compared to those of MCZ; 2) The UHS spectra deduced with MH in populations close to faults are nearby to those proposed in the INPRES-CIRSOC 103-2018 regulation, which includes coefficients that modify the design spectrum according to the distance to active faults. However, those deduced in our study though MH are higher than those of the regulations for periods T < 0.5 s; remaining below for higher periods. In light of the results of this study, the spectra of the code with the modification factors proposed by closeness to fault would only be conservative for long periods, greater than 0.5 s.

Interactions Between Megathrust and Adjacent Crustal Faults

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How do megathrust earthquakes interact with crustal earthquakes on faults adjacent to the subduction interface zone? Much evidence shows that earthquakes with magnitudes greater than Mw > 8 produce a release of stress in the upper crust that could trigger crustal faults and vice versa. To understand this problem, we build a 3D model of a northwest striking crustal fault that connects directly to a north-south striking subduction zone interface, where on both faults we prescribe rate and state frictional properties and effective normal stress consistent with the pressure and temperature conditions expected at depth. The convergence at the subduction zone is set to 70 mm/year, and zero for the crustal fault. We feed these data to a quasi-dynamic boundary element code, where we model slip evolution and tractions on both faults. Our results show that fault planes to the north of a Mw~ 8.6 interplate co-seismic rupture produce Mw7crustal earthquakes, with an average recurrence of ~1100 years. Similarly, our results demonstrate that active crustal fault are linked to seismic segmentation along the subduction zone, avoiding the propagation of large megathrust Mw~9. This means that with knowledge of crustal fault locations along subduction zones, one can potentially estimate earthquake recurrence models for both types of faults, as well as maximum magnitudes along different segments of subduction zones.

Modeling the Seismogenic Slab Sources in New Zealand

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Intraslab earthquakes within the Hikurangi and Puysegur subduction zones constitute more than 50% of the recorded ($M_W \geq 4.0$ events) seismicity in New Zealand. As part of the National Seismic Hazard Model 2022, we develop an advanced source model for the intraslab seismicity, using recently improved datasets that include an earthquake catalog, geospatial configurations of the subduction interfaces, and a regional moment tensor solution catalog. To obtain the smooth seismicity distributions, we apply a novel quasi-3D approach. The steps are as follows: (1) delineate the mid-slab based on the hypocentral locations, (2) get the orthogonal projections of hypocenters onto the mid-slab, (3) generate a uniform grid of 0.1 degrees on the mid-slab, and (4) finally, apply a Gaussian smoothing kernel. For each slab, we compute the magnitude frequency distributions. At the same time, we consider the maximum magnitude to range M_W 8.0 – 8.3, based on globally-observed historical intraslab earthquakes. To account for finite-fault ruptures, we construct a model for rupture mechanisms, by analyzing the moment tensor solution catalog. This model has the mean strike angles sub-parallel to subduction trenches and median dip angles ≥ 60°. The distribution of rake angles suggests that the Hikurangi slab has an extensional regime in the shallower parts but a compressional regime in the deeper parts, indicative of slab flexural. In contrast, the Puysegur slab predominantly exhibits a compressional regime.

Predicting Ongoing Induced Seismicity in the Groningen Gas Field After Shut-in Using Rate-Dependent Compaction

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Annual production in the Groningen gas field has been decreasing over the last years towards full cessation and shut-in planned in 2023/2024, motivated by safety risk and societal unrest from production-induced earthquakes. The shut-in is associated with an increase in reservoir pressure, which already occurs locally in the field . The current seismic source model (SSM), used as part of the seismic hazard and risk analysis (SHRA), formulates that directly induced earthquakes (i.e., main shocks) occur as a function of compaction, where compaction is a linear elastic function of reservoir pressure – suggesting an arrest of main shocks after shut-in. However, subsidence measurements and laboratory deformation experiments suggest that reservoir compaction, and thus generation of main shocks, continues after shut-in. Hence, the current SSM requires an update to be able to provide SHRA predictions after shut-in. Here, such a future-proofing exercise is carried out by reformulating the function relating pressure to compaction – assuming that total compaction (elastic and permanent) causes reservoir-hosted fault loading. The empirical Rate Type isotach Compaction Model (RTiCM) is used to describe reservoir compaction as the sum of the instantaneous elastic compaction and delayed rate-dependent creep. The model has been shown to accurately match experimental data as well as subsidence data. The RTiCM model parameters have recently been calibrated on Groningen field subsidence data. The results of the RTiCM-based SSM and elastic compaction-based SSM are compared. The earthquake event counts of the most recent years, where field production was strongly reduced, are reproduced better by the RTiCM-based SSM. In particular, the model can simulate seismic events in areas of limited pressure increase . The performance between the two models is further quantified using the CSEP testing framework. The RTiCM-based SSM is a viable option for a post shut-in SHRA.

Proposal of a New Method for Combining Seismological and Geological Information Aimed at Seimsic Hazard Analysis: Fams Method- Fault and Area Zone Moment Shearing.

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With the advent of precise timing of geological strata, GPS techniques, and more recently remote sensing techniques a much more detailed quantification of mapped faults has been made posible. This opens a new horizon in order to improve the knowledge of seismic hazard, allowing the modeling of faults as independent sources, thus considering fault-type sources. However, today it is necessary to combine this type of sources with other zone-type sources, which harbor scattered seismicity that cannot be directly correlated with faults. The recurrence of both types of sources is derived from very different data sources: geological data for the faults and seismic catalog for the zones. The problem that arises when combining both types of sources is how to distribute the seismic potential between both kind of sources. In this work, a new method is proposed to distribute the seismic moment, called: Fault and Area zone Moment Shearing (FAMS). The basis for this method is the hypothesis that seismic moment from magnitudes higher than a given magnitude (MMZ) is attributed only to the fault, whereas the lower magnitudes may be distributed in the fault and in the zone. MMZ is the maximum magnitude for the zone, but is not the minimum magnitude for the fault. A formulation is developed to arrive at deducing the fault recurrence law in the two ranges of magnitude in the faults: (Mmin, MMZ) and (MMz, Mmax), as well as the recurrence law for the zone considering only the residual seismicity. The advantage of this method is that it does not require assuming a prior or regional b value in the fault.

Recalibrating Earthquake Rupture Forecasts Using Long Catalogs From Multi-Cycle Earthquake Simulators

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Earthquake forecasting is of wide interest for the public, decision makers, and scientific community; however, the lack of long earthquake catalogs make the problem of calibrating forecasts difficult. Here, we develop an approach for assimilating the information from multi-cycle earthquake simulators into probabilistic rupture forecasts. We focus on recalibrating the time-independent Uniform California Earthquake Rupture Forecast Version 3 (UCERF3-TI) of Field et al. (2014) against long earthquake catalogs (~10^6 years) generated by the multi-cycle Rate-State Quake Simulator (RSQSim) of Dieterich & Richards-Dinger (2010). We map ruptures from the RSQSim catalog of Shaw et al. (2018) onto equivalent UCERF3 ruptures by maximizing the mapping efficiency while preserving the seismic moment. This mapping process, sometimes called the association problem, sets the framework for utilizing data from diverse earthquake simulators and, should they be available, real earthquakes as well. We map RSQSim into UCERF3 following different rupture criteria, yielding different synthetic earthquake subcatalogs. The statistics of these datasets remain nearly unchanged. Thus, our results show that RSQSim succeeds at representing the large earthquakes in UCERF3. Furthermore, we assume the sequence of equivalent UCERF3 ruptures is Poisson distributed and use the full UCERF3 logic tree to construct a joint prior distribution of rupture rates, which we represent by independent Gamma distributions. The differences in prior and posterior rates are attributed to the slip rate difference between RSQSim and UCERF3. Furthermore, our posterior model results in substantial lower rates in the Coachella, San Gorgonio, and San Bernardino San Andreas fault sections, reflecting the fact that RSQSim does not propagate ruptures through the San Gorgonio knot.

It is worthwhile stating that the results of this work are not intended to replace the current authoritative earthquake rupture forecasts, but to present a framework under which earthquake data is used to re-calibrate current models.

Review of Hybrid Methods for the Characterization of Seismic Hazard in Central America

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The introduction of faults as independent seismic sources in hazard assessment has a great impact on the results, with respect to those obtained with classical zoning methods (CZM) in probabilistic Seismic Hazard Assessment (PSHA). Currently, some approaches that have used hybrid models (HM) composed of zone-type sources and fault-type sources, reveal that expected ground motion values around main faults may double (on average) those obtained by zoned models, in agreement with observations in recent earthquakes (Rivas-Medina, A., 2018; Gómez-Novell O., 2020). This fact has a great impact on the hazard and seismic risk results that can be obtained in populations close to active faults. This presentation compares some methods that address two key aspects: how to quantify the geological information and transfer it to recurrence models, and how to distribute the seismic potential between the two types of sources. These methos are: 1) Moment rate method proposed by Bungum (2007), 2) Slip-rate method proposed also by Bungum (2007) ,3) Hybrid method developed by Rivas-Medina et al. (2018) and 4) the method to build hazard models including earthquake ruptures involving several faults (SHERIFS) by Chartier et al. (2019). This study is centered in all Central America region, which is a moderate to high seismicity region.

The Rates of Large and Moderate Earthquakes in Aotearoa New Zealand

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For use in the Seismicity Rate Model (SRM) component of the 2022 New Zealand National Seismic Hazard Model, we estimate the total magnitude-frequency distribution (MFD) of earthquakes in the greater New Zealand region and along the Hikurangi–Kermadec and Puysegur subduction zones. The former is a key input into multiple components of the SRM in the onshore and near-shore regions, while the latter is a key input into models of earthquake rupture rates on the subduction zones.

Recent work (Christophersen et al., 2022) has greatly improved and homogenized the earthquake magnitudes in the New Zealand earthquake catalogue for use in the NZ NSHM 2022. Other parameters in the catalogue remain of mixed quality, however, in particular earthquake depths. Therefore, we develop an augmented New Zealand earthquake catalogue in which we import higher-quality depths and depth uncertainties, focal mechanisms, and some locations and magnitudes from several relocated and global catalogues. Next, we use event depths, focal mechanisms, 3D models of the Hikurangi and Puysegur subduction interfaces, and relative plate motion directions to classify earthquakes as upper-plate, interface or intraslab.

Using this augmented catalogue and adapting an approach used previously in California, we estimate the MFD of earthquakes in the near-shore region incorporating data back to 1843, balanced with the better data in the more recent part of the instrumental catalogue. This method estimates both the mean earthquake rate and its uncertainty, and we supplement it with an alternative estimate of the rate uncertainty that is based on the rate variability in the catalogue over a range of shorter timespans. We estimate the MFDs on the Hikurangi–Kermadec and Puysegur subduction zones using a simplified version of the method used in the near-shore region, with more recent data. Finally, we describe a globally based method to estimate the potential earthquake rate uncertainty on the Hikurangi–Kermadec subduction zone.

The Rise and Fall of Earthquake-Size Distribution With Depth: Insights From the Calabrian Subduction Zone

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The magnitude distribution of earthquakes is generally represented by an exponential function controlled by one parameter, called the b-value. This parameter is related to different characteristics of the earthquakes, like the faulting mechanism, and the earth's crust, like the differential stress. Maps of the b-value have shown anomalies of high values associated with the depth of a number of subduction zones. Here, we investigated the possible dependence of the b-value with the subduction depth for intra-slab earthquakes by using a homogeneous instrumental seismic catalog and a high-definition model of the Calabrian Slab, which represents one of the oldest oceanic crust in the world presently subducting. We found a rise of the b-value until a depth of about 150 km, and then a fall from 150 to 300 km. This peculiar behavior is interpreted in relation to dehydration and partial melting of the subducting slab. Our results are important for characterizing the behavior of a subducting slab and for seismic hazard analysis, since they help to understand the earthquake size distribution of a subduction zone, usually the most seismogenic zones of the Earth. With a better spatial and depth resolution of the b-value variation it is possible to improve the modeled seismic hazard.

Seismology for the Energy Transition

Oral Session • Tuesday 18 April • 04:30 PM Pacific

Conveners: Lianjie Huang, Los Alamos National Laboratory (ljh@lanl.gov); Erkan Ay, Shell (erkan.ay@shell.com); Ting Chen, Los Alamos National Laboratory (tchen@lanl.gov); Verónica R. Rodríguez, Lawrence Berkeley National Laboratory (vrodrigueztribaldos@lbl.gov); Yingcai Zheng, University of Houston (yzheng24@central.uh.edu)

Technical Subsurface Workflows for Geological Carbon Sequestration

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Like a traditional oil and gas project, a geologic carbon sequestration project passes through the stages of prospecting, development, and operation. Details, of course, will differ. In the scoping and evaluation phase ("prospecting"), we identify depleted fields or saline formations, map the spatial extent and thickness of their reservoir and seal formations, create and simulate simple models, and identify key risks and uncertainties such as storage capacity, seal adequacy or the presence of legacy wells. During technical maturation ("development"), we characterize both reservoir and seal by determining properties and their distributions, build and simulate a detailed reservoir model, plan appraisal and injector wells, further assess risks, and define a monitoring program. During operation, we inject CO2, execute our monitoring campaigns for 1) containment, 2) conformance, and 3) confidence. Containment means that the injected CO2 plume is safely stored in the subsurface. Conformance means that CO2 and pressure evolve as modeled. Lastly, confidence means learning and understanding the system for optimization, step outs, or future projects.

In this presentation, we will discuss some subsurface workflows with an emphasis on geophysics and geosciences in general, examine some differences to traditional oil and gas workflows, and outline some gaps and needs.

Machine-learning Fault Detection on 3D Seismic Migration Images of the San Juan Basin CarbonSAFE Project Site

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The San Juan Basin CarbonSAFE Phase III project is performing a comprehensive site characterization for geologic carbon storage in the San Juan region located in northwest New Mexico, USA. Subsurface fault detection is crucial for site characterization and risk assessment. The project procured a legacy 3D surface seismic dataset acquired at the San Juan CarbonSAFE storage site for imaging subsurface structures using seismic migration. We refine the 3D velocity model using prestack depth migration velocity analysis and produce a high-resolution seismic migration image based on this updated velocity model. We then use our recently developed machine learning algorithm to perform 3D fault detection. Our result shows that the site does not contain significant faults that may lead to CO2 leakage, indicating that the site may be suitable for large-scale geologic carbon storage.

Adaptive Model Selection for the Maximum Magnitude Event During Injection

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As injection of fluids into the subsurface becomes more common, the need for a technique to assess the maximum magnitude of induced events (Mmax) becomes more pressing. There are some models in the literature (e.g., uncalibrated moment cap, calibrated moment cap, statistical formulation, residual moment, and convolutional) that relate the cumulative injection to the Mmax. These models incorporate different site characteristics and physics such as seismogenic index, Gutenberg-Richter b-value, pore pressure diffusion, and moment release. We hypothesize that the model that best describes a certain injection operation may vary during the course of the injection. In fact, the seismic response ranges from mild due to aseismic slip and up to hazardous as dynamic runaway rupture behaviors are developed. Thus, we present a dynamic calculation of the Mmax predictive model. The injection might take the form of deep saline carbon dioxide sequestration, enhanced oil recovery, hydrogen storage, or stimulation of a reservoir. The processes associated with each of these scenarios are different, and we conduct a comparison between the enhanced oil recovery operations at the Farnsworth, TX site and the stimulation of the enhanced geothermal reservoir at the Utah FORGE site in Milford, UT. The results show that no one model describes the two injection projects the best. Rather, dynamically updating the model based on a misfit calculation between observed seismicity and the tested models allows the operator to incorporate the physics and site characteristics that are most applicable for the injection. The best fitting model is used for the prediction and down the road, for risk management and mitigation.

Fracture Network Geometry as Revealed by Seismicity and Distributed Temperature Sensing During Egs Collab Experiment 2

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The EGS Collab experiment aims to validate numerical models of fracture propagation, permeability enhancement, and heat flow at a depth relevant to power-producing enhanced geothermal systems. The second and final phase of the experiment took place in the Sanford Underground Research Facility between March and August 2022 with a series of stimulation and flow tests at pressures both above and below the minimum principal stress at 4100 ft depth. A broad array of geophysical instruments was installed to monitor the experiment, including standard piezoelectric accelerometers, Continuous Active Source Seismic Monitoring (CASSM), electrical resistivity tomography, and a full fiber optic sensing suite including temperature, strain, and acoustic measurements on five separate interrogators. Here we present the catalog of detected seismic events along with the temperature measured by distributed fiber optics in four boreholes. The temperature data and seismic catalog, which contains hundreds of events, are two of our most powerful tools used to constrain the geometry of the fracture network created during the experiment. Our results provide information on the direction of fracture propagation and fluid flow in the testbed and show that subtle changes in flow rate drive dramatic changes in the flow through the stimulated fracture network.

Seismicity at the Coso Geothermal Field: Past and Present Applications

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The Navy's Geothermal Program Office (GPO) has been maintaining and operating a subsurface, 16-station, short-period seismometer array in the Coso geothermal field (CGF) since the mid-1990s. It was installed to assess seismicity triggered by the removal and reinjection of mass from this 270 MWe installed capacity field (Monastero, 2005). Over the years, multiple studies using this very large micro-earthquake (Meq) catalogue (~294,000 events) have included relocating earthquakes through various techniques (Lees, 1998; Foulger et al., 2008), evaluating siesmogenic deformation and structures (Unruh, 2007; Hauksson and Unruh, 2007; Kaven et al., 2012; Kaven et al., 2013), assessing time-dependent tomography (Julian et al., 2006; Mhana et al., 2018) and differentiating production-related (induced) from tectonic earthquake events (Schoenball et al., 2015). Evaluating seismic triggering and quiescence in and around Coso after the large July 2019 M6.4 and M7.1 earthquakes centered 30 km to the SE of Coso has been the focus of many recent workers (Kroll et al. 2021, Kaven, 2020). Since 2020, we have been building the first, static geologic conceptual model of the CGF in Leapfrog Geothermal subsurface software (Blake et al., 2021; Zimmerman et al., 2022). This has required a reevaluation and assessment of structures, most of which are interpreted through well data, prior geologic mapping and now, Meq data. A robust geologic model can do many things including informing the evolving CGF reservoir model, assist with an ongoing evaluation of a deep, supercritical resource and assist with water management and operations.

Seismology for the Energy Transition [Poster]

Poster Session • Tuesday 18 April

Conveners: Lianjie Huang, Los Alamos National Laboratory (ljh@lanl.gov); Erkan Ay, Shell (erkan.ay@shell.com); Ting Chen, Los Alamos National Laboratory (tchen@lanl.gov); Verónica R. Rodríguez, Lawrence Berkeley National Laboratory (vrodrigueztribaldos@lbl.gov); Yingcai Zheng, University of Houston (yzheng24@central.uh.edu)

Baseline Seismic Monitoring Survey for UKGEOS Glasgow Geothermal Production Using DAS

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The UK Geoenergy Observatories (UKGEOS) site in Glasgow has initiated a project to repurpose an abandoned coal mine as a shallow geothermal testbed to investigate its potential as a head source and sink. During the site construction, fibre-optic cables were installed along the 50- to 100-meter-deep boreholes that will be used for injection and extraction of water, providing a unique opportunity to examine the applicability of Distributed Acoustic Sensing (DAS) in an urban, shallow geothermal setting. Another major scientific question is to understand the fluid flow pathways and subsurface properties of the geothermal systems and potential changes as heat is extracted over time, which requires a baseline or initial state measurement of the mine before water is circulated. In January 2022, we visited the UKGEOS Glasgow site to conduct a cross-well seismic borehole survey using DAS and hydrophone arrays prior to the heat pump installation. Here, we assess the applicability of DAS as a monitoring technique in a noisy, urban, shallow geothermal setting through noise analysis and comparison to the hydrophone array. We find that while the DAS noise levels are higher and more likely to mask the source signal, DAS provides significantly higher spatial resolution compared to the hydrophone array and contains more information in the coda. Finally, we use cross-hole traveltime tomography to obtain a velocity profile between the two wells as a baseline measurement, which can after a repeated survey in the future be used to assess the subsurface effects of the water circulation over time.

Seismic Imaging, Full-Waveform Inversion and Inverse-Scattering

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Seismic imaging or seismic migration is widely used in both exploration and earthquake seismology, and plays an important role in both fields. I In this study, we try to build an intrinsic link between seismic imaging, full-waveform inversion, and inverse-scattering.

Seismic imaging can be defined as a time-space focusing process. Backpropagator, or the reverse-time propagator (e.g. reverse-time finite difference algorithm), is the focusing operator which refocuses the recorded scattered field on the surface back to their original locations and the imaging principle is a time-focusing (choice of correct focusing time). *Seismic waveform inversion* is closely related to *seismic imaging*. For example, the current FWI (full-waveform inversion) is basically an iterative process of imaging + medium parameter transform which converts the image field into a medium parameter field. Though closely related, there are important differences between *imaging* and *inversion*. First, in general, unlike the imaging process where the focusing operator is known (the velocity structure is known), the objective of inversion is to construct or reconstruct the *focusing operator* so that the imaging process can be performed and improved. In principle, the *velocity (or other parameter) structure* is *unknown* and obtaining such structure is the goal of inversion. The construction or reconstruction of the focusing operator is a highly *nonlinear process* and is critical to seismic inversion. Nevertheless, in current FWI the focusing operator is assumed approximately known, namely the initial model in the inversion is assumed to be fairly close to the true velocity structure. Inverse-scattering, based on the classic GLM (Gel'fand-Levitan-Marchenko) integral equation, is an exact solution for the inverse-scattering problem and tries to extend the 1-D exact theory to the 3-D case. We will also investigate the relationship between inverse-scattering and a recently proposed Direct Waveform Inversion (DWI) scheme.

Simulating Time-Lapse Seismic Monitoring of Geologic Carbon and Hydrogen Storage With a Stress-Dependent Rock Physics Model

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The Biot-Gassmann equation is widely used for generating elastic models of geologic carbon and hydrogen storage. Laboratory experiments show that rock units filled with free-phase CO_2 cause large changes in seismic shear-wave velocities because of chemical reactions between clays and CO_2; and numerous chemical reactions are expected to occur between hydrogen and various carbonate, sulfur-bearing, and iron-bearing minerals. However, the Gassmann equation only considers the impact of injected supercritical fluids/gasses on the fluid substitution and does not include the resulting chemical reactions or stress-dependent mechanical changes of rocks. Therefore, we develop a new rock physics model by incorporating stress-dependent rock physics and chemical dissolution/deposition mechanism into seismic models alongside the Gassmann equation for high-fidelity geologic carbon and hydrogen storage characterization and monitoring. For geologic carbon storage monitoring, we create time-lapse elastic models with our new rock physics equation to accurately capture elastic property changes caused by CO_2 migration at the Kimberlina CO_2 storage site in California. We find that our approach produces larger changes in V_p, V_s, and density than those obtained using classical Biot-Gassmann equation. We further investigate how these changes impact seismic signals computed using 3D finite-difference-based elastic wave equation modeling. For geological hydrogen storage monitoring, we apply our new equation to various types of hydrogen storage cases, including saline aquifers, salt caverns, and hard rock caverns, to study elastic property changes caused by hydrogen injection and extraction. The results are important for building reliable and accurate geological models for hydrogen storage monitoring. Our new rock physics model will serve as an accurate tool of quantifying reservoir changes caused by CO_2/H_2 leakage and migration and in principle can apply to any underground reservoir of interest to facilitate high-fidelity geophysical modeling, imaging, and monitoring.

LA-UR-23-20164

Vector Double-Beam Characterization for Discrete Fractures in Geological Carbon Storage Sites

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Geological carbon storage (GCS) is an important element in carbon management for mitigating global climate change. Knowing the existence of fractures is critical in selecting GCS sites and assessing potential supercritical CO2 leakage and induced earthquakes in basement rocks. In conventional 3D seismic images, these fractures are very hard to identify because they are associated with weak image amplitudes. We develop a new vector double-beam method to characterize subsurface fracture networks. Such information is useful in GCS site selection and can be used to infer stress state and assess potential seismic hazards caused by fluid injection. Results from both synthetic seismic datasets and field datasets demonstrate that our new method is effective in characterizing fracture orientation, density, and mechanical compliance.

Seismology's Role in Assessing Volcanic Hazard at Multiple Time Scales

Oral Session • Tuesday 18 April • 08:00 AM Pacific

Conveners: Charlotte A. Rowe, Los Alamos National Laboratory (char@lanl.gov); Jolante van Wijk, Los Alamos National Laboratory (jolantevanwijk@lanl.gov); Wendy McCausland, U.S. Geological Survey (wmccausland@usgs.gov); Glenn Thompson, University of South Florida (thompsong@usf.edu); Francisco Nunez-Cornu, Universidad de Guadalajara (pacornu77@gmail.com)

Analysis of the Seismicity Recorded Before the May 22, 2021 Eruption of Nyiragongo Volcano, Democratic Republic of the Congo

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We present an overview of the different seismic precursors of the Nyiragongo volcano eruption on May 22, 2021, as well as a statistical analysis of the seismic swarms recorded during the pre-eruptive period. The analysis of the seismic activity of Nyiragongo volcano during the pre-eruptive period shows that there was a particular seismicity composed of hybrid and/or volcano-tectonic type events that characterized the long-period seismic swarm recorded about a month before the May 2021 eruption. In February 2016, similar seismic activity was observed at Nyiragongo volcano, which led to the opening of a new vent within Nyiragongo's main crater on February 29, 2016, and which remained active until the May 2021 eruption. During the period from January 2016 to May 2021, the lava lake remained very active with significant fluctuation as evidenced by the Real Seismic Amplitude measurement at Rusayo and Kibati stations. The increase and stabilization of the lava lake to a higher level resulted in an increase and accumulation of stress on the flanks of the volcano since the lava lake had already reached a higher critical level. Whether in January 2016, November 2016, or April 2022, we show that a particular type of earthquake recorded during a swarm at Nyiragongo volcano will most likely lead to an eruption either inside the main crater (February 2016) or on the flanks in May 2021.

Precursory Seismicity and Explosion Seismoacoustics of the Recent Phreatomagmatic Eruption of Semisopochnoi Volcano, Alaska

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The main explosive phase of the ongoing phreatomagmatic eruption of Semisopochnoi volcano, Alaska began shortly after a complete upgrade of the monitoring network in 2021. The network now comprises six broadband seismometers, three broadband infrasound sensors, and two web cameras. The new network is capturing an unprecedented, high-quality record of the eruption that we are using to investigate explosion source processes and the evolving configuration and state of the shallow magmatic system throughout the eruption.

We are generating a near real-time explosion catalog through a novel implementation of the REDPy repeating event detector algorithm on the local infrasound network. We further refine the catalog through a workflow that includes a network matched filter and event locations using reverse time migration. The catalog contains over 1000 events to date, providing a rich research dataset to study the relationships between explosion earthquakes and infrasound, as well as the influence of local topography and seasonal atmospheric variability on the infrasound signals. The catalog events show a high degree of similarity in the infrasound waveforms with only one dominant family occurring since explosions began in July 2021, indicating a repeating source process. We also explore the seismicity preceding the onset of explosions and find a family of repeating long-period events that began ~1 month before the onset of explosions. We are investigating how the character of these events evolved with multiple techniques (e.g., frequency index, coda wave interferometry) to determine their source process and whether they could be used to provide early warning of impending explosive activity during future eruptions. This work highlights the potential of modern monitoring networks to produce research-grade data, even at remote volcanoes, which aids in advancing our knowledge by diversifying the types and styles of eruptions observed globally.

Temporal and Spatial Evolution of Cabeza De Vaca 2021 Rift Eruption (Cumbre Vieja Volcano, La Palma, Canary Islands) From Geophysical and Geodesic Paramethers Analyses

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The 2021 Cabeza de Vaca eruption is the most recent, damaging, and long-term eruption since historical records at La Palma, Canary Islands. The eruption produced lava flows and tephras (VEI 3) from several lava fountain with Strombolian and Vulcanian phases. We analyzed several geophysical parameters (seismicity, surface deformation, thermal anomalies, volcanic activity) with the aim to reconstruct the temporal development of the magma plumbing system. The eruption was accompanied by an intense seismic swarm and surface manifestations of activity. The earthquake catalogue includes over 9000 events, the largest with magnitude 5.0 (mbLg). The seismic sequence can be grouped into nine distinct phases, which correspond to well-separated spatial clusters and distinct earthquake regimes. A strong premonitory thermal anomaly was calculated on July 2021 at the South of La Palma, according to the seismicity pre-eruptive phase 1. The source of the magmas was between 40 and 20 km depth, according to a prolonged magmatic storage withing the upper mantle. The second source of seismicity is located at depths < 15 km, suggesting a short-term stagnation of basanitic magmatic system within the lower crust, near the Moho. These earthquakes outline delineating the magma pathway. In phases 2 and 3, just before and immediately after the beginning of the eruption, the seismicity in the mantle disappears completely, reappearing ten days after the eruption started. In both phases, the most superficial activity is registered in the shallow crust and coincides temporarily with the disappearance of deep seismicity. The pattern of deformation began before the eruption with a breakpoint around September 11, after which, deformation accelerated sharply followed by a stabilization in phase 3 and a decrease in following phases. The level of deformation never came back to the original background, suggesting that a shallow magma intrusion was stablished.

The February 2018 Seismic Swarm in the Island of São Miguel, Azores

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On February 2018, a seismic swarm occurred on the island of S. Miguel in the Azores archipelago. The Azores are located on the triple junction between the North American, Eurasian, and African plates and comprise 9 populated islands of volcanic origin. S. Miguel is the largest and most populated island and the one that is most seismically active. This work presents a detailed study of the February 2018 seismic swarm, the most recent unrest episode in S. Miguel.

We carried out an automated analysis of continuous waveform data. Our workflow includes detection and location using the back-projection of waveform-based characteristic functions, single-station magnitude estimation, clustering based on waveform similarity, and template matching to extend and complete the catalogue. We further computed moment tensor solutions for selected events.

We identified three clusters of earthquakes with similar waveforms. The first includes events that occurred during a 7-day precursory phase. The waveforms display high-frequency P- and S-waves, typical of brittle failure. A second cluster was activated on February 12, when the seismic rate increased abruptly, and the highest magnitude (M3.7) of the swarm was recorded. The waveforms of this cluster have a lower frequency content than those of the first one. Finally, a third cluster was activated, with a much lower number of events. These waveforms have a more harmonic character. From the first to the last cluster, earthquakes migrate slightly shallower (15 km to 7-10 km) and to the SE. Focal mechanisms indicate mostly normal faulting. We interpret the first cluster as brittle fracturing at depth, followed by the triggering of shallower structures (2ndcluster), and finally by events that occur already in a fluid-rich environment (3rd cluster). Interestingly, this seismic swarm marked the beginning of a period of aseismic surface deformation as observed by GPS over the subsequent 17 months.

This work was funded by the Portuguese FCT – Fundação para a Ciência e a Tecnologia, I.P., within the scope of project PTDC/CTA-GEF/6674/2020.

Precursory Seismic Signals Before Two Catastrophic Landslides at Irazú Volcano, Costa Rica

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At Volcanoes, complex landslide instabilities triggered by nearby earthquakes, rainfall, local deformation, or a combination of all, may induce changes in the lithostatic pressure of the edifice, suddenly affecting their internal dynamics and increasing the risk of catastrophic eruptions. The Irazú volcano in Costa Rica has been recognized to host massive rock landslides in the past. Just in December 2014 and August 2020, a total of 53 million m^3 of mass wasting were deposited along the basement of "Rio Sucio", one of the main tributaries of the Sarapiquí River. Using the near field monitoring network that OVSICORI-UNA operates in the region, we demonstrate that during these events, the nucleation initiated weeks prior to the catastrophic collapse with SSE generating repeating low frequency earthquakes (LFEs) localized along the basement. Our observations show that as the mass accelerates the number of LFEs increases progressively and the inter-event time between them decreases linearly until they merge forming a tremor signal 30 min prior to the collapse. Seismic data exhibit an exponential increase in tremor amplitude, and thus, moment, that suddenly reduces and become quiescent for 20 seconds before the catastrophic failure. We posit that transient embrittlement is the mechanism responsible for such a unique observation. As the slip rate increases, faulting regions with predominantly stable-sliding frictional properties become unstable, as previously observed elsewhere. As a result, the total effective area of contact between the sliding mass and the basement increases dramatically, modulating tremor amplitude with time. The shear strength from the coupled asperities is enough to provide temporal stability to the entire mass, inducing the seismic quiescence. However, the accrued shear stress imposed by the SSE episode on the weak asperities overcomes the frictional strength, inducing the catastrophic failure. Our results provide direct evidence that the mechanics that control landslide nucleation are very similar to those observed in laboratory experiments and at tectonic fault zones during earthquakes

A Look Under the Hood: Characterizing the Spatiotemporal Evolution of Mount Hood Seismicity Through Data Mining and High Precision Relocation

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The region right around Mount Hood volcano, located 80 km east from Portland, is the most seismically area in Oregon, producing ~3k earthquakes since 1979. Seismicity near and below volcanoes is typically generated by fluids or gas migration, magmatic recharge and intrusions, through changes in regional stress regimes, or a combination of each. Careful examination of high-precision earthquake catalogs can elucidate seismogenic structures and uncover spatial and temporal patterns and evolutions of those structures at various timescales. The goal of this study is to characterize the seismicity of Mount Hood, the variability in sequence/swarm duration and location, measure the orientations of the faulting structures at depth, and the effects of improving the station density through time. To accurately characterize the recorded seismicity at Mount Hood, we constructed a high-resolution earthquake catalog. This was done by mining all continuous seismic data for stations within 50 km of Mount Hood, hunting hidden earthquakes using waveform template matching. Our detection efforts yielded a catalog of 24k new earthquakes. Locations were performed using NonLinLoc SSST + Coherence and of the 27k earthquakes in the enhanced catalog, 7,667 earthquakes were located. Our preliminary results suggest a complex faulting network in space with earthquake clusters located at and just below the summit, and on the flanks to the west, southwest, and southeast. Additionally, our preliminary temporal analysis results show a range of durations for different clusters. Further analysis is needed to identify the sources of these short, intermediate and long duration seismicity patterns.

Solid Earth–atmosphere Interaction Forces During the 15 January 2022 Tonga Eruption

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Very large volcanic eruptions are rare, catastrophic events, for which modern geophysical observations can reveal energy and mass flux between the solid Earth and atmosphere. Only a few events such as the 1980 Mount St. Helens and 1991 Pinatubo eruptions have generated globally observed teleseismic body waves and/or long-period surface waves that constrain the space-time force histories from the eruptive process and coupled atmosphere-solid Earth interactions. On January 15, 2022 a series of powerful phreatomagmatic explosions at the Hunga Tonga-Hunga Ha'apai (HTHH) volcano sent an eruptive plume 58 km into the mesosphere, presenting an excellent opportunity to take advantage of extensive modern geophysical observations to study the eruptive process. In this work, we examine the source force system of the HTHH eruption as well as solid Earth-atmosphere interactions by analyzing long-period regional surface waves and teleseismic body waves directly excited by the eruption process. The source process is likely associated with pressure drop in the magmatic reservoir, and reaction forces to the ejection jet as erupted material vents to the atmosphere must occur. The latter process is more seismogenic than the related implosive process, so we assume a surface vertical point-force to deconvolve and model the seismic wavefield for periods less than 100 s. A simulated annealing non-linear inversion for a vertical source provides a complex force time history, F(t), which is in good agreement with estimates of F(t) from deconvolutions of stacked body waves and stacks of surface wave deconvolutions. Overall, the seismic observations are well-explained by a single force reaction to the explosion sequence which lasted ~4.2 hrs. The explosive stage was composed of multiple pulses (explosions) with peak magnitude of the vertical forcing of ~ 2 x 1013 N. Estimates of energy and mass flux through the process will be presented. Atmospheric acoustic standing waves near the source produced oscillatory peak forces of ~ 4 x 1014 N, exciting monochromatic Rayleigh waves in the solid Earth with peak frequencies of 3.7 and 4.6 mHz.

Temporal Velocity Variations Associated With the 2020 Eruption of Kīlauea Volcano in Hawai'i, Revealed by Ambient Noise Cross-Correlation

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Detecting and understanding changes in the magmatic system that occur before/during an eruption is essential for forecasting volcanic eruptions, which cause extreme environmental and societal hazards. Seismic ambient noise analysis provides an approach to observing variations in the shallow velocity structure, and supplies information about perturbations in the interior of the volcano that can be challenging to resolve with ground deformation detection techniques. Cross-correlation of ambient noise has been used in various studies to examine pre-eruptive activity. Here we investigate temporal velocity variations before and during the 2020-2021 eruption of Kīlauea volcano in Hawai`i, which was the first major activity after the dramatic 2018 eruption and may provide insight into how a volcano readjusts itself after such a massive event. We download one-hour segments of continuous waveform data from the Incorporated Research Institutions for Seismology (IRIS) spanning 180 days before to 180 days after the onset of the eruption (December 20, 2020). We focus on data recorded by 9 broadband seismic stations in and around the summit caldera operated by the U.S. Geological Survey Hawaiian Volcano Observatory. After removal of trend, mean, and instrument response, the data are resampled to a uniform 100-Hz sample rate and bandpass filtered from 1 to 5 Hz. We calculate the cross-correlation functions of these hourly segments for the 36 station pairs and stack them for each day during the study time period. We apply a time-domain stretching method to the stacked function pairs and solve for the best-fitting set of velocity changes for the entire time period. We observe an overall velocity decrease of 2% about 10 days prior to the eruption, which may be related to magma or fluid/gas movement in the crust or an increase in pressure. Our study shows that cross-correlation of ambient noise continues to show promising results for revealing precursors of volcanic eruptions.

High-Resolution Passive Imaging Beneath Valles Caldera

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As part of a UTEP/UNM collaboration, we aim to resolve the internal structure of Valles Caldera, one of North America's quaternary supervolcanoes located near several metropolitan areas, including Albuquerque and Los Alamos, New Mexico. Our study focuses on inferring the current state of the magmatic system beneath the volcano through leveraging scattering properties of the ~80km caldera system. We jointly implement horizontal-to-vertical ratios (H/V), noise autocorrelations (AC), and P-wave receiver functions (P-RFs) in a multi-scale effort to identify structural discontinuities and study previous hypotheses concerning the eruptive state of the edifice. 1-month passive seismic recordings on a line of 97 3-component nodes across the caldera in 2019 are used to study significant near-surface structures related to caldera collapse, backfill, and dome resurgence, and to extricate these features from deeper and more subtle Moho signatures that have been elusive to date. ACs, PRFs, and H/V ratios are strongly sensitive to the magnitude of discontinuities, and these will subsequently be jointly inverted with surface wave dispersion measurements made from ambient noise correlation. The ultimate product of this study will be an accurate joint velocity model of the volcano that will address knowledge gaps concerning eruptive potential, seismic activity, and the general state of the magmatic system, all of which are currently unconstrained.

Rapid Strengthening of the La Soufriere Volcano Monitoring During Eruption, Covid-19 and Dengue Fever Threats

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La Soufriere volcano of St. Vincent started to erupt effusively on 26 January 2020 and culminated in a series of explosions from 9-22 April. A team of personnel from the Seismic Research Centre (SRC) and the Montserrat Volcano Observatory (MVO) were rostered in and out of the island to strengthen the monitoring network, re-activate the Belmont Volcano Observatory and assist with the management of the crisis. A monitoring Network comprising 8 seismic stations, 6 GPS reference stations, 3 cameras, and an Electronic Distance Measurement network was established within days to a few weeks of the initial onset of the eruption. Most of the equipment was mobilized from the SRC headquarters in Trinidad and Tobago and shipped to St. Vincent on a Regional Security aircraft. This occurred at a time when the Covid-19 Pandemic was raging and there was a recent outbreak of Dengue Fever in St. Vincent. A subset of equipment was also mobilized from the MVO. During the explosive phase of the eruption, one station was destroyed, the power and communication links to two were severed and a fourth was covered with ash. With assistance from the Volcano Disaster Assistance Program, the seismic network was restored in July.

This presentation chronicles the experience of the team leads, recounts the challenges, and outlines the lessons learned during the ordeal.

Seismology's Role in Assessing Volcanic Hazard at Multiple Time Scales [Poster]

Poster Session • Tuesday 18 April

Conveners: Charlotte A. Rowe, Los Alamos National Laboratory (char@lanl.gov); Jolante van Wijk, Los Alamos National Laboratory (jolantevanwijk@lanl.gov); Wendy McCausland, U.S. Geological Survey (wmccausland@usgs.gov); Glenn Thompson, University of South Florida (thompsong@usf.edu); Francisco Nunez-Cornu, Universidad de Guadalajara (pacornu77@gmail.com)

20-Year Seismic Run-Up to the 2015-2016 Eruption of Volcan Momotombo, Nicaragua, and Final Acceleration by Adjacent 2014 m6.1 Tectonic Earthquake

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After 110 years of repose, Momotombo volcano began erupting on 1 Dec. 2015. Momotombo has very high temperature fumaroles (~800C) since at least 1978 and magma close to the surface. Since regional seismic monitoring began (1975), seismicity has been dominated by distal volcano tectonic earthquake (dVT) swarms. Precursory seismicity follows the Four Stage Conceptual Model of White and McCausland (2019), with Stage 1 (deep seismicity) and Stage 2 (dVTs) bot progressing since 1975, and Stage 3 (vent clearing seismicity) first prevalent in 2000. At least 56 dVT swarms occurred since 1975, indicating persistent small intrusions into the magma reservoir, helping to maintain the very high temperature summit fumaroles for decades. The recurrence rates of dVT swarms decreased from 261 days between 1975-83 and 1993-99, to 135 days between 2000-08, to 36 days in 2013, and to 23 days in the 17 months prior to the eruption. The latter decrease occurred immediately after nearby M6.1 and M5.3 tectonic events whose source models indicate both dextral and normal motion, with a combined net extensional change in the stress field at Momotombo (Higgins, 2021). We hypothesize that the resulting change facilitated increased magma supply. Seismicity reached Stage 3 (tremor and tornillos) twice prior to the eruption: in mid-2000 and in June 2006 when a phreatic emission occurred. After June 2006, seismicity was again dominated by Stages 1 and 2 with occasional Stage 3 tornillos. About 6 months before the eruption onset, two production wells at the geothermal plant (3 km south of the summit) recorded coincident, small, persistent, and unusual increases in water pressure. Four months prior to the eruption, unusually large numbers and magnitudes of Stage 1 deep earthquakes began to occur, reaching M3.8. No short-term forecast was provided nor was a final transition to Stages 3 and 4 observed, as the closest seismic station was inoperable. However, the Instituto Nicaragüense de Estudios Territoriales issued intermediate-term warnings based on the dramatic increases in Stage 1 and 2 seismicity during the 4 months prior to the eruption.

Anomaly Detection and Image Spectrometry in Assesing Multitemporal Activity of the Turrialva Volcano, Costa Rica, and La Palma, Spain

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The aim of this paper is to present a geospatial methodology that involves a new thermal anomaly detection technique compared to expert-based techniques for the analysis of the temporal evolution of volcanoes' activity. We want to know what's goin on not only in cases where volcanoes are close to urban areas, but also in relation to the regional environmental impact, where an important objective will be to establish relationships that allow linking spectral patterns with volcanic seismicity.This methodology means a multi-source approach, applied to the analysis of correlations between hydrothermal alteration materials and spectral, thermal and reflective anomalies in volcanic complexes. We will present the detection of changes in this sense in relation to time series from multisensor data acquired in the visible (VIS), shortwave infrared (SWIR) and thermal infrared (TIR) spectral ranges of multispectral and hyperspectral scenes from satellite data (Sentinel 2, ASTER, ALI, Hyperion) and airborne sensor data (HyMAP, MASTER, AVIRIS, AHS) at different time periods. We also analyze time series data from active systems by applying differential radar interferometry to study ground deformation in relation to volcanic and seismic activity. Results for two study scenarios, Turrialba Volcano (located in Costa Rica and the La Palma Eruption in Spain that took place in 2021, are discussed.

Geodetic Measurements Reveal Time-Averaged Surface Deformation in the Valles Caldera

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The Valles Caldera, located within New Mexico, formed through a sequence of rhyolitic eruptions ~1.6 and ~1.2 Ma and has been the host to more recent eruptions as young as ~69 ka along a ring fracture within the caldera. Extensive geophysical work has indicated the presence of a shallow crustal magma body and a near-surface geothermal system. However, few measurements exist to constrain the transient nature of this coupled system which is key to assessing hazards. Here, we present the results of a geodetic survey that measured time-averaged surface deformation across 20-years within and around the Valles Caldera. Thirteen GPS benchmarks originally installed and measured in 2002 and 2003 were reoccupied in 2022. The data from the survey network was process alongside 25 additional IGS and regional stations using GAMIT and GLOBK v10.72 to resolve surface horizontal and vertical surface deformation within mm scale uncertainties. We compare the time-averaged surface deformation to intra-caldera seismicity collected by the Los Alamos Seismic Network and source models to constrain likely scenarios that produce the deformation. We note that even though results present a necessary step in understanding the thermomechanical state of the Valles Caldera, continuous observations will ultimately be needed to get a complete picture of surface deformation which can vary across shorter timescales.

Linking Deep Long Period Earthquakes to Magmatic Processes Underlying Mauna Kea

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Understanding the physical processes that generate background seismicity at quiescent volcanoes is a key component to understanding and differentiating between seismic signals that suggest an impending eruption and those that do not. Deep long period earthquakes (DLPs) are a type of volcano seismicity that can occur in the lead-up to eruptions or during repose. A better understanding of how magmatic processes such as the movement of exsolved magmatic volatiles or magma through the crust may generate DLPs could aid in interpreting this type of seismicity at potentially active volcanoes. Between 2000 and 2019 over 1 million DLPs were detected beneath Mauna Kea, a dormant volcano in its post-shield stage. The large number and the remarkable regularity of DLP events during this time interval provide an excellent case study for exploring the magmatic processes that drive these events. We present a physics-based model for fluid-driven cracks at depth fed by a degassing crystal mush body as proposed in the conceptual model from Wech et al. 2020. We then use this model to generate synthetic seismograms that can be compared to real event timeseries. This approach allows us to quantitatively assess the conceptual model for the magmatic processes driving DLPs at Mauna Kea and develop insights into the conditions required to produce such frequent and regularly occurring events. More broadly, this modelling framework provides a more robust understanding of one potential magmatic source for background seismicity at other volcanoes around the world.

Repeating Low-Frequency Earthquakes Near Wrangell Volcano, Alaska

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The geometry and tectonics near the eastern edge of the Alaska-Aleutian subduction zone are not well constrained. Complications arise here as the Yakutat microplate is colliding into and subducting beneath continental North America at near-Pacific-plate rates. Even more enigmatic is the source of volcanism for the Wrangell volcanic field (WVF), which occurs on the eastern edge of both the subducting Yakutat terrane and the anomalous ~400 km long gap in arc volcanism between the Cook Inlet volcanoes and the WFV. The region is also host to tectonic tremors, which coincide with the edges of the downgoing Yakutat terrane and likely mark slow slip on the subducting interface. Here, we report new tremor observations east of the Yakutat edge that are distinct from the known subduction zone tremor. The activity occurs south of the WVF and about ~100 km from the edge of the previously observed Yakutat tremor. We perform a matched-filter analysis using low-frequency earthquakes (LFEs) embedded within the tremor signal as templates to create a catalog of thousands of LFEs from 2014 – 2022. The 1-5 Hz LFEs occur episodically, with major episodes recurring every several months. We use data from a network of campaign stations operating from 2016-2018 and create phase-weighted stacks to emphasize phase arrivals for subsequent location. Preliminary analysis suggests the events occur ~25 km south of the WVF at depths of ~30 km. Based on the location and episodic nature of the LFEs, we suggest these events are tectonic in nature, and work is ongoing to constrain the fault geometry.

The Hawai'i Magmatic System Resolved by High-Resolution Traveltime Tomography

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The volcanoes of Hawai'i island represent one of the most active volcanic systems in the world. The Hawaiian Volcano Observatory has been monitoring the activities of these volcanoes for more than 100 years. The long-term monitoring of the seismicity of this area provides an opportunity to determine the velocity structures underneath Hawai'i island. We present a study that utilizes over 700,000 local events recorded by 85 stations in the last 10 years for which P- and S-wave traveltime picks are obtained using PhaseNet. We invert these picks within an efficient adjoint-state Eikonal-tomography framework to retrieve the P- and S-wave structures of the area. The resolved velocity anomalies provide invaluable insights into the mechanisms with which fluids and melt move within the various magmatic chambers and how they eventually erupt to the surface from the complex network of volcanic conduits and vents. Moreover, the extent of the Vp and Vs anomalies allows the estimation of the melt fraction and the volume of eruptible material, enabling a better assessment of the volcanic hazard.

Two Decades of Seismicity at Mount St. Helens

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Detection and cataloging of seismicity from Mount St. Helens, the most active and well-instrumented volcano in the Cascade Range, is vital for imaging its active structures at depth. The Pacific Northwest Seismic Network (PNSN) earthquake catalog, assembled by analyst-picked earthquakes located with a one-dimensional regional velocity model, spans several decades and provides fundamental observations for many studies of the volcano's activity. The recent implementation of data-driven machine learning algorithms in seismic monitoring workflows has enabled the development of extremely detailed seismicity catalogs with several times as many earthquakes as analyst-picked catalogs. Additionally, relocations of the PNSN catalog earthquakes with 3D travel time grids derived from improved velocity models show a shift in location by several kilometers, and can change interpretations of volcanic processes.

To improve the quality of the earthquake catalog at Mount. St. Helens, we train a convolutional neural network to identify P and S wave arrival time picks in continuous seismic data starting in the early 2000s using analyst-made arrival time picks in the PNSN catalog. We then associate the phase picks using GaMMA, a Gaussian Mixed Model clustering algorithm, and compute absolute locations of the associated phase pick clusters via gridsearch of travel time grids derived from 3D velocity models of the Mount St. Helens region. Lastly, we refine locations using a double-difference location procedure to improve precision. With the improved seismicity catalog, we are able to further reveal the conditions that govern magma transport from deep and shallow environments, the origins of volcano tectonic earthquakes, as well as the evolution of the 2004-2008 eruptive period.

ShakeMap-related Research, Development, Operations, Applications and Uses

Oral Session • Wednesday 19 April • 02:00 PM Pacific

Conveners: David J. Wald, U.S. Geological Survey (wald@usgs.gov); Carlo Cauzzi, Swiss Seismological Survey ETH Zürich (carlo.cauzzi@sed.ethz.ch); Hadi Ghasemi, Geoscience Australia (hadi.ghasemi@ga.gov.au); Nick Horspool, GNS Science (n.horspool@gns.cri.nz); Eric Thompson, U.S. Geological Survey (emthompson@usgs.gov); Bruce Worden, U.S. Geological Survey (cbworden@contractor.usgs.gov)

ShakeMap: An Update

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The U.S. Geological Survey's (USGS) ShakeMap product has become a major source of post-earthquake information to emergency response and planning organizations, as well as for public awareness. The ShakeMap software has been adopted by dozens of regional and international seismic organizations as their principal tool for communicating earthquake effects. ShakeMap also provides the necessary inputs to several important "downstream" products, such as PAGER and USGS Ground Failure. ShakeMap is under continuous development, and in this presentation we will discuss several new features, which include: 1) Adoption of the Engler et al. (2022) approach to separating within- and between-event uncertainties in the ShakeMap output (ShakeMap v4.1), which facilitates spatially-correlated realizations of ShakeMap outputs; 2) A new installation procedure that eliminates many of the earlier dependency conflicts; 3) Major progress on moving ShakeMap to the cloud (specifically Amazon Web Services); 4) Development of tools to visualize network response to (scenario) earthquakes with finite faults; 5) Many other system enhancements and upgrades to support the latest versions of OpenQuake Ground Motion Models, Python 3.9, MacOS X, etc.; and 6) Moving the ShakeMap repository to GitHub Enterprise.

Dynamic Generation of Shaking Maps for Post-Event Response in New Zealand

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GNS Science is developing new tools to rapidly deliver near-real time ground shaking maps (ShakeMapNZ) for New Zealand. Maps will be available through the GeoNet website, a Shaking Layer data website, and an API. This project is a collaboration between GeoNet, New Zealand's geohazards monitoring agency, and the Rapid Characterisation of Earthquake and Tsunami (R-CET) science programme.

ShakeMapNZ uses the USGS ShakeMap software to combine observed strong motion data with ground motion model predictions, resulting in spatial estimates of ground shaking for each intensity type e.g. PGA, PGV, MMI, Sa(T). The New Zealand system is optimised with region-specific data, ground motion model weightings, and default tectonic classifications. In the first instance, maps are automatically generated and updated based on basic earthquake parameters (M and hypocentre) determined by GeoNet's 24/7 monitoring center. First maps are available within 10 – 20 mins and have provided robust representations of shaking for small to moderate sized events (up to M6) observed to date.

Large earthquakes such as the 2016 Mw 7.8 Kaikōura earthquake pose additional challenges for automatic shakemap generation, which is based on point source models. For example, a large extended source, rupture complexity and/or potential disruption to strong motion stations may lead to large inaccuracies in initial shaking intensities, particularly in the near-source region. In recognition of this challenge, we have designed an applicationvto allow seismologists to dynamically update ShakeMapNZ during an earthquake response. Advanced earthquake information such as finite fault rupture, Mww, focal mechanism, tectonic classification, felt reports or additional strong motion data can be integrated efficiently into shaking maps when available. To further this goal, the R-CET programme had also been developing new rapid source chracterisation tools, including real-time Finite-fault Rupture Detection (FinDer) and regional w-phase solutions. These tool outputs are being tested and optimised to improve the accuracy of shaking maps with promising results.

Shakemap-Eu: A European Seismological Service and a Laboratory for Collaborative Research and Capacity Building

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We present ShakeMap-EU, an initiative initially proposed in 2018 to: (i) provide an integrated archive of ShakeMaps at the European level built on EPOS Seismology (www.epos-eu.org/tcs/seismology) services & data products and modern community software; (ii) serve as a backup to authoritative ShakeMap implementations; (iii) deliver ShakeMaps for Euro-Mediterranean regions where no local capability is yet available. ShakeMap-EU products are accessible since mid-2020 at the web portal shakemapeu.ingv.it. Jointly governed by the institutions participating in the initiative, ShakeMap-EU is founded on voluntary institutional contributions and EC-funded projects. ShakeMap-EU has become a reliable European seismological service that can easily and consistently integrate authoritative models and workflows. The system is based on: (a) the latest version of ShakeMap® (usgs.github.io/shakemap); (b) the earthquake information delivered by the EMSC (www.emsc-csem.org); (c) the earthquake shaking data distributed by ORFEUS (orfeus-eu.org/data/strong); (d) the ground motion models adopted within EFEHR (www.efehr.org) for mapping seismic hazard across Europe; (d) the official ShakeMap configurations of some of the most hazardous countries in Europe. Configuration of, and input to the system are managed via a GitHub repository that allows automatic / manual triggering and interaction by authorized users. ShakeMap-EU provides a collaboration framework and laboratory for seismological agencies to address the challenges posed by the heterogeneity of ground shaking mapping strategies across Europe and the need to promote homogenization and best practices in this domain. ShakeMap-EU is used in research projects as the test platform for novel international collaborative research: among recent examples are the ongoing enhancements towards an evolutionary hazard information system including real-time seismicity characterisation and information on earthquake-induced phenomena.

ShakeMap4-Web: Visualizing the ShakeMap4 Products Using a Web App

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We have developed a web application that allows users to quickly visualize the products generated using the U.S. Geological Survey ShakeMap version 4 software. The possibilities include visualizing the ground-shaking maps, the ground motion model (GMM) regression curve, the list of stations and the metadata of an event. The ground-shaking maps can be displayed both dynamically (using Leaflet maps) and statically (standard ShakeMaps). The dynamic maps can be customized with various overlays, from the contours of different intensity measures to the points of DYFI observations, with the overlays being clickable to display additional information. Furthermore, a dual-view feature allows users to view maps with different intensity measurements side by side. The Analysis view page allows users to view the regression curve of the GMM with the observed values (for macroseismic intensity, PGA and PGV). Users can use the web application to access and download all the data that contributed to the calculation of each earthquake, along with information on the seismological models used. The station list page allows the users to access information about all the stations that contributed to the generation of a specific ShakeMap. All the metadata associated with an event can be accessed through the metadata page. All the above-mentioned pages, for each specific earthquake, can be accessed through the home and archive pages. In detail, the home page shows a list of the latest events, while the archive page allows the user to show all the events that satisfy certain criteria (time range, magnitude range). The appearance of the web portal can be easily customized by replacing logos and banners. The software can be easily installed on both laptops and server computers, and users can choose between using the Docker image or using the software directly after setting up a web server (e.g., Python server, NGINX, etc.).

Migrating Global ShakeMap to the Cloud

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The United States Geological Survey (USGS) has traditionally produced global ShakeMap products using on-premises virtual machines. With the Federal Government initiative to utilize cloud resources (https://cloud.cio.gov/strategy/), the USGS ShakeMap team has taken action to migrate ShakeMap to the Amazon Web Services (AWS) Cloud. Instead of doing a costly lift-and-shift, which is akin to setting up a virtual machine in the cloud, the ShakeMap cloud developers have adopted a hybrid approach that partially refactors the code to make it more cloud native and take advantage of serverless cloud resources. On the lift-and-shift side, the ShakeMap source code and dependencies are packaged into an Amazon Machine Image (AMI) that is updated weekly and runs on an Elastic Compute Cloud (EC2) instance. The remainder of the ShakeMap system, however, follows a more cloud native approach by using several low-cost, serverless resources. For example, the ShakeMap queueing system has been updated to use small AWS compute instances (Lambda functions) and a key-value NoSQL database (DynamoDB) that stores event and versioning details. Here we will discuss the cloud ShakeMap architecture in more detail and elaborate on the benefits of the cloud system (e.g., stability, security, and advanced monitoring) as well as difficulties encountered along the way.

Aggregate Behavior Analysis of Ground Motion Distributions and Their Effects on Loss Estimation

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The U.S. Geological Survey's (USGS) ShakeMap product provides estimates of ground motions in areas directly affected by an earthquake. It does this by combining estimated ground motions, their uncertainties, recorded and observed ground motions, and a spatial correlation model. We investigated the uncertainties on the output hazard and loss estimation arising from the assumed input uncertain distribution parameters (mean and correlation). Our focus in this work is on investigating the aggregate behaviors of shaking (the relative proportions of grid cells having different shaking intensities) when we include the uncertainty in ground motions. We employed a Monte Carlo approach to model the uncertainties' effects; wherein we generated numerous spatially correlated realizations of ground motions using a combination of circulant embedding and kriging. For each realization, we analyzed the relative number of grid cells having different shaking intensities and investigate the distribution of these relative counts across numerous realizations for various shaking intensities. A key outcome of our investigation is that the relative counts of ground motions given by the mean shaking grid underestimate the number of grid cells realized at the higher shaking intensities. That is, any given realization would mostly likely have a larger number of high shaking grid cells than the mean estimate). Hence, overall larger populations exposed to higher shaking. This in turn (on average) leads to higher loss estimates when shaking uncertainty is included. Understanding these aggregate shaking behaviors is important when incorporating shaking uncertainty into loss and hazard models that rely on aggregated shaking estimates.

Developing and Implementing an International Macroseismic Scale (IMS) for Earthquake Engineering, Earthquake Science, and Rapid Damage Assessment

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Macroseismology plays a crucial role in earthquake hazard and risk analyses, tying earthquake occurrences and impacts from the past with those of the present and future. In fact, the use of macroseismic intensity has grown recently as the hazard layer within essential USGS and others' real-time earthquake information products, including Earthquake Early Warning, ShakeMap, "Did You Feel It?" (DYFI), PAGER, and even in presenting probabilistic seismic hazard maps in a friendlier format to nontechnical users. However, even with best practices, there are several limitations to modern macroseismic data collection approaches. First, whereas crowd-sourced intensities such as DYFI are robust and definitive for lower intensities, they are poorly defined above intensity VII, where damage observations require expert knowledge of each building's structural system. Second, the United States, New Zealand, and others employ the Modified Mercalli Intensity (MMI) scale, which is consistent with—yet inferior to—the more recently developed European Macroseismic Scale (EMS-98). We report on an IMS Working Group meeting held in October 2022 at the USGS Powell Center to address these issues and to work towards an IMS. The workshop goals were, first, to harmonize the MMI scale with EMS-98 for the US and NZ—which share several similar building types—by considering those structures and associated damage grades not well represented in the current EMS-98 building vulnerability table. Second, formalize the process of augmenting EMS-98 with additional building classes and damage grades in other countries, thus promoting the development of a scale that can be used globally. Such efforts require reviewing and expanding the original EMS-98 explanatory documents and considering potential revisions. Finally, we discuss how standardized earthquake-damage data worldwide collection as part of genuine IMS could help facilitate earthquake hazard and engineering analyses.

Real-Time Ground Shaking Maps Reconstructions With a Hybrid ShakeMap Implementation

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Ground shaking maps have been applied to a variety of tasks but their most useful application is arguably for seismic monitoring and civil defence operations as they provide information about the area and amplitude of the ground motion relative to a seismic event. Shaking maps, expressed in terms of a ground motion parameter, are reconstructed constraining the theoretical values obtained from ground motion prediction equations (GMPEs), computed from the magnitude and location of the earthquake, with the ground motion parameters values recorded at the stations, accounting also for local site effects. The need for source parameters to evaluate the GMPEs prevents a real-time implementation of such a method. One possible solution to the problem is to develop algorithms that can constrain the interpolation process using only the ground motion parameters recorded at the stations. We propose a hybrid model combining the conditioned multivariate normal distribution (MVN) technique adopted by ShakeMap and a neural network replacing the GMPE. The neural network provides a purely data-driven approximation of the GMPE results based only on the spatially sparse ground motion parameters recorded at the stations, with possible correction for the site effects. Moreover, by limiting the use of a neural network to a specific task we improve its explainability with respect to end-to-end models. The proposed implementation has been trained and tested with data from the Italian territory and its results compared to the ones obtained with ShakeMap. This approach is easily integrable into the existing workflow, combines well-studied interpolation techniques and neural networks in an explainable structure, and provides high-resolution estimates of the ground-shaking fields with real-time capabilities and potential relevance in the context of early warning.

Ground Motion Processing Software at the U.S. Geological Survey: New Collaborations and Contributions

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For many years the U.S. Geological Survey (USGS) maintained software called "amptools" for basic waveform processing and intensity metric calculations in support of ShakeMap. In 2018, this software was renamed "gmprocess" and expanded to support more waveform processing protocols, a wider range of intensity measures, additional data formats, provenance tracking, and many other improvements. These improvements increase run time, and thus gmprocess does not replace leaner real-time processing software. These changes also resulted in the software being useful for more general research projects that required processed ground motion time histories and metrics. The expanded user base of gmprocess has led to vast improvements due to the identification and resolution of previously unknown bugs (e.g., an error in how the signal-to-noise was normalized) and refinements to the processing algorithms (e.g., selection of filter corner frequencies, preferring frequency-domain differentiation and integration). Furthermore, many new users have contributed code and developed new features. One of the most frequently requested features that was not previously available in gmprocess is a graphical user interface (GUI) for reviewing processed waveforms, and two GUIs have been contributed to gmprocess; one from developers at the University of California Los Angeles, and another from Geoscience Australia, both of which were developed in close collaboration with the USGS. In addition, the core gmprocess team has developed new tools for managing and reviewing data for large projects, including queuing processing jobs and monitoring completion status. The gmprocess developers are also collaborating with the USGS National Strong Motion Project and California Geological Survey to benchmark the software employed by each group to resolve discrepancies and facilitate consistent results as the software continues to evolve. This type of benchmarking has led to important improvements to gmprocess.

U.S. Geological Survey's ShakeMap Atlas 4.0 and AtlasCat

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The long-awaited update to the U.S. Geological Survey (USGS) ShakeMap Atlas, and its new companion catalog, AtlasCat, are now available. ShakeMap Atlas 4.0 is an openly available, self-consistent, calibrated collection of over 14,000 ShakeMaps of global earthquakes that occurred between 1900 and 2022. The Atlas 4.0 ShakeMaps depict the spatial distribution of shaking for a suite of historical events, focusing on earthquakes that were widely felt, caused reported damage, or resulted in casualties. Atlas 4.0 uses the latest, much-improved, and enhanced version of the ShakeMap software, an updated earthquake source catalog, weighted suites of prediction and conversion equations, expanded strong motion and macroseismic datasets, and finite-fault geometries. By coupling loss data for each event with a depiction of the shaking distribution for a suite of canonical earthquakes, the Atlas aims to provide a basis for earthquake loss model calibration, as well as seismic hazard, scenario, risk, and loss model development and testing. Therefore, we have compiled losses and the population exposed to each intensity level, along with metadata for input shaking constraints, for all Atlas events into a single catalog, AtlasCat. Previous versions of the Atlas had two companion catalogs, PAGER-CAT (loss-focused) and EXPO-CAT (exposure-focused); however, we have found it best to combine all the Atlas companion information into a single database for ease of use. While the initial motivation for developing the ShakeMap Atlas was calibrating the USGS Prompt Assessment of Global Earthquakes for Response (PAGER) system, over time, the Atlas has proved to be a valuable tool for other users and, as such, we have expanded its scope in this newest version.

ShakeMap-related Research, Development, Operations, Applications and Uses [Poster]

Poster Session • Wednesday 19 April

Conveners: David J. Wald, U.S. Geological Survey (wald@usgs.gov); Carlo Cauzzi, Swiss Seismological Survey ETH Zürich (carlo.cauzzi@sed.ethz.ch); Hadi Ghasemi, Geoscience Australia (hadi.ghasemi@ga.gov.au); Nick Horspool, GNS Science (n.horspool@gns.cri.nz); Eric Thompson, U.S. Geological Survey (emthompson@usgs.gov); Bruce Worden, U.S. Geological Survey (cbworden@contractor.usgs.gov)

Proposed Updates to the Finite-Fault Model Depiction for Shakemap Computations

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The U.S. Geological Survey's ShakeMap product relies on estimates of rupture geometry to provide accurate predictions of shaking intensity for large-magnitude earthquakes. We approximate the extent of the complex slip distribution with a quadrilateral (known as the "ShakeMap polygon") to compute fault-to-site based distances (e.g., Joyner-Boore distance, source-rupture distance, and other measures), which must be approximated from a point-source distance when a slip model is not yet available. Currently, the rapid finite-fault model we routinely produce at the National Earthquake Information Center (NEIC) following significant (M7+) earthquakes is constrained to be a single planar fault model, which is generally sufficient for rapid shaking and impact estimation purposes. However, even simplistic planar fault models may have multiple spatially separate slip asperities with dimensions poorly approximated by a single quadrilateral. Furthermore, as we enhance the NEIC finite-fault product methodology to allow more complex rupture orientations within the rapid response time frame (e.g., models that accommodate varying dip from the Slab2 subduction zone models), we aim to update the associated ShakeMap polygon computations to allow for non-planar orientations. In this presentation, we explore new methods for approximating the ruptured portions of the fault responsible for strong motion radiation from finite-fault models to improve downstream ShakeMap shaking estimates. We provide examples of the impact these changes can have on shaking estimates, including for locations where station coverage may moderate the importance of constraining fault-finiteness.

Re-Computation of the Mw6.4 on January 7, 2020 Shakemap Using Fault Characterization

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The Puerto Rico and Virgin Islands region is not exempt from destructive earthquakes. On January 7,2020 at 08:24 UTC a Mw 6.4 earthquake occurred in southwestern Puerto Rico (SWPR). This event was located near offshore and had a mixed normal and strike-slip motion (Liu et al., 2020, ANSS-ComCat) and cause severe infrastructure damage and economic property losses. In order to understand the seismic hazard is also important to understand if some tectonics boundaries where deformation remains diffuse over long periods of geologic time and do not coalesce into one or more mature faults. (Vanacore et al. 2020).

An efficient emergency response in the event of a damaging earthquake will be crucial to minimizing the loss of life and disruption of lifeline systems in Puerto Rico and facilitate a faster recovery. This event provides a real-life test to auto-evaluate the outcome of the current earthquakes and tsunami protocols and work towards improvements in case a larger event strikes in the future, focusing on the near field. The high seismic hazard and high tsunami potential in Puerto Rico together with the poor construction practice can result in a potentially devastating combination. This abstract presents the recalculation of the shakemap using recent fault characterization. The primary duty of the Puerto Rico Seismic Network (PRSN) is to identify and provide rapid information on local, regional, and teleseismic earthquakes and help the TSP (tsunami service provider) to broadcast tsunami messages to Puerto Rico and Virgin Islands.

Shakemap Implementation and Daily Operations in the Puerto Rico Seismic Network (PRSN).

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The Puerto Rico archipelago has a long history of damaging earthquakes. Major earthquakes from local sources have affected Puerto Rico in 1670, 1787, 1867, 1918 and the most recent in 2020 (Mueller et al, 2003; PRSN web site). Recent trenching has also yielded evidence of possible M7.0 events inland (Prentice and Mann, 2005). The high seismic hazard, large population, high tsunami potential and relatively poor construction practice can result in a potentially devastating combination. Efficient emergency response in the event of a large earthquake will be crucial to minimizing the loss of life and disruption of lifeline systems in Puerto Rico and facilitate a faster recovery.

The ShakeMap System (Wald et al, 1999a) was developed by the United State Geological Survey (USGS) to provide a near time map and disseminate information about the geographical distributions of ground shaking following a large earthquake. The ShakeMap system provides important information about the intensity that people felt during an earthquake. Implementing a robust ShakeMap system is among the top priorities of the Puerto Rico Seismic Network (PRSN) and the Puerto Rico Strong Motion Program (PRSMP). However, the ultimate effectiveness of ShakeMap in post-earthquake response depends not only on its rapid availability, but also on the effective use of the information it provides.

In 2004, the Puerto Rico Seismic Network (PRSN) initially developed some ShakeMap scenarios using the package V3.1. The scenarios proposed probable earthquakes and damaging in Mayaguez and San Juan, Puerto Rico, two of the largest cities in Puerto Rico (Huerfano et al, 2006). Earthquake source parameters were obtained from McCann and Mercado (1998), Zahibo et al (2003) and Huérfano (2003). After some testing and upgrades in the instrumentation and processing we upgraded to the new version V4.0 which is currently in place and used in daily operation in PRSN. Data collected using the Community Internet Intensity Maps (CIIM) are also used as an additional constraint.

Shakemap's Sensitivity to Origin Parameters in the Presence of Dense Instrumental Data

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The Pacific Northwest Seismic Network (PNSN) automatically generates ShakeMaps for earthquake rapid response following all M≥3.0 earthquakes in Washington and Oregon. Rapid growth of the PNSN in recent years has resulted in an almost doubling of stations available to feed data to ShakeMap. In the presence of instrumental data, ShakeMaps can show significant differences between versions when origins shift in location or magnitude. To evaluate these differences we create a suite of ShakeMaps for data-rich earthquakes including the 2020 M5.7 Magna, Utah, the 2021 M6.4 and M7.1 Ridgecrest, CA events and other recent events. We assess how sensitive ShakeMaps are to input parameters when combined with changes to the set of stations contributing data nearest the epicenter. We also explore the differences in ShakeMaps to resampling the data set with different station densities to understand the possible range of results for earthquakes in the eastern parts of our network where station density is lower.

The USGS Shakecast Application: An Update on Shakemap's Sibling

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ShakeCast® is a U.S. Geological Survey (USGS) software application that automatically retrieves ShakeMap shaking estimates and performs analyses using fragility functions for buildings and lifelines. As a user-focused application, ShakeCast has been developed with support from external organizations and is in close coordination with the developments in the ShakeMap application. The ShakeCast system identifies which facilities or lifeline segments are most likely impacted by an earthquake—and thus which ones should be prioritized for inspection and response—and sends notifications to responsible parties in the minutes after an event. ShakeCast can improve critical lifeline situational awareness, inspection prioritization, and reduce response times in the aftermath of a significant earthquake by focusing inspection efforts on the most damage-susceptible facilities in the severely shaken areas. Here we update the technical specifications regarding the code base, dependencies, documentation, and deployment options of the Python-based ShakeCast system and software. Engineering-based functionality improvements include our ShakeCast-AEBM (Advanced Engineering Building Module) library, the ShakeCast-HWB (highway bridge) library, the USGS Ground Failure Docker service, and integration with users' regulatory criteria, which inform their response protocol. We further emphasize new user-centric products and automated workflows for inventory, fragility, and notifications that facilitate improved post-earthquake inspections and response protocols. Lastly, we highlight recent earthquake case histories where critical infrastructure ShakeCast users employed the ShakeMap/ShakeCast combination in their decision-making.

Waveform Benchmarking Comparisons for Selected Earthquake Records Processed With Prism, Sara, and Gmprocess

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We present preliminary results of comparisons of processed waveform products and waveform intensity metrics calculated by three different software programs. The Center for Engineering Strong Motion Data (CESMD) provides raw and processed strong motion waveform data to the earthquake engineering community at strongmotioncenter.org. These data are an important resource for both ground motion research and for practitioners who need to understand the impacts quickly after an earthquake. Currently, the software used by the U. S. Geological Survey (USGS) National Strong Motion Project (NSMP) and the California Geological Survey's Strong Motion Instrumentation Program (CSMIP) to process waveforms is the Processing and Review Interface for Strong Motion data (PRISM) and the Strong-motion Automated Recovery and Analysis (SARA), respectively. In parallel, USGS has developed ground motion processing software (gmprocess) in part to support

ShakeMap operations that provides expanded functionality. We begin these comparisons starting with ground motion records for the M6.4 December 20, 2022, Ferndale, CA; M5.3 February 27, 2021, Point MacKenzie, AK; and the March 18, 2020, M5.7 Magna, UT, earthquakes. This selection of earthquakes offers a variety of epicentral distances and near-surface characteristics from a sampling of different tectonic domains. These comparisons focus on quantifying differences in acceleration, velocity, displacement, and spectral acceleration products at both free-field stations and structural (building, dam, bridge, and geotechnical) arrays. With these comparisons we aim to streamline and standardize our waveform processing workflows and identify and resolve any inconsistencies between the different software programs.

Single-station Passive Exploration Methods: Status and Perspectives

Oral Session • Tuesday 18 April • 04:30 PM Pacific

Conveners: Martín Cárdenas Soto, Universidad Nacional Autónoma de México (martinc@unam.mx); José Piña Flores, Universidad Nacional Autónoma de México (jpf@unam.mx); José Francisco Sánchez Sesma, Universidad Nacional Autónoma de México (sesma@unam.mx)

Modeling Noise Hvsr in Media With Lateral Irregularity Using the Diffuse Field Assumption and Ibem for an Irregular Soft Layer

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Modeling noise horizontal-to-vertical spectral ratio (HVSR) using the diffuse field assumption (DFA) requires the imaginary part of Green's tensor when source and receiver coincide at the point of interest, precisely the point of data gathering. This approach has been applied for horizontally layered medium to model HVSR. The ensuing inversion leads to vertical profiles of mechanical properties. For irregular profiles, the issue was explored by Matsushima et al. (2017) in Onahama, Japan. Data processing revealed significant directional differences in HVSR. They used the spectral element method to compute the time domain response and Fourier analysis of results close to the load point allowed retrieval of the imaginary part of Green's function. This exercise was not a formal inversion but the modeling showed improved matching of calculations and observations when the known irregularity was accounted for. A similar case for the Ijen volcano, Indonesia is due to Perton et al. (2017). The exposed layering at the crater edge allowed to model HVSR.The scarcity of results reflects the difficulties for computation the imaginary parts of Green's tensor at load points. Looking for a practical approach we used the indirect boundary element method (IBEM) in 3D to study the case of a single layer over a half-space. We reproduced the semi-analytical solution using an adaptive mesh that changes with frequency. This result reveals the crucial role of diffraction at low frequencies and the asymptotic behavior in high frequencies. These results clearly show the strong localized behavior of the solution which also holds for irregular profiles. We model HVSR for a layer over a half space with lateral variations. We obtained the directional HVSR and observe both the changes in peak frequency and the variations in amplitude for both longitudinal and transverse directions.ACKNOWLEDGEMENT. This research was partially supported by the UNAM through projects DGAPA-PAPIIT IN107720 and IN105523.

Single-Station Microtremor HVSR Curve Inversion and Ambient Noise Tomography of the Three-Component Seismic Data From a Nodal Array in Downtown Reno, Nevada

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An accurate quantitative representation of subsurface features and velocity structure at the basin scale is essential in successfully predicting strong ground motions and assessing site amplification responses in sedimentary basins. This improved understanding is advantageous to better address earthquake hazard mitigation in urban centers such as the Reno basin. Single station microtremor horizontal to vertical spectral ratio (HVSR) inversion is a helpful technique for producing one-dimensional (1D) velocity structures using a single three-component seismic node recording ambient acoustic emissions due to natural and anthropogenic sources. The usefulness of the single-station HVSR inversion technique particularly holds in urban centers, where deploying a linear nodal array, as in the refraction microtremor technique, may be logistically challenging. Furthermore, the first and second peak amplitude and frequency of the HVSR curve provide relevant information on site fundamental frequency, impedance contrasts, and depth to bedrock. To better understand the capabilities of the single-station microtremor HVSR curve inversion technique and improve current understanding of the subsurface Reno basin structure, a large-scale ambient noise data gathering effort was undertaken with several three-component nodes scattered across the city of Reno, Nevada. The ambient noise recording was conducted over two weeks. The extracted ambient noise data was used to generate HVSR curves for each station separately to provide several 1D velocity profiles of the subsurface structure. The generated 1D velocity profiles are interpolated to provide a three-dimensional rendering of the subsurface velocity variations. An ambient noise tomography using dispersion curve inversion of surface waves is also performed and compared to the HVSR curve inversion.

Directional Amplification and Ground Motion Polarization in Casamicciola Area (Ischia Volcanic Island) After the 21 August 2017 Md 4.0 Earthquake

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We investigated ground motion directional amplification and horizontal polarization using ambient noise measurements performed in the northern sector of Ischia Island which suffered damage (VIII EMS) during the 21 August 2017, Md 4.0 earthquake. Over 70 temporary seismic stations were installed by the INGV EMERSITO task force, whose aim is to monitor site effects after damaging earthquakes in Italy. To investigate ground motion directional amplification effects, we have applied three different techniques, testing their performance: the HVSR calculation by rotating the two horizontal components, the covariance matrix analysis, and time–frequency domain polarization analysis. These techniques resulted in coherent outcomes, highlighting the occurrence of directional amplification and polarization effects in two main sectors of the investigated area. Our results suggest an interesting pattern for ground motion polarization, that is mainly controlled by recent fault activity and hydrothermal fluid circulation characterizing the northern sector of the Ischia Island.

Estimating VS30 From Horizontal-to-Vertical Spectral Ratio Based on Supervised Machine Learning

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Average S-wave velocity (Vs) to 30 m depth (VS30) is an important proxy to estimate site amplification. Invasive and non-invasive methods, such as velocity loggings or active/passive surface wave methods, have been generally used to directly measure the VS30. Those methods are expensive and time consuming. The VS30 is also indirectly estimated by empirical methods based on geology, geomorphology, elevation, or slope angle etc. Those methods are inexpensive but not accurate. We intend to use a horizontal-to-vertical spectral ratio (H/V) to roughly estimate the VS30. The measurement of H/V is much easier and quicker compared with active surface wave methods (MASW) or microtremor array measurements (MAM). The inversion of the H/V is essentially non-unique and it is impossible to obtain unique Vs profiles only from H/V spectra. We apply supervised machine learning to roughly estimate the

Vs profiles or VS30 from H/V spectra together with other available information, such as site location or geomorphology etc. Our machine learning consists of a neural network with one hidden layer. The pairs of the H/V spectra (input layer) and Vs profiles (output layer) are used as training data. Input layer consist of an observed H/V spectrum site coordinate, and geomorphological information. Output layer is a velocity profile obtained from the velocity loggings, surface wave measurements, or inversion of H/V. We have applied the machine learning to several different sites in U.S. and Japan. This presentation introduces a study at Napa Valley in California. We measured MASW, MAM and H/V at approximately 100 sites at the Napa Valley. The pairs of H/V spectra together with their coordinate and Vs profiles obtained from the inversion of dispersion curve compose the training data. Trained neural network predicts Vs profiles from observed H/V spectra. The VS30 calculated from predicted Vs profiles are reasonably consistent with those calculated from true Vs profiles obtained from the dispersion curves. The results implied that the machine learning could roughly estimate VS30 from H/V spectra together with available other information.

Detecting and Locating Underground Cavities by the Finite-Interval Spectral Power of Seismic Ambient Noise

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Detection and location of underground cavities is of great importance in urban development and civil constructions because undetected cavities of natural or artificial origin pose a serious geotechnical hazard.Of special interest are the underground cavities produced by underground nuclear explosions. There are several reasons for this. One of them is vitally related to the Comprehensive Nuclear-Test-Ban Treaty (CTBT) – an international treaty banning nuclear weapon test explosion or any other nuclear explosion which is yet to come into force. Detection and location of a cavity generated by an underground nuclear explosion can be an important proof of an underground nuclear explosion in the framework of CTBT on-site inspections.We present two validation cases of the method that we have recently developed for detecting and locating an underground cavity – one for a CTBT test site near Felsőpetény in Hungary, the other for a site of the Tiny Tot underground nuclear explosion in Nevada USA.We show that mapping the Finite-interval Spectral Power of seismic ambient noise makes it possible to identify a place at the free surface above an underground cavity. The method can utilize single-station measurements at a set of potentially irregularly distributed points in the area on the Earth's free surface over a suspected cavity.

Single-station Passive Exploration Methods: Status and Perspectives [Poster]

Poster Session • Tuesday 18 April

Conveners: Martín Cárdenas Soto, Universidad Nacional Autónoma de México (martinc@unam.mx); José Piña Flores, Universidad Nacional Autónoma de México (jpf@unam.mx); José Francisco Sánchez Sesma, Universidad Nacional Autónoma de México (sesma@unam.mx)

Dynamic Characteristics Assessment and 3D Site Effects Analyses of Earth Dams Based on Ambient Noise Measurements.

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The HVSR method has undergone a great evolution for the evaluation of dynamic parameters in free-field condition. Its application for more complex systems, i.e. 2D and 3D systems, is under development but much less widespread. This paper presents case studies applied to a large dam built in a narrow valley and dikes built on very thick deposits, very complex sites.

As part of the study, sets of ambient noise measurements were acquired for each earth structure using six velocimeters, aiming to evaluate the possible 3D site effects and determine the fn values. Analyses of these experimental data consisted of processing the individual signals with the simple "reference dependent spectral" and "ambient vibration horizontal-to-vertical spectral ratio (HVSR)" methods. Modal analysis combining synchronized measurements led to the establishment of additional higher vibration frequency modes and modal shapes. The consistency between the f_n values obtained using the simple methods and those from the advanced modal analysis are noticeable.

For the large dam, the seismic data provided an exceptional opportunity to validate the experimental data. A comprehensive analysis was thus conducted to compare the dynamic parameters calculated from the processed experimental data with those resulting from the seismic data and proved the values to be similar. All of these analyses demonstrate the potential of the ambient noise technique for identifying the dynamic characteristics of large earth structure built in narrow valleys or on very thick deposits.

High-Resolution Imaging of the Firn Layer in Antarctic Near the West Antarctic Ice Sheet Divide Camp

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We analyze the 7-day seismic recordings from Antarctic near the West Antarctic Ice Sheet (WAIS) Divide Camp to image velocity structure of the firn layer. The WAIS array includes 76 3-component Z-Land Gen2 Fairfield seismic stations along a ~2.2 km line with station spacing of 30 m. We estimate high-resolution near-surface seismic velocities, especially at the firn layer, using ambient noise data recorded by this array. We first calculate the ambient noise cross-correlation, and use phase-matched filter to isolate different signals in the cross-correlation. Then three-station interferometry is applied to denoise the surface wave signals for accurate Rayleigh wave travel-time measurements in the 3-30 Hz frequency band. We also obtain the H/V ratios of the Rayleigh wave at 5-25 Hz by stacking the waves at a target station from different virtual sources after removing the phase difference between different station pairs, which improves the signal-to-noise ratio of H/V ratio measurement. Joint inversion of Rayleigh wave phase velocity and H/V ratios suggests that S-wave velocity (Vs) increases from ~200 m/s to ~1200 m/s in the top ~20 m with a sharp velocity interface at ~5-10 m depth, and varies slightly in the horizontal direction. The Vs gradually increase to 2000 m/s from 20 m to ~80-100 m in depth, and remains relatively homogeneous in the horizontal direction. This is likely a firn layer and the transition zone. Particle motion analysis reveals potential higher mode Rayleigh waves traveling at a phase velocity of ~2 km/s with little dispersion at ~15-30 Hz, and P-type body wave with an apparent velocity of ~4 km/s around 20 Hz. Updated results will be presented in the meeting.

Seismic Energy Partition Applied to Dispersion Diagrams of Surface Waves

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Ambient seismic noise (ASN) has been used in various studies to obtain Rayleigh wave dispersion curves. The main objective of these studies is to obtain shear-wave velocity profiles and assess site effects for a given location. Different geophysical methods allow obtaining dispersion diagrams using ASN, highlighting the Spatial Autocorrelationmethod (SPAC); Frequency-Wavenumber Analysis (FK), among others. However, the high-energy bands in the dispersión diagrams are usually interpreted as the "true" phase/group velocities of modal dispersion. Misidentifying the multiple modes of Rayleigh/Love waves in layered media can reproduce an effective phase velocity dispersion curve. Several studies have attempted to mitigate the problem of identifying modes in dispersion curves that exhibit multiple modes and kissing effects in surface wave dispersion. This work applies the seismic energy partition concept in the dispersion curves, generating theoretical dispersion diagrams from the energy distribution corresponding to each mode. On the one hand, this procedure would allow an understanding of the nature of the propagation of surface waves and will support, in the dispersion diagrams, the manifestation of multimodal and kissing effects that limit the identification of the fundamental mode. On the other hand, it will make it possible to obtain an explicit relationship between the dispersion diagrams and the H/V spectral ratio with the seismic energy partition, which will facilitate obtaining complementary information for passive seismic prospecting techniques.

Strong Ground Motion Variation due to Local Complex Geology During the Earthquake of September 19, 2017 (Mw 7.1)

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September 19, 2017, earthquake considerably affected buildings, neighborhoods, and even plumbing lines buried in the geotechnical transition zone of Mexico City. This zone is associated with a high geological hazard due to faults, cracks, subsidence, landslides, and mine collapses. The lesson learned from this earthquake showed that much remains to be known, and detailed subsoil characterization is needed to define vulnerable sites that allow for the reduction of seismic-geological risk. This study used various geophysical methods to explore the subsoil structure under a housing unit south of Mexico City. The houses began having structural damage, and the land surface presented cracks in the last ten years, problems that were magnified after the earthquake. We apply electrical tomography, seismic noise interferometry, and H/V methods. The results show the subsoil properties vary drastically both in the lateral direction and in-depth. In particular, it highlights the presence of a discontinuity that divides the area into two different structures. Our interpretations show that observed damages could be associated with the subsoil irregularity (that substantially modifies and amplifies the seismic input motion) and the local differential subsidence produced by groundwater overexploitation.

The Use of the H/V Ratio for Back-Calculation of Normalized Shear Modulus G/g0

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The HVSR technique is a passive single-station method used to identify the fundamental resonant frequency of a site under specific conditions. The obtained fundamental resonance frequency can be analyzed using nonlinear regression relationships between bedrock depth and average shear wave velocity. The application of the HVSR method to case studies has greatly increased in recent years due to the simplicity and high cost-effectiveness of the required types of equipment.

In this study, the empirical HVSR method was performed by the use of earthquake records selected from the Turkey Strong Ground Motion Database. For a strong ground motion station with a bedrock depth of 30 meters, approximately 300 earthquake records from past events ranging in magnitudes from 3 to 7 were used for the strong ground motion based HVSR analysis. In this regard, this study aimed to estimate the normalized shear modulus curve of the soil profile underlying the selected station, based on the back-calculation of the average HVSR curves obtained as a result of the analyses.

Site-specific Modeling of Seismic Ground Response: Are We Quantitative Enough to Predict?

Oral Session • Wednesday 19 April • 08:00 AM Pacific

Conveners: Marco Pilz, GFZ Potsdam (pilz@gfz-potsdam.de); Chuanbin Zhu, University of Canterbury (chuanbin.zhu@gfz-potsdam.de); Hiroshi Kawase, Disaster Prevention Research Institute, University of Kyoto (kawase.hiroshi.6x@kyoto-u.ac.jp); Andres Olivar Castano, University of Potsdam (andres.olivar-castano@uni-potsdam.de)

Spectral Decomposition of Ground Motions in New Zealand using the Generalized Inversion Technique

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In this study, we perform spectral decomposition of the Fourier amplitude spectra (FAS) of ground motions in the New Zealand Ground-Motion Database (GMDB v3.0) compiled during the National Seismic Hazard Model (NSHM) 2022 update project. We apply a non-parametric generalized inversion technique (GIT) to isolate source, path, and site effects from ground motions of selected events (1367 crustal, 910 intra-slab and 431 interface). Each channel (HN, BN, HH and EH) is treated as an independent "site" (total no.: 693). We will present the preliminary results on site responses at each "site", the attenuation (geometric spreading and frequency-dependent quality factor) for different types of events, as well as the source spectra of each earthquake and its corresponding source parameters (seismic moment, corner frequency and Brune stress drop) assuming an omega-square model.

Obtaining Site Effect-Free Hard-Rock Time Series in Japan From Surface Recordings based on the Generalized Inversion Technique

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The computation of time series for hard-rock site conditions, either as input motion for site response calculations or for applications to installations constructed on this site type, is a crucial step for seismic hazard assessment. The current state-of-the-art is to apply physics-based corrections to surface motions to eliminate the influence of site effects for retrieving the underlying bedrock motion. Here we evaluate the application of the generalized inversion method (GIT) for deconvolving surface recordings to obtain hard-rock time series at the amplification-free seismic bedrock. The method includes an event-specific phase scaling approach on the surface recordings that takes changes in the signal duration between the surface and the seismic bedrock into account.We choose a total of 90 KiK-net surface-downhole sites for validation which do not have a significant velocity contrast below the downhole sensors and with the latter being located at sufficient depth so that they are not significantly impaired by downgoing waves. By comparing the empirical predictions from surface recordings with time series that have been recorded at the downhole sensors, we assess the accuracy of the predictions. In contrast to empirical and one-dimensional modelling approaches, which significantly overestimate the level of hard-rock ground motion for frequencies greater than a few Hz, we find quite high correlations and small variations in both spectral shape and amplitude over the entire frequency range. This approach delivers a data set that facilitates the development of reference ground-motion models.

Ground Motion Model for Predicting Significant Duration Constrained by Seismological Simulations

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We developed a GMM for predicting significant durations based on the normalized Arias intensity. Using seismological simulations through a 3D finite difference code (SW4), we showed that a GMM based on an additive behavior between the source, path and site terms provides better physics fundamentals on the behavior and makes us more confident in extrapolating the data than multiplicative-behaved models. Our data distribution exploration led us to define a site term with a log-normally distributed random effect, with a larger heteroskedasticity on small values of VS30, i.e., the variability is larger for softer sites than for stiffer sites. Then, we constrained the source term based on stochastic finite source simulations. We found a coupling scaling pattern between the source term with the rupture dimensions (i.e., magnitude) and the source-site distance. This aspect of the model shows that not only is the time window where the energy is released from the source important but there is also an important contribution from the relative ground motion amplitude. Furthermore, distance from the site to different rupture sub-segments influences the duration differently because of the relative amplitude-distance atten-

uation. To take advantage of all the benefits of working with normally distributed data, we applied a power-transformation to the model and to the final predictive GMM to ensure it follows a normal distribution. In conclusion, the significant duration process has a skewed distribution, being in between the skewness of the log-normal and the symmetry of the normal distribution. The complexities of the model formulation (event and site terms) require more advanced statistical tools than used for standard ground motion models development (i.e., random effect with least squares).

Searching for Empirical Nonlinear Site Response Applicable to Greater Vancouver, British Columbia

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Greater Vancouver, British Columbia, Canada, is an area prone to strong earthquakes, located at the northern end of the Cascadia subduction zone. All recorded earthquake motions are weak; maximum PGA of 0.053 g. To constrain the expected nonlinear soil response in Greater Vancouver, we are searching for seismic stations elsewhere in the world with available weak-to-strong motion recordings that have similar linear site response to Greater Vancouver as well as similarities in peak frequency (f_0), shear wave velocity (V_s) depth profile and geological setting, to then constrain the degree of empirical nonlinear soil response for future large earthquakes affecting Greater Vancouver.

We have identified seismic stations in Alaska, Japan, Mexico City, Spain and Grenoble-France that meet our equivalency-to-Vancouver criteria. Stations in Spain and Grenoble have an equivalent Vs depth profile to the Fraser River (FR) delta, but lack strong motion recordings and are therefore eliminated. 17 stations in Japan have f_0 = 0.1-0.3 Hz equivalent to deep FR delta sites, with at least 3 recorded earthquakes that exceeds PGA of 0.1 g. For five selected stations in Mexico City, we have calculated earthquake Horizontal to Vertical Spectral Ratios (eHVSR) to quantify variation in amplification spectra with shaking intensity. Four lakebed stations (CE23, AE02, CH84, TH35) have f_0 = 0.1-0.3 Hz equivalent to the deep FR delta, the 5th transition zone (DR16) station has f_0 = 1-2 Hz equivalent to the FR delta edge. CE23, AE02, CH84 and DR16 exhibit nonlinear site response as reduced amplification of f_0 but without a significant shift in its frequency. This study highlights continued need for *in situ* site characterization at seismic stations worldwide to achieve international standards in station metadata. The challenges thus far include not finding stations that meet all three of our equivalency-to-Vancouver criteria and an overall lack of strong motion recordings worldwide.

Characterization of Nonlinear Soil Behavior in a Systematic Manner at Japanese KiK-Net Sites and Correlation With Geological and Geotechnical Parameters

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Local soil conditions at a site can greatly influence incoming earthquake ground-motions. For small ground motions and stiff sites, the local soil-response behaves linearly, while for larger ground motions and softer sites, nonlinear site-effects are expected. In this study we systematically characterize the nonlinear soil-behavior for 210 instrumented sites in the Japanese Kiban–Kyoshin Network (KiK-net). This is done by measuring the effects of nonlinear soil-response in the stations' surface-to-borehole ratios, i.e. the change in amplitude and shift in frequency between strong-motion events and the linear site-response. These empirical measurements are then consistently analyzed to derive station-specific parameters for nonlinearity. We use these parameters to explore the correlation between strong nonlinear soil- behavior and a selection of geological and geotechnical indicators. Our results indicate that nonlinear soil-behavior is very site-specific and that finding site parameters for predicting nonlinear site-effect remain a challenge.

Evaluating Alternative Approaches to Model Local Site Effects in Physics-Based Ground-Motion Simulations: Insights From Small-Magnitude Earthquakes Recorded in Canterbury, New Zealand

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One of the current challenges in physics-based ground-motion simulations is to refine the modeling of local site effects. These effects require a finer spatial resolution in the material modeling than that generally considered in regional-scale simulations. Because of this, empirical amplification factors are typically applied to capture these unmodeled phenomena. The ergodic nature of this approach suggests that there is room for improvement. In this study, the predictive capability of simulations is evaluated using alternative methods for capturing local site effects. In addition to the conventional empirical approach, two methods are examined that allow for more site-specific information to be incorporated: the square-root impedance method and the 1D time domain site-response analysis. The three approaches are tested using 1000+ observed ground motions from 150+ small-magnitude events (3.5 ≤ M_w ≤ 5.0), recorded at 20 strong-motion stations in the Canterbury, New Zealand, region. These 20 well-characterized sites represent a wide range of soil conditions, including stiff gravels with V_{s30} values greater than 500 m/s, and sand and silt deposits with V_{s30} values less than 200 m/s. Multiple intensity measures are computed and prediction residuals are partitioned using mixed-effects regression to rigorously assess the relative performance of the different approaches considered. The results indicate that the benefit of using more sophisticated methods is highly dependent on the characteristics of the site. Key site parameters and trends are identified and discussed in light of the assumptions and limitations of each approach.

Are There Unique Parameters and Proxies for Predicting Site Response? Examples From Selected Borehole Strong Motion Arrays

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Although the physics governing site response are well understood as the increase of shear-wave impedance (ρVs) with depth, scientists and engineers have yet to reach a consensus on the most important parameters and proxies to quantify or characterize site response. For example, there is no agreement on whether the fundamental frequency (f_0) or peak frequency (f_p) is a better parameter. It has also been found that *Vs30* is not an appropriate proxy despite widespread use. In this study, we collected weak (PGA ≤ 0.05g) and limited strong (PGA > 0.05g) ground motions and *Vs* profiles from 54 borehole arrays penetrating bedrock from the United States and Japan. We derived empirical transfer functions (*TF*s) from the ground motions and linear theoretical *TF*s from 1D site-response analyses. We also characterized the *Vs* profiles using the impedance ratio (*IR*) and velocity ratio (*VR*). Our results show that site response is dependent not only on the overall velocity structure of the sediments and bedrock, but also the details of sediment velocity structure in terms of *IR* or *VR* distribution, the maximum impedance (IR_{max}) or velocity ratio (VR_{max}) in particular. Our results also show that site response is nonlinear: f_0/A_0 and f_p/A_p change with increase of ground-motion level. Due to data limitations, we only extracted the linear site parameters, including the fundamental-mode (i.e., base mode) frequency (f_0) and its associated amplification (A_0), and peak-mode frequency (f_p) and its associated amplification (A_p), from the empirical and theoretical *TF*s, and site proxies, including IR_{max}, VR_{max}, the depth to the interface with IR_{max} (Z_{max}), *Vs30*, *Z1.0*, and *Z2.5* from the *Vs* profiles. We compared these parameters and proxies and showed that there is no single parameter or proxy which can be used uniquely to quantify or characterize linear site response. Our results demonstrated that the complexity of site response is determined by the complexity of site conditions and nonlinearity.

Estimating the Earthquake Site Response From Ambient Noise Using the SSRh Approach: Overview, Application and Comparison With Other Techniques

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Earthquake site effects have a major impact on the seismic hazard. However, evaluating the site response over a broad frequency range and with a high spatial resolution remains difficult. Empirical site effect assessment has shown good reliability up to high frequencies but relies on earthquake recordings, which requires long station deployments. In contrast, seismic ambient noise can be rapidly recorded anywhere at any time. The hybrid standard spectral ratio (SSRh) combines both the spectral ratio from earthquake recordings at a few sites and the spectral ratio from ambient noise recordings at many sites from short duration deployments. Here we present and discuss the results of different studies applying the SSRh techniques on various sites in France, in Greece and in Switzerland. In addition, we investigate the site response at high-spatial resolution using the SSRh in the industrial areas of Cadarache and Marcoule, France. On every tested soil sites, we report a good agreement between the SSRh method and the referenced method based on earthquake observations. We discuss the uncertainties and limitation of the SSRh methods and we evaluate its performance compared to other techniques based on site proxies or/and on ambient noise recordings.

Using Microtremor-Based Horizontal-to-Vertical Spectral Ratios to Improve Linear Site Response Predictions in the Sacramento-San Joaquin Delta Region of California

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Sites located in the Sacramento-San Joaquin Delta region of California typically have peaty organic soils near the ground surface which are characteristically soft, with shear wave velocities as low as 30 m/s. These unusually soft geotechnical conditions will produce site effects that are not represented in datasets used to derive existing global ergodic site amplification models. We therefore perform nonergodic site response analyses using weak ground motion data recorded at 36 seismic stations in the Delta region. First-order site effects are modeled using a period-dependent multilinear V_{S30}-scaling model, which provides unbiased predictions for Delta sites as a whole by smoothing over site-specific effects. Microtremor-based horizontal-to-vertical spectral ratios (mHVSR) are developed for 34 sites, from which additional site parameters such as peak frequency (f_p) and average H/V amplitude over some frequency bandwidth (μ_{mHVSR}) are derived. Sites with prominent mHVSR peaks are interpreted as exhibiting site resonance effects, while sites without prominent peak features do not. A hybrid Ricker wavelet – Gaussian pulse function conditioned on f_p is used to model peak resonance effects, while a short-period constant computed from μ_{mHVSR} which smoothly transitions to zero at long periods is used to model general levels of amplification. These mHVSR-informed models are implemented as additive components to the V_{S30}-scaling model. The regionally-calibrated V_{S30}-scaling model and mHVSR-informed variant significantly reduce bias when compared to predictions provided by an ergodic model. The V_{S30}-scaling model does not appreciably change the aleatory variability (ϕ_{S2S}) for periods shorter than about 1.5 s, however significant reductions around the order of 0.1 (natural log units) are observed at long periods. When the mHVSR-informed model components are used, ϕ_{S2S} is reduced by about 0.05 to 0.1 (natural log units) for short-to-intermediate periods. Ongoing work is investigating nonlinear effects for the purpose of developing a comprehensive regional site response model for forward application.

Quantifying Site Amplification for Seismic Hazard in a Complex Shallow Basin: Case Study of the Wellington Basin, New Zealand.

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A global challenge for the seismological community is the treatment of complex local site/basin effects in urban seismic hazard analysis. Gobal global ground motion models (GMMs) and associated Vs30-based site models have been shown to perform well overall in New Zealand, forming a robust foundation for the national seismic hazard model (NSHM). However, it is widely recognised that the treatment of site response based on the single site metric of Vs30 is limited. This is evident when such models are applied to basins where significant localised amplification effects occur, such as the Wellington Basin, New Zealand.

To further the goal of more fully capturing site/basin amplification in future iterations of NSHM, the New Zealand NSHM team are using the Wellington Basin as a case study to explore and compare different modelling methods. We will present an overview of the basin study including basin characterisation and exploration of (i) NSHM site models, ii) site-to-site residuals (site terms) with respect to NSHM GMMs (iii) HVSR/SSR analysis and iv) physics-based ground motion modelling techniques. Particular challenges are posed in the Wellington Basin due to small-scale and relatively complex local structure that generates significant, but spatially variable amplification in the 0.5 to 2s period range. Nonlinear effects may also be influential at the softest soil sites for larger earthquakes that dominate the hazard.

Site-specific Modeling of Seismic Ground Response: Are We Quantitative Enough to Predict? [Poster]

Poster Session • Wednesday 19 April

Conveners: Marco Pilz, GFZ Potsdam (pilz@gfz-potsdam.de); Chuanbin Zhu, University of Canterbury (chuanbin.zhu@gfz-potsdam.de); Hiroshi Kawase, Disaster Prevention Research Institute, University of Kyoto (kawase.hiroshi.6x@kyoto-u.ac.jp); Andres Olivar Castano, University of Potsdam (andres.olivar-castano@uni-potsdam.de)

A Bayesian Kriging Approach for Site Period Mapping of Santiago Basin, Chile

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Seismic site classification plays an important role in estimation of site amplification, which directly influence earthquake-induced damages. Site effects are strongly dependent on site-specific conditions as well as the spatial distribution of the geotechnical parameters in the region. Since the fundamental site period depends on the subsurface condition, surficial maps such as terrain or geology have a high probability of being well constrained only to shallow depths. At the same time, it is hard to find a consistent source of bedrock depth parameter around the globe. The use of geostatistical methods such as ordinary kriging or simple kriging can resolve this issue by relying on a spatial variogram for predictions at unsampled locations. However, an uneven or sparse data distribution usually creates unrealistic patterns. This study proposes the use of Bayesian kriging interpolation method for site period mapping in Santiago basin, Chile. A low precision model using depth to basement is used as prior information and ~200 fundamental site period measurements are considered as precision data within the basin. This study shows that the spatial prediction accuracy can be further improved over ordinary kriging approach by the use of Bayesian kriging technique.

Classification of Aleatory Variability and Epistemic Uncertainty for Probabilistic Seismic Hazard Analyses

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Aleatory variability and epistemic uncertainty are used in Probabilistic Seismic Hazard Analysis (PSHA) to differentiate between aspects of the source models and ground-motion models that are treated as alternative credible models (epistemic uncertainty) and those that are treated as randomness (aleatory variability). The concepts of aleatory variability and epistemic uncertainty have been widely used in PSHA since the 1980s, however, confusion remains concerning their distinction in specific applications. One cause of confusion is that the classification of aleatory or epistemic terms is not absolute and depends on the parameterization of the models used. In general, models with a greater degree of simplification will have larger aleatory variability. This non-uniqueness is often a source of concern for earthquake scientists and has contributed to the belief that the distinction between aleatory variability and epistemic uncertainty is arbitrary; however, once a model is selected with a certain level of simplification, there is no ambiguity for the classification into aleatory and epistemic terms. We present a classifying framework for the source and ground-motion model parameters into the following aleatory and epistemic components: aleatory standard deviation about the median, epistemic uncertainty of the model for the median, and epistemic uncertainty of the size of the aleatory standard deviation. For each parameter, the terms are separated into two parts: modeling and parametric. The modeling parts are based on comparisons to data, and the parametric parts are based on modeling a range of inputs into the model. This framework provides clarification for checking that all parts of aleatory variability and epistemic uncertainty are systematically categorized and included in the models without double counting.

Delineating Shallow Sedimentary Structure of Matanuska and Eagle River Areas, Alaska, by Inversion of Horizontal-Vertical Spectral Ratio From Local Earthquakes.

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In the aftermath of the 2018 M7.1 earthquake, the Matanuska-Susitna (Mat-Su) Valley and Eagle River areas north of Anchorage suffered extensive damage. There were widespread ground failures, soil liquefaction throughout the region, and damage to schools and residential buildings. However, no strong-motion stations were operational in these areas during this earthquake. As part of a collaboration with the Alaska Earthquake Center, seven strong-motion sensors (Etna2 of Kinemetrics Inc.), including three in the Mat-Su Valley and four in Eagle River, were installed to capture strong-motion data during future earthquakes and examine spatial variations in ground response and its relationship between subsurface geological formations. The network has recorded several local earthquakes of magnitude 4.5 to 6.1 since February 2021. All analyzed recordings were detrended, baseline corrected, and bandpass filtered between 0.1 and 25 Hz to remove dominated noise. The amplitude spectrum of each component was computed using a fast Fourier transform (FFT) and was smoothed by the Konno and Ohmachi window. The Fourier spectra were calculated in a time window of 15 sec starting at the onset of the S waves after tapering with a 5% cosine function. The horizontal-to-vertical spectral ratio (HVSR) for the individual earthquake was calculated by dividing the root-mean-square average spectrum of the north-south and east-west component spectra and that from the vertical. The inversion of computed HVSR was performed using a global optimization technique via simulated annealing (SA) to obtain a 1-D layered earth model with P- and S-wave velocity, density, thickness, and frequency-independent attenuations of P- and S-wave as the model parameters for each layer. The results will show the variation in shallow structures at each station site. A detailed interpretation of ground motion characteristics in terms of layered-earth structure and their relation with the local geology will be presented.

Determining Shear Wave Velocities at a Deep Sediment Site in the Mississippi Embayment Using Rayleigh Wave Dispersion From Active and Passive Sources

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Rayleigh wave dispersion curves for a deep sediment site near Memphis, TN, are determined from small-scale refraction data, ambient noise interferometry from a dense 3km long profile of 60 nodal seismometers, and direct observation of explosion surface waves from two 91 kg explosions at the ends of the same profile as part of the Embayment Seismic Excitation Experiment (ESEE2022) that occurred in late July/early August 2022. The data span two orders of magnitude in frequency from 0.5 to 50 Hz and offer an opportunity to evaluate the consistency between dispersion measurements taken from passive and active seismic sources and resulting differences in derived shear wave velocity models. We have initiated this comparison using the two active-source, 48-sensor linear arrays for near-surface soil characterization. Multichannel Analysis of Surface Waves (MASW) and refraction microtremor (ReMi) were used to provide model estimates to depths of approximately 30m. Because hammer blow sources excite higher frequency Rayleigh waves than occur in ambient noise, MASW has less resolution for deep layers than REMi. Constrained inversion of dispersion gives near-surface shear wave velocities of 175-225 m/s increasing to 600-800 m/s at 30m depth. The shear wave velocity structure of the entire 900m thick unconsolidated sediment section is the target of using dispersion from ambient noise interferometry and explosion Rayleigh waves recorded by the 3km nodal array. A comparison of Rayleigh dispersion and models from these two datasets is in its initial phase and will be presented.

Examining Differences in Basin Amplification Between Interface and Intraslab Subduction Sources From the Kanto Region in Japan

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The basin amplification models used for subduction sources do not currently distinguish between intraslab and interface earthquakes. However, interface sources may generate stronger surface waves and S-to-surface wave conversions at the basin edge due to the shallower incidence ray path of the incoming waves. In contrast, deeper intraslab sources feature steeper incidence angles that could result in weaker surface waves at the basin-edge. Numerical simulations for sources near the Seattle basin provide support for this hypothesis (Wirth, 2019). We use recordings selected from the NGA-Subduction database in the Kanto Basin, where the city of Tokyo is located and compute the predicted response spectra for spectral periods from 0.01-10s using the four NGA-Subduction GMMs regionalized for Japan. The predictions are for a uniform site condition and without the basin term. We use a mixed-effects regression to partition each set of total residuals into the bias, between-, and within-event terms. The within-event residuals are plotted against the depth to the shear-wave velocity (Vs) horizon where Vs=2.5km/s (Z2.5). We find differences in basin-depth scaling for intraslab and interface sources, with interface earthquakes producing steeper gradients for periods greater than 1s. Basin amplification factors (BAF) are computed using the ratio of the average effective site terms within the Kanto Basin to those in a reference region outside of the basin. The uncertainty in the BAFs is accounted for by selecting random subsets of the recordings and examining the variability across the different subsets. BAFs suggest that interface sources typically show larger amplification than intraslab sources at longer periods (T>1s). We examine the influence of station selection and incidence angles, which have significant effects on the character and amplitude of the BAFs. Our results can inform weights of alternative basin models in the logic trees for subduction regions.

Local Eikonal Tomography Using Ambient Noise Records From a Dense Array of Seismic Nodes Deployed in a Sediment-Filled, Deeply Incised Valley With an Extreme Subsurface Topography (Rhône Valley, Southern France)

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Surface waves extracted from ambient noise recordings are often used to image the shallow subsurface structure through linearized tomographic approaches. These approaches require a-priori information such as a reference model and the trajectories of the surface waves between virtual sources and receivers, as well as the introduction of regularization equations which may reduce the resolution of the resulting group and/or phase velocity maps. In recent times, the eikonal tomographic approach has quickly gained popularity for dense seismic deployments, as it avoids posing and solving the linearized inverse problem. Instead, local phase velocities are computed from the gradient of the phase traveltimes measured between the virtual source and receivers. In this work, we applied the eikonal approach to data from a dense seismic deployment carried out in the heavily industrialized area of the Tricastin Nuclear Site (Rhône valley, southern France). This area is situated above a sediment-filled, deeply incised canyon with a extreme subsurface topography dug during the Messinian Salinity Crisis. The deployment consisted in 400 3-component nodes installed over a 10 x 10 km area, which recorded continuously during February-March 2020. The recorded ambient noise wavefield shows to be complex, i.e. higher mode propagation and non-uniformly distributed sources of ambient noise are clearly observed. Despite the wavefield complextiy we have been able to implement a practically fully-automated method that performs higher mode discrimination and measures the phase traveltimes of the fundamental mode from the phase spectra of the cross-correlations of

the ambient noise recordings. We then applied the eikonal approach to the measured phase traveltimes to build a set of phase velocity maps for Rayleigh waves. The resulting maps cover frequencies ranging from 0.4 to more than 5 Hz and show a good correlation with the existing knowledge of the geological structures.

mHVSR-Based 3D Modeling of a Late Quaternary Paleovalley System From Italy: Influence of Internal Facies Architecture on Resonance Frequencies and Shear Wave Velocities

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Late Quaternary paleovalley systems are shallow subsurface incisions formed during the last episode of global sea-level fall and filled with sediment during the Holocene sea-level rise. They are typically buried beneath flat, modern coastal plains, with no geomorphic expression. Paleovalley systems are increasingly studied worldwide, as their occurrence is related to greater damage in case of earthquake, due to the soft and unconsolidated nature of their sedimentary fill. Previous work along the Adriatic Sea coastal plain of Italy reconstructed the 2D geometry of the buried valley beneath the city of Pescara, but complete seismic site characterization and 3D paleovalley modeling, including shear wave velocity and resonance frequencies, are lacking. In this context, we acquired 85 microtremor measurements in a 10 km^2 wide area and performed the microtremor-based horizontal-to-vertical spectral ratio (mHVSR). We used a pre-existing geological dataset as a framework to constrain the mHVSR curves to create a Frequency-Depth model and transform the mHVSR curves from the frequency to the spatial domain, thus reconstructing the paleovalley geometry. We obtained a 3D model of the paleovalley fill, which is about 40 m thick. The fundamental resonance frequency shows considerable variability over very short distances (700 m only), ranging from 4.5 Hz on the interfluves to 0.9 Hz in the depocenter. Through high-resolution stratigraphic cross-sections, we reconstructed the internal facies architecture, mapping in 3D the main sedimentary bodies and delineating facies changes within the paleovalley fill. Using Down-Hole data, we classified major sedimentary bodies into five classes, with distinct Vs; Coastal Sand Vs ≈ 260 m/s, Swamp clay Vs ≈ 170 m/s, Poorly Drained Floodplain clay Vs ≈ 220 m/s, Fluvial Gravel Vs ≈ 650 m/s, Substrate Vs ≈ 310 m/s, providing information about geometry, resonance frequency, and shear wave velocity that can be used for future seismic simulations.

Seismic Hazard Potential in Punjab Province of India Through Site Response Analysis and Its Liquefaction Assessment

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Punjab is a flat low land state occupied by thick deposits of various types of loose to dense soil due to active sedimentation and constitutes 1.53% of the geographical area of the country. The flat alluvial plains of Punjab have been formed by the deposition of Indo-Gangetic alluvium, with a maximum thickness of 300 meters over the base rocks of the Pleistocene and Holocene Siwalik Systems. Much of the Punjab shelf is bounded to the east by active fault systems viz MBT and MCT. All the geomorphological units in the region can easily amplify ground motion due to large impedance contrast and are liquefiable under strong seismic shaking. Effective shear wave velocity for soil/ alluvium column derived from both Geophysical and Geotechnical investigations at 350 locations in the region categorizes Punjab into D4, D3, D2 and D1 site classes according to the NEHRP and Global standard nomenclatures. 1D nonlinear/equivalent linear site response analysis has been performed employing stochastically synthesized ground motion for a few near field earthquakes at engineering bedrock for all soil types. Site-specific generic Site spectra have been generated for all four site classes, together with Predominant Frequency (PF) and Site Amplification Factor (SAF) distribution in the region, with SAF varying between 2.21-3.77 times and PF varying between 1.0-5.8 Hz. Surface-consistent hazard is estimated by spectral convolution of firm rock Peak Ground Acceleration, which varies between 0.12g and 0.30g. Liquefaction susceptibility analysis performed for both the 1905 Kangra earthquake of Mw 7.8 and the probabilistic scenario exhibit Liquefaction Potential Index (LPI) variation from Low to Severe. These results are expected to aid in adopting safe building code provisions and also help in working out regulatory measures for safeguarding against earthquake-induced devastations and promulgating management practices toward effective relief, rescue and rehabilitation.

Site Effects and Soil-Structure Resonance Study in Santo Domingo (East) and Santiago De Los Caballeros (Dominican Republic) Using Microtremors and Active Seismic Sources

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The Dominican Republic has high seismicity, due to the position of the Hispaniola Island, right in the interaction between the North American and Caribbean tectonic plates. More specifically, on the northern edge of the Caribbean plate, where seismicity is especially intense, causing the entire island to be affected by a high seismic hazard. In this tectonic context, a seismic data acquisition campaign has been carried out in several cities of the Dominican Republic to determine site effects and to carry out seismic microzonation studies. These studies have been carried out within the framework of the research projects MICROSIS-I (seismic microzoning in urban areas of the Dominican Republic, based on active and passive seismic) and "KUK ÀHPÁN: Integrated Regional Study of Structure and Evolution 4D of the Lithosphere in Central America". Implications in the Calculation of Seismic Hazard and Risk").In the present study, a campaign of urban noise recordings processed with the horizontal-to-vertical (H/V) spectral ratio and the spatial autocorrelation (SPAC) methods was carried out, in order to extract valuable information about the fundamental frequency peaks and geological shallow structure Vs30 and the bedrock interface under the investigated urban areas of Santo Domingo and Santiago de los Caballeros.Investigations were performed on a 10x10 km dense grid with two broad band 120s seismic stations, five three components short period seismic stations of 1 Hz and 36 single channel seismic stations provided with 4.5 Hz vertical component seismometers.In addition of those studies, a Multichannel Analysis of Surface Waves (MASW) experiment of some 40 km has been carried out with a land streamer of 16 three component 4.5 Hz geophones and an active source of surface waves providing Rayleigh and Love waves along de main geological structures identified in both studied cities. The computed H/V curves suggest the existence of multiple interfaces within the geological structure of both cities. The observed resonance peaks were interpreted according with the available geological information.

Site Specific Seismic Hazard, Vulnerability, Risk and Damage Potential Modelling of Bangladesh With Seismic Hazard Microzonation for the Cities of Dhaka and Chittagong

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The riverine country of Bangladesh, located on the world's largest fluvio-deltaic sedimentary basin, called unified Bengal Basin, is exposed to extreme seismic threats due to proximity to seismogenic blocks of the Northeast India, East-Central Himalaya, and the basin itself, also impinging many strong earthquakes in the past with MM Intensity of VIII-XI in near-source region. The thick Holocene alluvium covering the region can contribute to ground motion amplification and liquefaction effects, thus affirming the necessity of surface-consistent seismic hazard and risk assessments. Consideration of both areal and tectonic sources in three hypocentral depth ranges along with 14 ground motion prediction equations including 6 site-specific next generation spectral attenuation models has delivered Probabilistic Peak Ground Acceleration (PGA) at engineering bedrock ranging from 0.14-0.59g for 475years of return period. Geophysical and Geotechnical investigations at around 2200 sites yielded effective shear wave velocity in the range of 119-936m/s. Systematic nonlinear/equivalent linear site response analysis amplified the firm rock PGA by 1.06-4.05 times providing surface-consistent hazard in the range of 0.30-1.17g. Liquefaction Potential Index (LPI) using the estimated PGA places Dhaka, Mymensingh, Chittagong and Sylhet into "severe (LPI>15)" zone whereas in the Socio-Economic Risk Map, Dhaka and Chittagong are classified as "high to severe" category. Holistic Seismic Hazard Microzonation performed for the capital city of Dhaka and the Port City of Chittagong,

integrating several geo-hazard and seismic hazard themes has microzoned the cities into four zones. Structural damage potential using SELENA-based Capacity Spectrum Method has been assessed for both the cities on eleven model building types in five damage states from 'none' to 'complete'. Complete understanding of this comprehensive study is expected to guide city planners to provide seismic-resilient urbanization.

Site-Specific Seismic Hazard Assessment of Northeast India Including Bhutan With Special Emphasis on Microzonation Studies of Imphal City

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Northeast India with complex geology and active tectonics has witnessed several devastating earthquakes *viz*. 1869 Cachar of M_W 7.4, 1897 Shillong of M_W 8.1, 1950 Assam of M_W 8.7 with maximum MM intensity of VII-X, presenting a serious case for site-specific seismic hazard study. An updated Probabilistic Seismic Hazard at bedrock level with 10% probability of exceedance in 50 years for Northeast India has predicted Peak Ground Acceleration (PGA) variation of 0.19-0.80g. Systematic site-specific response spectral analyses have been performed for the terrain resulting in a site amplification variation of 1.06-2.31. Surface-consistent PGA for a return period of 475 years has been assessed for the study region by convolving the soil/sediment amplification with the PGA at firm rock level, thus predicting a variation of 0.343-1.885g. Imphal, the capital city of Northeast Indian State of Manipur is located within the belt of Indo-Burma Subduction Zone and falls under seismic zone V being frequently affected by moderate to large magnitude earthquakes with the maximum felt MM Intensity of IX. As majority of the state's population is concentrated within the Imphal valley, with massive infrastructure development and unplanned but rapid urbanization, necessitates comprehensive microzonation studies of this city. A detailed geophysical and geotechnical investigation conducted throughout the city generated effective shear wave velocity (V_S^{30}) distribution classifying the City into D2, D3, D4, E and F site classes with predominant frequency distribution of 1.59-5.88Hz thereby conservatively guiding the probabilistic surface-consistent PGA distribution of 0.59-0.83g wherein its compliant Liquefaction Potential Index (LPI) categorized the City into 'Low' to 'Severe' zones. This comprehensive study provides necessary protocol for its adaptation in carrying out similar exercises and help designing seismic resilient structures in all the cities in this deadliest seismogenic province.

Statistical Green's Function Method Based on Spectral and Phase Characteristics Estimated by Generalized Inversion Technique for Japanese Data -Case Simulations for the 2011 Ibaraki-Oki Earthquake and Hypothesized Nankai-Trough Megathrust Event

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We need a method that can predict strong ground motions with sufficient accuracy at any target site for quantitative evaluation of the hazard and subsequent risk of large earthquakes. However, our knowledge of the source, path, and site factors of the observed strong motions has not been fully utilized. First, we performed the analysis to investigate the properties of these factors mentioned above based on a generalized inversion technique on Fourier spectra of strong motion networks deployed in Japan. We tried to model not only spectral amplitude but also phase information in the frequency domain, using the group delay time. Once we obtain statistical properties of the amplitude and group delay time, we can produce ground motions at an arbitrary site from an elemental source at an arbitrary location on the fault surface, which can be used as a Green's function in the statistical Green's function method. The statistical Green's function method is not the same as the stochastic Green's function method as the former can take into account variabilities in the Green's functions based on the statistical properties of the separated factors. Next, we constructed a procedure for predicting the strong motions considering both the spectral difference between the whole duration of motion and the S-wave portion and the effects of soil nonlinearity.

As a validation exercise, we confirmed that the proposed method can work well for the reproduction of ground motions generated by the 2011 Ibaraki-Oki earthquake, which was the largest aftershock (Mw7.8) of the 2011 Tohoku earthquake sequence. Matching with data was good because we considered its smaller stress drop as a regional source characteristic. Then we simulated the ground motions in the Kinki region from the hypothesized Nankai-Trough megathrust event based on the scenario proposed by the Central Cabinet Office (2012). As a result, we obtained waveforms with realistic characteristics in the spectra and envelop shapes.

Towards a 3D Geotechnical Model of the Greater Beirut Area for Seismic Ground Motion Prediction

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Soil heterogeneity has a strong influence on the seismic motion variability. Local site conditions (lithological and topographical) can indeed generate amplification of ground motion at specific frequencies. Furthermore, small-scale heterogeneities of the lithological layers can redistribute the energy of the trapped waves, increasing the variability of the seismic movement recorded at the surface. The Greater Beirut (GB-Lebanon) region is exposed to high seismic risk because of its location near major faults which can generate earthquakes of high magnitudes (>7). Moreover, the city is built upon a large variety of soils. The geology of GB (Dubertret 1944) shows that the area is divided into two categories: quaternary deposits and rocky outcrops. Quaternary zones are mainly composed of Embankments with Limestone Pebbles, Sand, Fixed Sand Dunes, and moving Sand Dunes. Rocky outcrops are made of Cenomanian, Senonian and Miocene. As the area is not a classical sedimentary basin, mixing colluviums, wind- and fluviatile-deposits, site effects assessment is challenging. A 3D geotechnical model of the uppermost geology is thus established combining the scarce dataset of about 500 geotechnical boreholes and 700 geophysical measurements, randomly distributed over the area. First, combining H/V measurements and boreholes data allows us to define the average S-wave velocity propagation (Vs_mean). Then, knowing Vs_mean, we estimate the soft soil thickness at all of the measurement sites. These data helped us in reaching a primary simplified model of 2 layers, sediments over bedrock. The results show variability in the sedimentary thickness over the area. This model will be used in numerical computations based on Finite Element Method to simulate the seismic wave propagation. To assess for the impact of small scale soil heterogeneities, a statistical study will be carried on aiming to estimate the vertical and horizontal correlation lengths of the soil layers mechanical properties from the borehole database.

What Constitutes Knowledge of "Site Response"? the Embayment Seismic Excitation Experiment 2022 (ESEE2022)

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Thick, weakly consolidated sediments of the Gulf and Atlantic coastal plains blur the distinction between "path" and "site" effects in the commonly assumed phenomenological model of "source-path-site" used for representing wave propagation from earthquakes. In the absence of empirical strong motion data, this requires that sediment physical properties need to be determined for realistic wave propagation simulations. ESEE2022 was conceived to determine seismic velocity and attenuation structure of a ~900m thick section of Mississippi Embayment sediments near Memphis, TN. A 3km profile of 60 nodal seismometers recorded body and surface waves from 91 kg explosions detonated in 15m depth boreholes at both ends of the profile on the nights of 25 and 26 July 2022. Strong motion velocity data were collected within 150m of each explosion and small-scale P and SH refraction profiles taken at each shot point the week before. Because the nodal seismometers were deployed over a two-week period, there is also a large data set of ambient ground motions along the profile. The working hypothesis for analyzing this large data set is that a single, vertically inhomogeneous velocity and anelastic attenuation earth model can be constructed to fit surface wave dispersion measurements, body wave travel time and amplitude measurements, Greens functions from ambient noise interferometry, and H/V spectral peaks, culminating in full waveform inversion of the explosion data. Near-source strong motion accelerations ranging from 0.5g to 4g may have induced non-linear changes to near-surface materials which might be observed by comparing near-surface velocity structures determined with small scale refraction and the near-station explosion data. We suspect that this dataset will offer information on the limitations and veracity of both passive and active source methods to infer information on thick unconsolidated sediments.

WUS and CEUS Graizer's Ground Motion Models and Anelastic Attenuation of Response Spectral Accelerations

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Ground Motion Models (GMMs) are a centerpieces of seismic hazard assessment and ShakeMaps. In the two recent GMMs: G-16v2 for the stable continental regions (SCR) (Graizer, 2017) and GK17 for the active crustal regions (ACR) (Graizer, 2018) uniform approach was used to the functional forms of the models each composed of two predictive equations (Graizer and Kalkan, 2007, 2009). The first equation predicts PGA, and the second equation constructs the spectral shape. In both GMMs I am assuming bilinear attenuation slope reflecting geometric spreading of shear and surface waves: The average transition points between body-waves R^{-1} and surface waves $R^{-0.5}$ geometric spreading were found to be 50 km for the ACR (Graizer, 2018) and 70 km for the SCR (Graizer, 2017). In contrast to seismological Q, I introduced apparent anelastic attenuation of spectral accelerations Q_{SA}. Multiple inversions performed to estimate Q_{SA}(f) demonstrated the best fit to be ~ $Q_{SAA}(f) \approx 120 f^{0.96}$ for the ACR for frequencies between 0.1 and 100 Hz and the best fit to be ~ $Q_{SAS}(f) \approx 186 f^{0.99}$ for the SCR for frequencies between 0.1 and 40 Hz. Apparent attenuation was found to be magnitude dependent with Q_{SA} factor increasing with magnitude. Resulting apparent attenuations of response spectral amplitudes at rupture distances of more than 50 km for the ACR and more than 70 km for the SCR are practically linearly dependent upon frequency demonstrating significantly different behavior compared to the "seismological" Q-factor. Considering that seismological quality factor Q is usually determined using *S*-, *Lg*- or coda-waves not necessarily responsible for the SA attenuation it may not be used in GMPEs. Assuming $Q_{SA}(f) \approx Q_{SA0} f^{1}$ apparent anelastic attenuation becomes practically frequency independent and only dependent upon fault distance and magnitude. Regional Q_{SA}(f) different from the average one used in an ergodic model can be used in creating a partially non-ergodic GMM better reflecting area attenuation (e.g., Southern and Northern California).

Structure and Properties of Subducting Slabs and Deep Earthquakes

Oral Session • Wednesday 19 April • 02:00 PM Pacific

Conveners: Marco Pilz, GFZ Potsdam (pilz@gfz-potsdam.de); Chuanbin Zhu, University of Canterbury (chuanbin.zhu@gfz-potsdam.de); Hiroshi Kawase, Disaster Prevention Research Institute, University of Kyoto (kawase.hiroshi.6x@kyoto-u.ac.jp); Andres Olivar Castano, University of Potsdam (andres.olivar-castano@uni-potsdam.de)

From the Lab to the Slab: Transformational Faulting at High Pressure and Temperature in Fe-Rich Olivine and Implications for Deep-Focus Earthquakes

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A major unresolved question in earth science is how earthquakes can occur under the high-pressure (P), high-temperature (T) conditions found hundreds of km below the surface. One theory is that deep-focus earthquakes (350-700 km depth) occur in association with metastable olivine transforming to its high-pressure polymorphs wadsleyite and/or ringwoodite. While this mechanism has been shown to operate in the olivine/ringwoodite analogue Mg_2GeO_4 at <4 GPa, there is a scarcity of experimental evidence confirming it conclusively in silicate olivine at higher pressures. To test this hypothesis, deformation experiments were performed on Fe-rich olivine, $(Mg_{0.25},Fe_{0.75})_2SiO_4$, under various P,T conditions in both the olivine and ringwoodite stability fields. Acoustic activity was monitored in situ, as well as stress and strain, which were measured via synchrotron X-ray diffraction and radiography respectively. Experiments run under conditions that promoted transformation to ringwoodite (P = 6-9 GPa; T = 600-900 ºC) generated bursts of acoustic activity which, in contrast to ordinary brittle failure, was enhanced with increasing pressure. Focal mechanisms of acoustic events indicate exclusively shear failure with no detectible volumetric change or tensile crack components. Tomographic imaging of the samples recovered from >7 GPa reveals the existence of macroscopic faults. In every seismogenic experiment, the presence of ringwoodite was confirmed through SEM imaging. The ringwoodite phase develops in the form of long thin bands of nano-grained material which, due to the reduced grain size, cannot support shear stress leading to strain localization at seismogenic strain rates. In contrast, experiments run under P,T conditions that prohibited transformation were acoustically quiet and the samples remained intact. The results of this study demonstrate that seismogenic fracture is associated with the olivine to ringwoodite transformation in Fe-rich silicate olivine lending experimental support to the hypothesis that transformational faulting is responsible for deep-focus earthquakes in the mantle transition zone.

Numerical Study on Phase Transformation Induced Material Fracture

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The physical mechanisms triggering intermediate-depth earthquakes remain a puzzle for the scientific community. However, many studies discussed phase transformation as the primary mechanism behind generating these earthquakes. The objective of this study is to develop a numerical model for simulation of phase transformation-induced failure in geo-materials. The materials of interest include different minerals found in the mantle transition zone such as olivine. To study the phase transformation behavior under the loading condition mimicking earth's crust, a thermo-mechanical finite element modeling approach has been taken. A multiscale model, based on Mahnken et al., 2015, has been developed to capture the evolution of phase transformation. The results from the model capture the signature behavior reported in the literature and validate the experimental phase diagram for olivine to spinel transformation. To study the microstructural failure induced by phase transformation, extended finite element method has been used with the above model. The results show an early and higher amount of crack propagation with phase transformation and a higher volume fraction of transformed mineral near the crack. A multigrain model with micro defects has been constructed to study the fracture evolution under confining pressure, and temperature conditions and has been validated with the load-displacement data from the laboratory experiments (Wang, Y et al., 2017).The model will be further upscaled to simulate the fault generation at the macroscale to investigate the role of phase transformation in the formation of large-scale faults.

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A Weak Subducting Slab at Intermediate Depths Below Northeast Japan

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Knowledge of the state of stress in subducting slabs is essential for understanding their mechanical behavior and the physical processes that generate earthquakes. Here we develop a novel framework which uses a high-resolution focal mechanism catalog to determine, for the first time, the full deviatoric stress tensor within the subducting slab at intermediate depths. We show that by combining the static stress calculated from coseismic slip distributions with the stress orientations before and after the mainshock, that deviatoric stress within the slab at intermediate depths must be very low (~ 1 MPa). These results preclude earthquake source mechanisms that require large background driving stresses, favoring a mechanically weak subducting slab, thus providing quantitative constraints on the physical processes that generate intermediate-depth earthquakes.

Subduction Zone Events Around Japan and Wavefield Anomalies - Structure Beyond Tomography

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The dense networks of seismic stations across the Japanese archipelago allow detailed investigation of the patterns of ground motion and the nature of the seismic wavefield, in an area with a complex configuration of subduction involving both the Pacific and Philippine Plates. Tomographic studies can delineate the general morphology of the subducted material because it has higher seismic wavespeeds than its surroundings. However, the wavespeed contrasts alone are not sufficient to duct high-frequency energy from deep events to the surface. Internal heterogeneity with longer correlation lengths (10-20 km) along slab than across (0.5-1.0 km) provides a good description of the behaviour, but the high frequencies require a boost from the low wavespeeds associated with a modified olivine wedge for the deepest events. The presence of only a small area with high frequency waves from the 2015 Mw 7.9 Ogasawara event at 680 km depth indicates that this event lies outside the main slab.During moderate to deep (35–260 km) earthquakes within the Philippine slab along the Ryukyu arc, distinctive later phases after S are observed across the Japanese archipelago for epicentral distances from 1500 km to 2200 km, producing anomalous amplification of ground motion in central and northern Japan, associated with reflections from the upper mantle discontinuities and the top of the Pacific slab. The character of these reflections indicates that the weak tomographic signal for the PAC slab below 200 km beneath western Japan is more likely associated with a thinned than a torn slab.

Influence of a Dipping Anisotropic Slab on Shear Wave Splitting in Japan

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Strong intra-slab seismic anisotropic fabric of laminated type (~25% shear anisotropy) within the vicinity of deep subduction earthquakes (focal depth > 60 km) was proposed to explain the cause of the large non-double-couple radiation patterns. If it is true, a predicted consequence is that the dipping anisotropic slab should produce shear wave splitting (SWS). Due to the dipping geometry, the measured splitting parameters (delay time and polarization directions) should depend on incident angles of the S-wave ray paths with respect to the slab. We evaluate this prediction by analyzing teleseismic waveforms of around ~600 global earthquakes recorded by a dense network coverage (>800 Hi-net stations) in Japan. After acquiring >8,000 high-quality SWS measurements for various S phases (S, ScS and SKS), we explore SWS patterns using the event backazimuth, focal depth, and forward seismic modeling. Our measured results indicate that the delay time between the fast and slow shear waves vary significantly up to ~3 s but also with numerous null measurements (~950 observations). In addition, the measured fast S polarization direction has a complex but systematic relation with respect to the source location and depth, likely due to source-side anisotropy weakening with event depth. We also notice a spatial variation of the measured SWS patterns across Japan for the same earthquake, showing the influence of Pacific and Philippine Sea slabs on SWS which cannot be attributed to source-side anisotropy. Finally, we perform seismic forward modeling using the propagator matrix method to explain these measurements. We find that a 20km thick anisotropic layer in the slab can cause similar delay times and a systematic rotation of the fast S polarization axis. These outcomes show that in teleseismic SWS analyses, we need to consider the dipping anisotropic slab, not just the sub/supra-slab anisotropy and earthquake source side anisotropy. Our approaches and analyses provide new tools for understanding slab anisotropic structure, important for deep earthquake generation and recycling of volatiles back into the Earth mantle.

Structure and Properties of Subducting Slabs and Deep Earthquakes [Poster]

Poster Session • Wednesday 19 April

Conveners: Marco Pilz, GFZ Potsdam (pilz@gfz-potsdam.de); Chuanbin Zhu, University of Canterbury (chuanbin.zhu@gfz-potsdam.de); Hiroshi Kawase, Disaster Prevention Research Institute, University of Kyoto (kawase.hiroshi.6x@kyoto-u.ac.jp); Andres Olivar Castano, University of Potsdam (andres.olivar-castano@uni-potsdam.de)

A Micro-Mechanism for the Nucleation of High-Pressure Phases During Transformational Faulting in Olivine

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In the transformational faulting hypothesis for deep-focus earthquakes, metastable olivine in the subducted lithosphere transforms to wadsleyite and/or ringwoodite below ~300 km depth, triggering mechanical instability. Detailed physical mechanisms of this hypothesis are still under debate. We conducted controlled deformation experiments with acoustic emission (AE) monitoring to investigate this process. We examined three olivines: Mg_2GeO_4, Mn_2GeO_4, and $(Mg_{1-x}Fe_x)_2SiO_4$ (with x=0.25 and 0.5). Under our experimental conditions, Mg_2GeO_4 olivine transforms directly to spinel (ringwoodite) structure, Mn_2GeO_4 to wadsleyite, whereas $(Mg_{1-x}Fe_x)_2SiO_4$ into a mixture of olivine and ringwoodite.

Mechanical behavior of all three metastable olivines can be divided into three regimes, depending primarily on temperature. At low temperatures, metastable olivines are strong but ductile, with no AEs produced up to ~30% strain. At high temperatures, they are weak and ductile, with no AEs observed. Only within a narrow range of intermediate temperatures do these olivines behave in a brittle manner, emitting numerous AEs. Recovered brittle samples contain macroscopic faults. High-pressure products are primarily in the form of sub-parallel, long and narrow bands (widths on the order of 100 nm) cutting through individual olivine grains, sometimes shearing the olivine grains into several parts. These nano-shear bands (NSBs) are oriented about 30 – 60 degrees from the maximum compressive principal stress. Detailed microstructure analyses show that at intermediate temperature, olivines deformed by kink band formation and NSBs are primarily located within kink bands boundaries (KBBs). Within KBBs, olivine crystal lattice is severely distorted due to high density of dislocations, thereby promoting nucleation of high-pressure phases. The self-organization of NSB network produces macroscopic faulting, as evidenced by subsets of NSBs, which are either in the fault zone or very close to the faults.

Along-Strike Variation in Aftershock Productivity of Intermediate-Depth Earthquakes in Japan

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We show that some intermediate-depth aftershock sequences behave similarly to shallow, crustal earthquakes, even though intermediate-depth earthquakes occur at temperatures and pressures thought to prohibit brittle fracture and are often deficient in aftershocks compared to shallow earthquakes. We search for aftershock sequences of M > 5.5 intermediate-depth earthquakes in two subducting slabs under Japan, and perform a statistical analysis to see if variations in aftershock productivity can be linked to slab properties. Our study regions are the older, colder and steeper Pacific Plate and the younger, warmer, shallower Philippine Sea Plate. We find that productive aftershock sequences have similar spatial extents and decay rates to those of crustal earthquakes and tend to appear mainly within the Pacific Plate where they are significantly correlated with along-strike variations in VP–VS ratio, suggesting a role for fluids in enabling intermediate-depth aftershock activity. Finally, we correlate variations in observed seismic source parameters, such as stress drop and radiated energy, with observations of aftershock productivity.

Complex Martinique Intermediate Depth Earthquake Hints at Early Atlantic Break-Up

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Earthquake rupture is the result of complex physical properties and stresses. In the last decade, more and more observations were reported that large earthquakes consist of multiple ruptures on a network of faults within the continental crust and oceanic lithosphere. Similar observations are lacking for intermediate-depth (70 - 300 km) earthquakes posing the question if multiple fault ruptures are hindered by the physical properties and stresses in subducting lithosphere. On November 29, 2007, an Mw7.4 earthquake struck the central islands of the Lesser Antilles Island Arc close to the island of Martinique. The earthquake occurred at a depth of ~150 km near the lower end of the Wadati-Benioff-Zone (WBZ) of the Lesser Antilles subduction zone. Restricted by limited coverage and unfavorable distribution of regional seismic stations at the time of the earthquake, a detailed examination of the rupture process of the Martinique event was challenging if not impossible. Here, we compile seismic data from different studies and perform regional moment tensor (RMT) inversion to show that the earthquake is a doublet consisting of at least two oblique fault planes. Our analysis suggests that the earthquake ruptured along a re-activated ridge-transform fault at the plate boundary between the subducting Atlantic/Proto-Caribbean lithosphere.

Exploring Remote Triggering of Intermediate-depth Earthquakes in Japan following the 2004 M9.1 Sumatra and 2012 M8.6 Indian Ocean Earthquakes

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It is well established that large magnitude earthquakes, especially strike-slip events, can generate static and dynamic stress perturbations that are capable of triggering subsequent shallow earthquakes, deep tremors, and slow slip events at nearby and long-range distances. In particular, the 2004 Sumatra and the 2012 Indian Ocean earthquakes, with the moment magnitude (M_w) of 9.1 and 8.6, respectively, are known to be two of the largest events in the past two decades that have triggered seismic and aseismic events around the world. Most of those triggered events occurred at depths above 60 km. Only a few recent studies focused on remote dynamic triggering of intermediate-depth earthquakes (IDEQs) between 60-350 km depth. In this study, we use Japan Meteorological Agency (JMA) catalog combined with seismic waveform data provided by excellent seismic network coverage of Hi-net to investigate how IDEQs in Central and Northeastern Japan responded to the passage of seismic waves generated by these two large earthquakes. Preliminary results indicate that there are subtle increases in the number of IDEQs in the study region shortly following both mainshocks. We plan to further examine seismic waveforms long before and after both distant mainshocks to detect additional IDEQs in Central and Northeastern Japan. The obtained results can be used to better understand the stress sensitivity of structures hosting those IDEQs and their physical mechanisms.

Faulting in Deforming Natural Lherzolite at High Pressure and Temperature: Implications for Intermediate-Depth Earthquakes Generation in the Lower Seismic Zone

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Intermediate-depth earthquakes (IDEQs), occurring at ~50-300 km depths, often form a double seismic zone along subducting slabs. The origin of these earthquakes has been in debate for decades, as rocks are expected to deform plastically under the high pressure (P) and temperature (T) conditions in the Earth's interior rather than faulting. For many years, the cause of IDEQs has been attributed to the dehydration-triggered embrittlement. However, for earthquakes in the lower seismic zone (LSZ), which lies ~10-50 km below the slab surface within the oceanic lithospheric mantle, the hydrous minerals required for the dehydration mechanism may not be present.

In this study, we performed deformation experiments coupled with acoustic emission (AE) monitoring on a natural lherzolite, one of the major constituent rocks of the LSZ in oceanic lithospheric mantle. The natural lherzolite sample was collected from Western Alps (kindly provided by Drs. Julien Gasc and Alexandre Schubnel from Laboratoire de Géologie, CNRS UMR 8538, École Normale Supérieure, PSL University), providing realistic lithology for testing the physical mechanisms of earthquakes in the LSZ. The experiments were performed at GSECARS beamlines at the Advanced Photon Source (APS), using DDIA and DDIA-30 (a large version of DDIA with a double-stage configuration) deformation apparatus, coupled with synchrotron monochromatic X-ray diffraction for stress measurements, radiographic imaging for strain measurements and in-situ AE monitoring using PZT transducers attached to the back of each anvil. The experiments were performed at confining pressures of 3-5 GPa, temperatures from 500 to 1200°C, and strain rates of ~10^{-5} s^{-1}. AE activities and faulting in the sample were observed in the temperature range from ~600 to 1000°C, whereas below ~600°C and above ~1000°C, the sample was ductile. We will present detailed experimental results and microstructural analyses of the recovered samples, as well as the implications of the new results to our further understanding of the triggering mechanisms of intermediate-depth earthquakes.

Imaging Ore-Forming Fluids in Porphyry Copper Deposits Using Local Earthquake Tomography

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An essential part of the world's remaining mineral resources is expected to reside deep in the crust or under post-mineralization cover. For porphyry copper deposits, the world's primary source of Cu, Mo, and Re, identifying the dynamic processes that control their emplacement in the upper crust can guide future exploration. Seismic tomography can constrain these processes through imaging deep-seated structures at the regional scale. Here we construct a three-dimensional model of the Vp/Vs ratio, based on arrival times of P and S seismic waves, beneath the Cerro Colorado porphyry Cu-(Mo) deposit in northern Chile. Our images show that *low Vp/Vs* (~1.55-1.65) anomalies extend to ~5-15 km depth that coincides with the location of known copper deposits and delimits structures that host orebodies and related hydrothermal alteration zones. *Medium Vp/Vs* (~1.68-1.74) and *high Vp/Vs* (Vp/Vs~1.85) bodies correspond to intermediate-felsic plutonic precursors for porphyry intrusions and mafic magma reservoirs that underlie shallower orebodies, respectively. Imaging these precursor and parental plutons is crucial to the identification of orebodies as they act as the source of fluids for porphyry copper generation. This study demonstrates the potential of local earthquake tomography as a tool to identify future deep mineral resources with minimal environmental impact.

The Magnitude Difference Between Mainshocks and Their Largest Aftershock Increases With Depth for Shallow and Intermediate-Depth Earthquakes Within the Japan Subduction Zone

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Earthquakes at all depth ranges, from the surface to ~700 km depth, are observed to share many similar source properties, but the number and size of aftershocks are observed to be larger for shallow earthquakes than for deeper earthquakes. This change in aftershock behavior may be caused by a change in the rupture mechanism and/or fault properties with increasing pressure and temperatures with increasing depth. The cause of this change can be investigated by studying the change in aftershock behavior with depth and across the transition zone from shallow to intermediate-depth earthquakes. Using the largest aftershock of an aftershock sequence as a proxy for aftershock productivity, we quantify how the magnitude difference (ΔM), time delay (ΔT), and the distance (ΔD) between the mainshock and largest aftershock change with depth within the Japan subduction zone. From January 1983–February

2019, the Japan Meteorological Agency (JMA) hypocenter catalog contains 911 mainshocks (local magnitude $M_J \geq 5.0$; 0–200 km depth). While ΔT and ΔD do not change with depth for these mainshocks, average ΔM values show a statistically significant gradual increase with depth from ~1.0 at the surface to ~3.0 at 200 km depth. Increasing ΔM values suggest that, as depth increases, more energy is partitioned to the mainshock relative to the aftershock sequence. This partitioning may be attributed to a less complex fault geometry that promotes a more complete mainshock rupture or decreasing structural heterogeneity resulting in a less localized stress transfer for aftershock triggering.

Volume Collapse Instabilities in a Phase Transformation Under High Pressure Yield a Double Couple Deep Earthquake Driven by the Pressure

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The deep-focus earthquakes(DFEs) (400-700kms) are events involving the nucleation and growth of phase transformations under high pressure for which instabilities occur as to minimize the energy spent to move the boundary of phase discontinuity. While in the problem of Randall (Bull Seism. Soc. Am., 1964) a sudden volume change preserves symmetry, expands spherically emitting pressure waves, under high pressure also exists a symmetry-breaking unstable solution. It was shown (Markenscoff, J. Mech. Phys. Sol. (2021),152,104379) that high-pressure phase transformations can emit the elastic waves of a shear source with little or no volumetric component, even under conditions of material and pre-stress isotropy. Due to instability at a critical nucleation pressure, an arbitrarily small densified region generated in the shape of a pancake-like flattened ellipsoid nucleates and grows, expanding self-similarly at constant potential energy, while driven by the pressure acting on the change in volume. Deviatoric stresses are developed to maintain material continuity, as the large volume collapse is accommodated in the thin inclusion, and the energy can radiate out in the only possible way as a Double Couple (DC). The DC radiation is consistent with the vast majority of observations of DFEs and the radiated energy entailing a "pressure drop" explains their large energies, while the model explains the range of appearance of the DFEs with depth in the Mantle. The mathematical modeling is based on properties of the self-similarly expanding ellipsoidal inclusion with transformation strain (dynamic Eshelby problem), which possesses the lacuna property of zero particle velocity in the interior domain allowing the phase transformation to take place under equilibrium conditions, while the growth energetics are derived through Noether's theorem (M integral). The Eshelby solution and lacuna property are also valid for Newtonian fluids and the analysis of the instabilities could be extended to account also for coupling with dehydration. The instabilities are applicable to other phenomena, e.g., amorphization, planetary impacts, etc.

Subduction Zone Structure From Trench to Arc

Oral Session • Wednesday 19 April • 08:00 AM Pacific

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Improved Quantification of the Volume and Distribution of Water in Incoming Upper Oceanic Crust of Subduction Zones Using Long Offset Streamer Data

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Water carried by the downgoing oceanic plate is known to influence subduction zone processes such as megathrust slip behavior and arc magmatism. Yet, the volume and distribution of water transported into subduction zones often remain elusive despite recent progress. The water content in the oceanic crust either in the form of free water or hydrous minerals varies between subduction zones as water content depends on the full lifecycle of oceanic plates, from accretionary processes at the ridge axis to their bending outboard of the trench axis as well as their thermal structure and the thickness of the sediment cover.

Here we focus on estimating free water content present in upper oceanic crust of three subduction zones: the Sumatran, Alaska Peninsula and Mexican subduction zones. The age of oceanic lithosphere, thickness of sediments, and extent of intraplate deformation vary significantly between these locales. We use long-offset streamer data to examine the upper oceanic crust; reflection imaging is used to illuminate faulting and layer 2 properties, and downward extrapolation of the wavefield followed by traveltime tomography and differential effective medium theory is used to constrain velocities and water content. Results from the mature incoming plates offshore Alaska and Sumatra show that the uppermost crust is significantly hydrated in both areas but that the mechanisms for hydration are different. Offshore the Alaska Peninsula, the water content increases towards the trench suggesting that bending faults facilitate the ingress of water there. Offshore Sumatra, we mostly relate the high-water content in the uppermost crust (Layer 2A) and heterogeneous hydration within Layer 2B to the widespread intraplate deformation of the Indo-Australian plate. Analysis of the long streamer data from the Mexican subduction zone across the young, sediment-starved Cocos oceanic plate is ongoing. Preliminary results will be presented at this meeting and water estimates will be compared to those from Alaska and Sumatra to better understand major controls on crustal hydration prior to subduction.

Structural Variations and Seismogenic Character of the Hikurangi Margin, New Zealand

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The Hikurangi margin of New Zealand exhibits contrasting slip behavior from south to north. Whereas the southern Hikurangi margin has a locked plate boundary that can potentially produce large megathrust earthquakes, the northern section of this margin accommodates plate motion by creep and recurring shallow slow-slip events. To investigate these different modes of slip we use marine seismic reflection data to image the reflectivity and seismic velocity structure along profiles across the accretionary wedge. Seismic velocity images up to 12 km deep and prestack depth migrations together characterize the nature of incoming basement, sediment subduction and accretion, and faulting and compaction of the accretionary wedge.

Our seismic velocity models show that a layer of sediment,with seismic wavespeeds of ~3.5 km/s, is entrained beneath the accretionary prism in the southern Hikurangi margin, but there is no coherent subducted sediment layer to the north. This is a significant result, because it implies that the sediment layer covers basement roughness and forms a smoother plate boundary in the south. In addition, the deepest sediments on the incoming plate in the southern Hikurangi margin are believed to be quartz-rich turbidites, which are prone to unstable slip along the plate boundary. In contrast, the accretionary prism of the northern Hikurangi margin exhibits more variation in accretionary wedge thrust geometry due to interactions with large seamounts on the downgoing oceanic basement. These findings are consistent with the geodetically locked nature of a smooth, quartz-rich plate boundary along the southern Hikurangi subduction zone, and the creeping nature of a heterogeneous plate boundary along the Hikurangi margin to the north.

Fluids Control Along-Strike Variations in the Alaska Seismogenic Zone

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The seismogenic zone usually displays high interseismic coupling between the downgoing slab and the overriding plate. The highly coupled seismogenic zone is bounded by creeping transition zones in both up-dip and down-dip directions. However, more complexities beyond this 2D model are observed, suggesting varying sizes and properties of seismic asperities on the plate interface. The Alaska Peninsula shows large along-strike variations from the fully coupled Kodiak segment in the northeast to the lowly coupled Shumagin segment in the southwest. Changes in seafloor fabrics, slab hydration states, and sediment thickness have been proposed to explain the variations of slab coupling along the trench. However, the controlling factors of the interface slip behaviors have not been fully understood. Here we image high-resolution 3D Vp/Vs structures along the Alaska Peninsula using the newly available onshore/offshore seismic data. The overriding plate and the plate interface display distinct changes in the Vp/Vs signature across different segments. A very high Vp/Vs (~1.88) anomaly at the plate interface at 20-30 km depths in the eastern Shumagin segment indicates the migrated free fluids released from deep sources and ponding beneath the overriding plate Moho. The 2020 M7.8 Simeonof earthquake nucleated from this high Vp/Vs anomaly. In contrast, the Vp/Vs ratio is much lower (~1.72) at 20-30 km depths in the western Semidi segment, adjacent to higher Vp/Vs anomalies (~1.82) in the up-dip and down-dip directions. The 2021 M8.2 Chignik earthquake nucleated from the down-dip high Vp/Vs anomalies and ruptured across the low Vp/Vs anomaly. The Vp/Vs ratio in the overriding plate is anti-correlated with the variations of slab coupling. This striking anti-correlation suggests that free fluids migrated from deep sources play an important role in controlling slab slipping behaviors. In addition, we image low Vp and high Vp/Vs anomalies in the mantle wedge, indicative of sub-arc melting. The Vp/Vs variations in the mantle wedge can shed light on the distribution of free fluids and help us better understand mantle wedge processes.

Imaging the Taltal Segment in Northern Chile: Tectonic Implications Inferred from Seismicity Distribution, Local Earthquake Tomography and Moment Tensor Calculations

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Northern Chile sets an ideal laboratory to perform seismic experiments and collect high-quality data to better understand the subduction process in highly erosive margins. In terms of tectonics, the setting is mainly driven by the convergent margin where the Nazca plate subducts beneath the South American plate. In particular, the Taltal segment between ~22°S and ~26°S has been the subject of notable scientific attention; however, the previous studies have put their focus mainly on the coastal areas affected by large earthquakes during the past 30 years, leaving unattended the processes in the overriding plate from the coastline to the volcanic arc.By benefiting from a large temporary deployment with 84 short-period geophones and the high rate of seismicity in the region, we tectonically characterize the Taltal segment by deriving regional 3D *Vp*, *Vs,* and *Vp/Vs* velocity models together with a seismic catalog with 23,000 earthquakes and regional moment tensors for the events with M> 4.0.*Vp* and *Vs* models illuminate first-order structures such as the Nazca plate with a Vp~ 7-8 km/s, Vs~4-5 km/s anomaly dipping eastward; and the upper crust of the South American plate with values of Vp~ 5-7 km/s and Vs~ 3-4 km/s. *Vp/Vs* model highlights changes from high to low ratios in the overriding plate that collocate with large-scale structures such as the Atacama fault system (AFS) in the coastline and the West Fault System (WFS) towards the Andes.The distribution of seismicity is mainly located along the plates interface between 20-150 km depth; however, we observe a dip change at intermediate depths (150 - 200 km) that could be related to the slab-pull activity. We also identify clustered seismicity at the coast that might be associated with splay faults reaching down to the plate interface. Finally, upper-crust activity is mainly related to the active AFS and WFS but also to the circulation of fluids around the Lascar volcano.

P-Wave Attenuation Structure and Melting Processes of the Tonga-Lau Mantle Wedge

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The fast-converging Tonga subduction zone and its adjacent Lau back-arc form a complex system where the melting mechanisms show significant along-strike variations. To estimate melt fraction and further investigate the thermal and rheological structures in the Tonga Lau mantle wedge, we present an improved P-wave attenuation tomography model. We first incorporate independently constrained source parameters to invert for the path-average attenuation operator t*. Then, based on the refined t* dataset, we apply a Bayesian Markov chain Monte Carlo technique to image the Tonga-Lau subduction system's 3D attenuation structure. The tomography results exhibit high attenuation anomalies in the Tonga-Lau back-arc mantle and beneath the Taveuni Volcano. Compared to the previous attenuation model in the Tonga-Lau mantle wedge, this new high-resolution model is more consistent with published velocity tomography models. With the help of the Very Broadband Rheology (VBR) Calculator, we can quantitively estimate along-strike variations in melt fraction and temperature. Preliminary results show an increasing trend of melt fraction from south to north. The highest melt fraction reaches up to ~6.5% in the Central Lau Spreading Centers in the north.

Converted-Wave Reverse Time Migration Imaging in Subduction Zone Settings

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We use a newly developed 2D elastic reverse time migration (RTM) imaging algorithm based on the Helmholtz decomposition to test approaches for imaging the descending slab in subduction zone regions using local earthquake sources. Our elastic RTM method is designed to reconstruct incident and scattered wavefields at depth, isolate constituent P and S wave components via Helmholtz decomposition, and evaluate normalized imaging functions that leverage dominant P and S signals. This method allows us to target particular converted-wave scattering geometries, e.g., incident S to scattered P, which may be expected to have dominant signals in any given dataset. We intend to apply this method to dense seismic array observations that adequately capture both incident and converted wavefields. We draw a direct connection between our imaging functions and the first-order contrasts in shear wave material properties across seismic discontinuities. Through tests on synthetic data using either S to P or P to S conversions, we find that our technique can successfully recover the structure of a subducting slab using data from a dense wide-angle array of surface stations. We also calculate images with seismic data from a small-aperture array to test the impact of array geometry on image resolution and interpretability. Finally, we demonstrate that our method successfully recovers the topographic shape of the surface of a subducting slab and yields high-resolution information even when the starting model is highly smoothed and does not include topography. We also discuss plans for an implementation of our method in 3D and explore regions that may be imaged via our method with existing seismic datasets.

Multi-Resolution Imaging the Downdip Extent of the Subduction Megathrust

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Subduction zone megathrusts exhibit transitions from areas of large seismogenic moment release to small patches to segments undergoing slow slip. Imaging the megathrust region has the potential to assess the relative roles of rock rheology and pore pressure at different depths, and the length scales over which both vary. Because much of the megathrust remains resistant to active-source imaging, earthquake-based methods provide the primary method of sampling deeper portions. We have taken advantage of a number of recent broadband deployments along the Alaska subduction segments, the forearc is relatively accessible. Array-based receiver function studies map out a regional low-velocity channel with thickness a few km or less, which appears to define the megathrust. It extends from the Canadian border west through the rupture area of the Mw9.3 1964 earthquake with little variation in properties along strike or downdip. New methodologies show that the layer is characterized by Poisson ratios similar to those of common rock lithologies without evidence of substantial overpressure; past estimates of high Vp/Vs likely result from signal bias. At higher frequencies (1-10 Hz), large-amplitude P-to-S waves are observed for nearby earthquakes. They systematically arise from the top of the same low-velocity zone, but show much greater heterogeneity in amplitude over length scales of tens of km. This scale is reminiscent of scales associated with rupture processes, indicating an important role for small-scale material heterogeneity along the fault surface. Overall, these observations highlight the importance of rock material properties and their heterogeneity in controlling slip behavior.

The Comparison of Depth-Dependent Seismic Azimuthal Anisotropy Beneath Alaska-Aleutian and Cascadia Subduction Systems

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In North America, the oceanic Pacific plate beneath Alaska is old and cold, in contrast with the young, warm Juan de Fuca plate subducting beneath Cascadia. The two subduction systems differ from each other due to various tectonic characteristics, such as the age and morphology of the subducted slab, convergence direction, the surrounding mantle dynamics, and so forth. Due to these factors, different subduction systems can produce distinctive structural heterogeneities and leave diverse observable seismic anisotropic signatures. The comparison of seismic anisotropic structures beneath these two subduction systems can help to illuminate differences in dynamic processes that occur under different conditions.

Benefiting from the improvements in seismic instrumentation both onshore and offshore in Alaska (e.g., Alaska Amphibious Community Seismic Experiment (AACSE) and USArray) and Cascadia (e.g., Cascadia Initiative (CI) and USArray), we have constructed high-resolution surface wave dispersion databases with associated uncertainties in these two regions. Based on Rayleigh wave isotropic phase speed and azimuthal anisotropy in these two databases, we construct models of depth-dependent azimuthal anisotropy for both the crust and the uppermost. The anisotropic models in these two subduction zones reflect similarities and differences in both forearc and backarc regions. The characteristics of azimuthal anisotropy suggest different mantle flow patterns beneath the Alaska-Aleutian and the Cascadia subduction systems.

Imaging the Rivera and Cocos Plates Shape in Western Mexico From Local Seismicity Studies.

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A total of 5,220 hypocenters located in the region of Jalisco, Colima, and Michoacan states in western Mexico are used to study the subduction and geometry of the Rivera and Cocos plates beneath the North American plate. In our study, we observe that the geometry and seismic characteristics of the subduction at Jalisco Block, Colima Rift Zone, and Michoacan Block are different. The Jalisco Block is approximately 30 km thick. The contact between the Rivera plate and the Jalisco Block is tectonically complex and can be separated into at least four sections: two located between Bahía Banderas and Purificacion River and the other two between Purificacion River and Colima Rift Zone. South of Bahía Banderas, the slab is observed until 130 km with a dipping angle of 24°. In the Tomatlán River and San Nicolas River areas, the slab is observed until 85 km from the trench dipping 26°, while in the region of Purificacion River, the slab is divided into three segments with different dipping angles, up to 140 km from the trench. In the area of the Marabasco River, the slab can be observed in two segments, with dip angles of 26° and 35°, respectively, and up to 145 km from the trench. There is no evidence of a slab below the Colima Rift Zone due to seismicity being scarce, except in the Colima Volcano area and on the coast, where deep earthquakes (> 70km) are located below Colima Volcano that could be associated with the magmatic process. The crustal thickness in the Michoacán Block is 30 km. To the south, the Cocos Plate subducts with an angle between 24° and 30° and is slightly bent in the west direction. The Cocos plate seismicity related to the subduction process seems homogeneous, except for a seismic cluster at the mouth of the Coalcoman River, which corresponds to the epicentral area of the 1973 and 2021 earthquakes.

Physical Properties of the Mantle Beneath Patagonia From Surface and Body Wave Tomography

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The subduction of the Chile Spreading Ridge beneath South America 12-16 Myr ago opened a gap in the subducting slab beneath southern Patagonia. Paleo-reconstructions show a northward migration of the Chile Triple Junction to its present location around 46ºS, but structure anomalies and geodynamic processes associated with the slab window have been poorly understood. The recent deployment of broadband seismic instruments in Patagonia by the GUANACO experiment (2018-2021) and the Chilean National Seismic Network present an opportunity to image the slab window and associated structures in more detail. Here, we will discuss first our recent Vsv model using receiver functions, ambient seismic noise, and earthquake Rayleigh waves showed a thinning of the lithosphere between 46ºS and 49ºS as a consequence of thermal erosion induced by the slab window (Mark et al, 2022). Then we will discuss our recent seismic anisotropy results constraining mantle flow beneath Patagonia (Ben-Mansour et al., 2022). Using shear wave splitting analysis, we observe strong splitting of up to 2.5 s with an E-W fast direction just south of the triple junction and the edge of the subducting Nazca slab. This region of strong anisotropy is coincident with low uppermost mantle shear velocities implying an absence of mantle lithosphere. This indicates that the mantle flow occurs in a warm, low-viscosity, 200-300 km wide shallow mantle channel just to the south of the Nazca slab. Finally, we will show the latest results of our body wave finite-frequency tomography that provide adding information on the the geometry of the subducted slab, the extent of the slab window, and the mantle dynamics associated with slab window formation.

Subduction Zone Structure From Trench to Arc [Poster]

Poster Session • Wednesday 19 April

Conveners: Daniel E. Portner, Arizona State University (dportner@asu.edu); Jonathan R. Delph, Purdue University (jdelph@purdue.edu); Harm Van Avendonk, University of Texas at Austin (harm@ig.utexas.edu); Lindsay L. Worthington, University of New Mexico (lworthington@unm.edu)

Along-Strike Variations in Sub-Arc Melting Beneath the Alaska Peninsula

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Volatiles are expelled from the slab in the subduction and facilitate partial melting in the overlying mantle wedge, leading to arc magmatism and volcanic hazard. Many active volcanoes in the Alaska Peninsula have diverse eruptive activities and eruptions are more intensive in the northeast than in the southwest. Diverse eruptive behaviors of these volcanoes may reflect variations in magma flux and sub-arc melting. Here we investigate the sub-arc melting by measuring seismic attenuation in the mantle wedge as attenuation is sensitive to fluids and temperature. The recently deployed seismic arrays in the Alaska Peninsula provide an unprecedented opportunity for high-resolution attenuation tomography. The preliminary result of path-average attenuation shows that attenuation is stronger in the northeast than in the southwest and the weakest attenuation is observed in the middle part. These changes in seismic attenuation are in agreement with a separate study of Vp/Vs, indicating the along-strike variations in sub-arc melting beneath the Alaska Peninsula.

Earthquake clustering and statistics at the Alaska Peninsula

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The Alaska Peninsula section of the Alaska-Aleutian subduction zone exhibits notable along-strike variations in seismic activity and plate coupling. These variations reflect heterogeneities in the megathrust and are presumably controlled by the sedimentary and crustal structures of the subducting slab and the overriding plate. However, due to the limited seismic and geodetic data, the megathrust heterogeneities are not well defined in detail. Here, we try to explore the megathrust heterogeneities with a more complete regional earthquake catalog powered by machine learning techniques. We used the deep-learning earthquake detection package to analyze seismic data in the Alaska Peninsula and adjacent regions from 2018 to 2021, including the Alaska Amphibious Community Seismic Experiment (AACSE), EarthScope Transportable Array, Alaska regional network, National Tsunami Warning Center Alaska Seismic Network, and Global Seismograph Network. With a two-month test dataset, we achieved a 10.4% precision score, implying the potential of an almost 10 times larger catalog. However, the recall score is only 56.7%, indicating that the detection accuracy needs to be improved, particularly on OBS data. Then all detected phases are associated using a machine-learning-based associator GaMMA. The test on manual picks from the ACE catalog has a precision of 0.6 and a recall of 0.99, showing there is a large space to improve. We will retrain the deep-learning models using the manually picked regional earthquake catalog to improve the accuracy of detection and improve the associator to achieve a better performance, then apply them to the three-year dataset. The new catalog will present more clues about the characteristics of the plate interface, especially near the trench. It will also help us observe variations of outer-rise seismicity in the incoming plate, as outer-rise faulting is regarded as one of the controlling factors on the along-strike variations of the entire subduction zone. More analyses including the delineation of fault systems and defining the aftershock zones of three recent large earthquakes will be done.

Imaging the Marine Forearc Structure of the 2014 Iquique Earthquake Rupture Area Using Passive and Active Sources

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The area of the 2014 M8.2 Iquique earthquake in northern Chile is of interest to the scientific community as evidenced by the great number of studies and data available. Different approaches have been taken to understand the complex rupture process, as well as the dynamics of the fore- and aftershock sequences. Here we present a 3D seismic tomography that combines active-offshore and passive sources, both recorded at an inland temporary seismic network. When compared to tomography models derived only with natural seismicity, this amphibious approach serves to improve the estimation of body wave velocities in the overriding plate at the marine forearc, as well as in the subducting slab.The active seismic dataset used in this study correspond to marine airgun shots from 2016 PICTURES project recorded at the temporary inland seismic network, which also registered natural seismicity that was used as an input for the tomography. We complemented these datasets with local seismicity recorded at three different networks and time periods. First arrival times of the shots were estimated using CORREL, a novel technique for automated picking of active seismicity developed by the authors, while onsets of local seismicity were estimated with the Regressive ESTimator package (REST).This work highlights the contribution of using offshore active seismic sources to better image the structure and features of the plate above the seismogenic zone, which could give insights of what controls the complex rupture processes of large earthquakes.

Investigating Plate Interface Structure and Potential Splay Fault Geometry in the Southern Mw 9.2 1964 Great Alaska Earthquake Rupture Area Using a Dense Node Array

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The 1964 M_w 9.2 Great Alaska Earthquake is the largest earthquake ever recorded in North America. The Alaska-Aleutian megathrust produces some of the world's most devastating earthquakes, which makes it an excellent setting for studying the nature of subduction zones in terms of seismicity, rupture mechanisms, and structural heterogeneity. Preliminary studies have shown that the 1964 Great Alaska earthquake rupture area is divided into two major segments: the northern (Kenai) asperity and southern (Kodiak) asperity.The Kodiak nodal array was deployed along a ~60 km road system on Kodiak Island during the 2018-2019 Alaska Amphibious Community Seismic Experiment (AACSE). These three-component 5 Hz geophones were deployed for 25 days between mid-May and mid-June, recording at 500 Hz with an average station spacing of ~200 m, enabling a spatially dense seismic data acquisition for high-resolution imaging and microseismic event detection. Recent imaging studies using teleseismic sources suggest that, unlike the Kenai rupture zone, the Kodiak segment lacks a low-velocity zone above the plate interface. This difference in interface structure implies a variation in rupture behavior between the two asperities, with a low impedance contrast across the plate interface beneath Kodiak Island. The 1964 Great Alaska earthquake is known to be associated with major splay faulting, generating a near-field tsunami. Recent fault mapping offshore Kodiak suggests that the newly identified Ugak fault was the most probable source of local tsunamis on Kodiak island in 1964. Here, we leverage the higher frequency content of local earthquake sources to further investigate splay faulting and plate interface structure within the Kodiak asperity. Current results using four events show a coherent plate interface beneath the Kodiak array; we further aim to delineate potential splay fault geometry along the bounding interface.

Mantle Deformation in a Young Mountain Belt: Insights From Shear Wave Splitting in the Greater Caucasus

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The convergence of the Arabian and Eurasian plates during the Cenozoic led to the formation of the Greater and Lesser Caucasus, whose tectonic history is not yet well understood. The purpose of this research is to better understand mantle deformational fabrics by analyzing local direct-S derived azimuthal seismic anisotropy using only mantle earthquakes. We have used eigenvalue minimization to determine the shear wave splitting parameters for local seismic S-waves. The data used in this study was collected from permanent and temporary broadband seismic stations deployed across southern Russia and Azerbaijan. We have found that within the mountain range, the uppermost mantle fast polarization direction is parallel to the orogen, but as you move from the mountain belt to the Scythian platform (northward) and Kura basin (southward), the fast polarization direction shifts to orogen perpendicular. We have found north-south fast polarization directions in the Apsheron Peninsula which may be due to the slab rollback in the Caspian subduction zone. The splitting time delays primarily falls between 0.2 to 1.0 seconds. Splitting time delays shorter than 0.4 seconds are likely to be the result of crustal anisotropy and larger lag times likely have significant component in the uppermost mantle. We have also found that fast polarization directions tend to be homogeneous for larger splitting delays, but inconsistent for smaller delays. We have also conducted a preliminary study of deeper source anisotropy using receiver-side corrected teleseismic S-waves. The variations of these measurements combined with our local measurements should give us an idea of how mantle anisotropy varies with depth in the Caucasus region. Future research work plans to include more data from significant earthquake events to gain a more comprehensive understanding of how seismic anisotropy changes with depth across the Greater Caucasus.

Receiver Function Imaging of the Complex Plumbing System Feeding Mount St. Helens, Washington

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Mount St. Helens in Washington state, the most active volcano in the Cascade arc, was recently instrumented with a dense, expansive network of seismometers through the imaging Magma Under Mount St. Helens (iMUSH) Seismic Experiment, providing a unique opportunity to characterize the lithospheric structure of a magmatic system at an active volcano. With data collected from this experiment, the magmatic plumbing system feeding Mount St. Helens has been characterized by a variety of independent seismic imaging studies. These have identified an upper crustal (~4-15 km depth) low velocity zone interpreted as the primary magma reservoir containing up to an estimated 10-12% of partial melt and large lower crustal high velocity zones interpreted variably as magmatic cumulates or accreted high velocity terrane. Here, we attempt to further constrain the seismic properties of this system using receiver function-based analyses including adaptive common conversion-point (ACCP) stacking and Ps-P tomography. ACCP stacking reveals a three-dimensional model of seismic impedance contrasts within the crust and across the crust-mantle transition, highlighting clear variations in the amplitude of the Moho correlated with the presence of previously interpreted lower crustal cumulates as well as upper-crustal velocity contrasts associated with the shallow magma reservoir. Ps-P tomography reveals a three-dimensional model of V_P/V_S within the crust, highlighting strong variations in V_P/V_S related to previously interpreted upper crustal magma reservoirs while also providing relative V_P/V_S constraints in the lower crust. This ongoing work allows us to integrate constraints from the varied multi-scale seismic imaging studies of the Mount St. Helens plumbing system and validates the efficacy of receiver function based imaging in volcanic settings.

Seismic Attenuation Imaging in the Central Andes Using Local and Teleseismic Earthquake Spectra: Insights Into Fluid Migration in the South Amerian Lithosphere Above the Pampean Flat Slab

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Hypocenter locations and wavespeed models derived from prior analysis of data recorded by the SIEMBRA and ESP networks located above the Pampean Flat Slab in the Central Andes (Maharaj et al., 2022) revealed evidence for potential fluid migration from the subducted Nazca plate through the upper mantle and lower crust of the South American plate. Because fluids are likely to promote anelasticity, in this study we analyze seismograms from the same networks to examine the potential for attenuation (Q_p and Q_s) imaging to provide additional constraints on this type of devolitization in a flat slab environment.The methodology we employ combines a local event approach based on that described in Bennington et al (2008) with a teleseismic procedure that follows from an algorithm discussed in Byrnes and Bezada (2020). For local events, earthquake spectra are used to both sequentially and simultaneously solve for source spectral plateau and corner frequency, local receiver response, and the attenuation parameter t*, along with a frequency independent term and accounts for effects such as radiation pattern, the free surface, and geometric spreading. For teleseismic events, we follow Byrnes and Bezada (2020) and model waveforms in the time domain to generate estimates of relative t*, but do so by solving for variations from averaged spectra that form a minimum phase wavelet. We also include receiver site responses as part of the teleseismic procedure. As is the case with arrival time tomography, the joint inversion of local and teleseismic estimates of t* reduces the coupling between the crust and mantle.Out of the nearly 40,000 events cataloged by Maharaj et al., (2022) from the SIEMBRA and ESP networks, we were able to recover usable spectra from about 500 events dispersed throughout the crust of South America and the subducted Nazca plate. A review of the available teleseismic records shows that a similar number (about 370) are suitable for this joint analysis.

Seismic Images of the Crustal Structure Beneath Cordillera Central and Cordillera Oriental, Dominican Republic

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Hispaniola Island is a tectonic collage produced by the oblique convergence between the Caribbean and North American plates. The west to the central part of the island consists of high topography bounded by dominantly reverse and oblique-slip faults along the edges of the uplifted mountain ranges. The eastern part is lower in elevation, and no important active faults are identified. In this work, we analyzed the seismic data corresponding to Profiles A and D of the CARIBE NORTE project (2009) in the frame of the current KUK ÀHPÁN and MICROSIS-I projects. These profiles were registered by a seismic array of vertical and three-component land stations along N-S and W-E seismic transects of 425 and 450 km, respectively. The seismic sources used in these lines corresponded to land borehole explosions 1 Ton (S1, S2, and S3), three marine shooting lines (LM1N, LM1S for Profile A and LM4, for Profile D), and one earthquake that occurred during the registering period.We constrained the seismic structure of the Dominican Republic by the inversion of wide-angle seismic travel-time data for the previous 2D P-wave velocity model of both profiles. The results show marked differences between the western and eastern regions of the island. In the eastern zone, the Moho discontinuity rises to 24 km deep, while it increases towards the island's interior with a maximum depth value of approximately 30 km deep in the west and central part of the transect. The analysis and relocation of an earthquake occurred on April 11, 2009, using the CARIBE NORTE temporary seismic network, allowed obtaining a structure dipping towards the eastern interior of the island with a dip angle of 18º reaching 120 km.

Seismological and Geodetic Investigations in the Atacama Region of Chile: Investigations of Links Between Plate Interface and Intermediate Depth Processes

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The Atacama region of Northern Chile likely to be a mature seismic gap, with the last segment-breaking great earthquakes in 1819 (Mw~8.0) and 1922 (Mw~8.4). As such it provides the opportunity to study processes during the final stage of the seismic cycle but also the time-dependent hazard can be considered to be severe. Several episodes of silent slip events have been reported from GNSS time series analysis (by Klein et al., 2018), the last one from 2014-2016. The same area is also known to have given rise to several earthquake swarms of plate interface and intermediate depth seismicity, indicating a propensity for transient behaviour. This region is only sparsely sampled by permanent seismic and GNSS stations.Here we report on preliminary results from the recently completed temporary deployment of more than 100 seismic stations and ~30 continuous GNSS stations, which complement the permanent stations mostly operated by the Chilean seismic network. Automated analysis of data from this network yielded more than 30,000 events which are relocated in a 2D model using a double-difference relocation scheme, with a magnitude of completeness of ~2.0. The located seismicity clearly delineates two bands of seismicity within the oceanic slab, and in some areas, a third one is associated with the plate interface; the upper plate only shows sparse activity. The seismicity can be compared to the plate-locking map derived for the same area. Most of the seismicity is located between an extended offshore locking zone and the shoreline, probably representing the transition to velocity-weakening material. To first order, intensity of intermediate depth seismicity seems to follow the intensity along the plate interface.

Subduction Segmentation Revealed by Full-Wave Ambient Noise Tomography of the Aacse Data

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The subduction of oceanic plates is a key component of plate tectonics theory. Previous studies have shown that subduction zones are segmented both along-strike and along-dip with the variations in seismic activity, magmatism, slip behavior, and subduction geometry. However, the processes leading to the segmentation of subduction zones remain poorly understood. Here, we focus on the western Alaska-Aleutian subduction zone within the footprint of the Alaska Amphibious Community Seismic Experiment (AACSE), where strong along-strike variations in slab dip, volcanism, plate fabrics, seismicity, and locking fraction have been observed. We use full-wave ambient noise tomography (FWANT) to construct a high-resolution 3-D shear wave velocity model of the subsurface to understand the along-strike structural segmentation. We combine the AACSE data with other available seismic data in the study area to maximize the data coverage. Preliminary data analyses have shown high-quality empirical Green's functions between both onshore and offshore station pairs. We will present the preliminary tomography results and discuss the implications on subduction dynamics.

The HIPER Project: An International Collaboration on the Ecuadorian Margin

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The Mw 8.8 1906 earthquake that occurred at the Ecuador-Colombia subduction zone was a megathrust earthquake, with an estimated rupture length of 500 km between Buenaventura, Colombia to Manta, Ecuador. Its southern end has ruptured twice: in 1942 (Mw 7.8) and more recently in April 2016 generating another devastating Mw 7.8 earthquake, causing hundreds of deaths and millions of dollars in damages along an increasingly populated coastline. The seismological and geodetic network in place since several years and a dense international post-seismic deployment, contributed to observe and define the rupture zone as well as aseismic slip on the megathrust fault. In this region, episodes of aseismic slip have been recorded at the shallow updip part of the subduction interplate fault, in the form of both slow slip events (Vaca et al., 2018) and afterslip in the aftermath of the 2016 Mw 7.8 Pedernales earthquake (Rolandone et al., 2018). Those hints of transient slip behaviors, for which fluids have been invoked to explain their occurrence, bring Ecuador to the forefront of natural laboratories to study the link between fluids, interplate roughness, the nature of sediments, upper plate and lower plate's structural heterogeneity in seismic/aseismic slip behavior.

Between 2020 and 2022, we acquired data of the HIPER Project based on an international collaboration funded by the French Oceanographic Fleet, the French ANR, Karlsruhe Institute of Technology (Germany), American NSF and IG-EPN (Ecuador). It implies researchers, engineers and students from France, Germany, United States and Ecuador, giving us access to a large number of OBS (47), land stations (~200) and nodes (~500) to record both French R/V Atalante's shots and the seismic activity. Our collaboration allowed a high density onshore/offshore deployment to perform shots and earthquakes FWI (Full Waveform Inversion), ambient noise tomography, receiver function, 3D earthquakes location and obtain a high-resolution multi-parameters image of the Pedernales earthquake rupture zone.

Tectonics and Seismicity of Stable Continental Interiors

Oral Session • Wednesday 19 April • 10:30 AM Pacific

Conveners: Will Levandowski, Tetra Tech, Inc. (bouldergeophysics@gmail.com); Zhigang Peng, Georgia Institute of Technology (zpeng@gatech.edu); Miguel Neves, Georgia Institute of Technology (mjgfgn3@gatech.edu); Anji Shah, U.S. Geological Survey (ashah@usgs.gov); Jessica T. Jobe, U.S. Geological Survey (jjobe@usgs.gov); Oliver S. Boyd, U.S. Geological Survey (olboyd@usgs.gov)

Seismicity Triggering by Stress Transfer of Recent Strong (M > 6.0) Earthquakes in Greece

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We explore a series of recent earthquake sequences in Greece where the seismicity was substantially elevated not only on the fault associated with the main shock but also on the adjacent fault segments. There is accumulated evidence that static Coulomb stress transfer can promote or inhibit subsequent seismicity, the means that the background rate is amplified if the stress change is positive or suppressed if it is negative. When a strong (M>6.0) earthquake occurs to examine the stress imparted to the adjacent fault segments we consider in addition to the background seismicity rate, background and aftershock focal mechanisms, and the main shock finite fault models. Even the most known and extensively investigated faults that might be considered isolated, exhibit geometrical and kinematic complexities, when they are detailed by double–difference relocated seismicity and focal mechanisms. Those complexities are associated with the inherited fault network, fault bends, and breaks, and their obliquity to the dominant stress component or properties of the local seismogenic layer. We used catalogs of precisely relocated aftershocks and examined in several cases whether the static changes caused by the coseismic slip of the main shock promoted failure considering one of the nodal planes of the closest mechanism to each aftershock. We have found that static stress changes are the driving mechanism that triggered the vast majority of the off–fault aftershocks, by unveiling that these stress changes attained positive values at their locations and were efficient to trigger both major and minor adjacent fault segments. Analysis has not evidenced the existence of stress shadows inside areas of negative stress change.

Seismicity and Seismotectonics in the Kefalonia Transform Fault Zone (KTFZ), Greece

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The Kefalonia Transform Fault Zone (KTFZ), which extends for more than 150 km offshore and along the western coastlines of Kefalonia and Lefkada Islands, is one of the largest sources of seismic hazard in the Aegean region. It is composed of five major and numerous secondary fault segments and bends. We have synthesized the characteristics of this seismogenic zone by analyzing earthquake data recorded during the past 20 years (2003–2022). The seismicity is mainly distributed onshore along the coastline, in the depth range from 5 to 15 km, primarily associated with strike–slip faulting. From the seismicity and fault plane solutions analysis we integrated the major physical features of the regional seismotectonic. We suggested a comprehensive seismotectonic model that improves our understanding and must be taken into account in any seismic hazard model. Fault plane solutions confirm that the direction of maximum horizontal stress is dominantly northeast–southwest over almost the entire area. From analyzing groups of earthquakes, we can infer temporal and spatial variations of earthquake source properties, as well as the properties and the evolution of the stress field. Although the major faults are dipping to the east, and southeast, the northern continuation of the Lefkada fault is dipping to the northwest. We are then suggesting that the dextral strike-slip dies out to the north of the Lefkada branch of KTFZ as it is probably transferred to the neighbor fault populations as at this edge it meets continental collision to the north. Between the Lefkada and Kefalonia branches of the KTFZ step-over secondary faults are developed that might be considered as splays beyond the major faults representing a broad damage zone. Such damage zones are interpreted to be due to the stress concentrations at fault tips and linking zones. Our seismotectonic model illustrates that the KTFZ is a long, continuous structure with multiple segments that exhibit complex geometries and kinematics.

Did You Feel It 50 Years Ago? the 1969 M7.9 Cape Saint Vincent Earthquake

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On February 28th 1969 a major earthquake took place offshore SW Iberia, on the diffuse boundary between the Eurasian and African plates. The earthquake was widely felt in Iberia and Morocco, with maximum intensities of VIII recorded in SW Portugal. With an estimated magnitude Ms 7.9, this event is currently the highest magnitude felt earthquake in the European historical catalog. The earthquake was recorded in Portugal by one WWSSN seismic station in Oporto and another two stations in Lisbon and Coimbra, but all records were saturated. One strong-motion accelerometer located in the pier of a recently built bridge over the Tagus river provided the closest non-clipped record of the earthquake.

Whereas source parameters for this major earthquake were studied mostly from teleseismic records, information on the ground motion was mostly obtained from macroseismic observations. In 2019, on the occasion of the 50th anniversary of the 1969 earthquake, we revisited this topic by launching a Did You Feel It (DYFI) inquiry about the 1969 earthquake. This initiative occurred at a time when many testimonies of the 1969 earthquake are still alive and have a clear – often even vivid – memory of the earthquake.

In this presentation we will discuss the key aspects of our study, namely: limitations of the DYFI questionnaire made 50 years after the earthquake; new information revealed by the DYFI; comparison between our DYFI intensities and the traditional macroseismic intensities; comparison between the intensi-

ties / ground motion pattern revealed by the DYFI and that observed in recent moderate magnitude (M5-6) earthquakes; intensities pattern revealed in the capital city of Lisbon.

Revealing Activate Fault Structures in the Slow-Deforming Region of Iberia by Applying Deep Learning Techniques to Dense Seismic Recordings

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The seismic behavior of slowly deforming regions (≤1 mm/yr) remains a challenge due to the small tectonic loading rates, complex fault systems and episodic and migrating seismic activity that complicate the imaging of subsurface faults and hazard assessment. We combine deep learning techniques and dense seismic recordings to study Iberia, a slowly deforming region in Southwest Europe (except near the plate boundary between Nubia and Eurasia), and to gain new insights into the seismicity behavior in these regions.From 2007 to 2014 several dense temporary seismic networks were deployed in the target region that hold untapped data. We use a deep-learning earthquake detector and phase picker, the Earthquake Transformer (EQT, Mousavi et al., 2020), to analyze the Iberian datasets. Using a small dataset of 28,622 waveforms from the region, we fine-tune the EQT model to our study region and to accommodate larger epicentral distances. When applied to this small data subset, our newly trained model detects 98% of the seismic phases in the catalog up to epicentral distances of 250 km, compared to 77% and 75% detection of P and S phases, respectively, by the original EQT model. Applying our new model to 7 years of continuous data from 555 seismic stations, we detect 28 times the number of seismic phases in the current ISC catalog. After associating the detected phases, we compile a new earthquake catalog with 69,281 earthquakes, more than doubling those in the current catalog. Most of the new detections are located near the plate boundary, but several clusters are also identified in the interior of the study region, where only sparse seismicity was detected before. Some of these events located near regions of active mining activities. Our results demonstrate that deep learning models can be adapted to identify active fault structures in slow deforming regions and with small initial information. The new catalog provides opportunities to better study the deeper seismicity in Southwest Iberia and the anthropogenic seismicity in the region.

The 2022-23 Reno, Northern Alberta Earthquake Sequence

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Although geographically part of western Canada, tectonically, most of Alberta is located within the North American craton and experiences relatively low levels of seismic activity. On 23 November 2022, a very active earthquake sequence began near Reno in northern Alberta with the largest event (M_W 5.1) occurring on November 30. It was the largest earthquake in Alberta in the last twenty years and one of the largest ever recorded there. To date there have been several hundred events in the ongoing sequence including 13 of magnitude greater than 4. We have studied these events to better understand the regional seismotectonics. Our regional centroid moment tensor inversions (RCMT) of the largest events indicate thrust faulting on a NW-SE striking plane at shallow depths (< 5km) and are consistent with the regional NE-SW maximum compressive stress field. Additionally, the surface displacement of the largest event was captured by INSAR and is consistent with our RCMT solutions and points to the NE-dipping plane as the probable fault plane. The maximum displacement is 5 cm. RCMT M_Ws for these events obtained in this analysis are generally significantly smaller than the ML magnitudes routinely used for small earthquakes in Alberta, more typical of cratonic than tectonic Canada. Although RCMT inversions provide robust MWs for moderate and large earthquakes, the relatively long periods modeled render the method unsuitable for small earthquakes. Instead, we are using the coda envelope moment magnitude method, to calibrate the region through the use of ground truth events and then calculate M_W (M_{WC}) for smaller earthquakes. We also consider how our results may aid in the discrimination of the source of the earthquake sequence.

Exploring the Relationship Between Subsurface Structure and Seismicity for the Eastern United States

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The Eastern United States hosts several seismically active regions such as the New Madrid, the Wabash Valley, the South Carolina, the Central Virginia, and the West Quebec seismic zones. It is not clear what factors control the occurrence of these intraplate earthquakes. Previous geodynamic studies have suggested that some intraplate earthquakes may be due to localized stress concentrations. Since subsurface structure heterogeneity can cause stress concentration, we examine the three-dimensional subsurface structure of the Eastern United States to investigate potential relationships between subsurface structure and seismicity. To constrain the subsurface structure, we simultaneously inverted smoothed P-wave receiver functions, Rayleigh-wave phase- and group-velocity measurements, and Bouguer gravity observations. Our velocity model agrees relatively well with previously published seismic models. Comparing the earthquake locations and subsurface structure variations, we found that earthquakes in the Eastern United States often, but not always, locate near regions with seismic velocity variations. However, not all regions of significant subsurface wave velocity changes host detectable seismicity. We also observed a weak correlation between upper mantle shear velocity and earthquake focal mechanism in the Eastern United States. Thrust faulting earthquakes are often located in regions with relatively slow upper mantle velocities within the study area.

Fault Reactivation Potential in Intraplate North America, From Major Seismic Zones to 3D Gravity Imaging of the Sparta, NC Epicentral Zone

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The crustal stress field varies across eastern North America, controlling which of the many orientations of inherited faults may reactivate in future damaging earthquakes. Aftershocks, too, preferentially occur on pre-stressed faults, such that comparatively small coseismic and post-seismic perturbations trigger slip. This study introduces new maps of fault slip potential across much of the eastern United States. Stress inversions are used to map geomechanically favorable fault orientations and disambiguate focal plane orientations at several scales. For instance, oblique extension in the Eastern Tennessee Seismic Zone is accommodated mainly by faults striking between N20E and N85E (and diametric), perhaps without slip on planes in the NW or SE quadrants. In the New Madrid Seismic Zone, significant differences in stress favor strike-slip in the vicinity of the Axial/Cottonwood Grove Fault and reverse motion around the Reelfoot Thrust, independent of the existence of those specific structures. Differences between the southern and northern halves of the Reelfoot Thrust may influence multi-segment rupture propagation onto the adjacent Axial, Risco, and New Madrid North Faults. Finally, the 2020 Mw5.1 Sparta, NC earthquake provided an unprecedented opportunity to examine the reactivation of multiple generations and orientations of inherited faults. Regional gravity data illuminate the structural controls on the exceptionally shallow (~ 1 km) mainshock/aftershock zone. Results will be presented from a microGal-precision, locally decameter-resolution terrestrial gravity survey and associated 3D modeling of the mainshock/aftershock fault network. These findings will add to the growing dataset of reactivated fault orientations that both demonstrate that the stress field across the eastern United States is not uniform, and that there is enough information now available to begin prospectively mapping potentially active fabrics.

The 2020 Mw 5.1 Sparta, North Carolina, USA Earthquake: Surface Deformation and Paleoseismicity of the Little River Fault

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The M_w 5.1 2020 earthquake near Sparta, North Carolina, was a shallow oblique reverse earthquake with a surface rupture, the first documented in the eastern U.S. This was an unexpected event because: 1) the WNW trending Little River fault was previously unknown, and 2) a surface rupture generally is not expected from an M_w5.1 earthquake. Initial surveys recognized a 2-km-long surface rupture with topographic steps trending ~N110°. Reverse scarps and associated folding of the uplifted southern hanging wall were recognized during initial field surveys, consistent with an oblique-reverse focal mechanism and N108°-striking 60° SW-dipping nodal plane. Although no lateral displacement was recognized along the rupture trace, post-earthquake surveys of geodetic monuments corroborated an off-fault left-lateral displacement. A post-earthquake lidar revealed an additional ~2.5 km of surface rupture and helped recognize additional vertical deformation expressed by a wider folding of the hanging wall leading to recognize a larger co-seismic deformation area.

To further investigate the fault zone, we conducted ground-penetrating radar (GPR) and electrical resistivity surveys at favorable locations across the rupture trace. Results highlighted a 10-15 m wide fault zone, and GPR showed south-dipping reflectors. Combined geophysics and geomorphology guided site selection for paleoseismic trenching. At two trenches, a sequence of Quaternary soil and colluvium overlaying the weathered bedrock was deformed by several WNW-NW fault strands in a complex, 15-m-wide fault zone. The 2020 rupture was accommodated by three reverse strands, with a total along-fault dip-slip of ~50 cm, associated with a ~30 cm high scarp. An upper Bt soil horizon of probable Late Pleistocene age has a cumulative displacement of ~1 m, providing evidence for previous surface ruptures. The Little River fault is an example of a previously unknown but active fault lying outside of known seismic zones, raising the question of how many similar, unknown faults pose a seismic hazard to the eastern U.S.

Seismic Quiescence in the Rome Trough: Implications for Earthquake Potential and Crustal Structure

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The Rome Trough extends from eastern Kentucky across West Virginia and Pennsylvania into southern New York and forms the easternmost expression of a larger intraplate failed rift system. To characterize earthquake potential of the trough, we used fault, stress, and earthquake data in and near the trough compiled as part of the DOE-funded Midwest Regional Carbon Initiative. Very few earthquakes have occurred inward of the trough's bounding faults, which contrasts with active earthquake zones abutting the trough to the north and south, including the Eastern Tennessee Seismic Zone (ETSZ). These zones of elevated activity appear to be bounded to the west by a topographic gradient in the Moho that is subparallel to and just east of the Grenville tectonic front and stretches from northern Kentucky to northern Georgia. Thinner crust (~47 km) east of the gradient, excluding the trough, contains the currently active faults while thicker crust (~54 km) to the west is largely quiescent. Thus, the trough appears to bisect crust containing the northern part of a large zone of seismicity, which stretches from southern Ohio to northern Georgia and includes the ETSZ. To understand the dearth of seismicity beneath the trough, we investigated the relationship between stress and major crustal faults. Initially, we evaluated $SH_{\max}$ orientations in the trough, separated into three subregions delineated by large changes in fault trends, each of which is in a strike-slip regime as determined by previous studies. Mean $SH_{\max}$ (σ_1) orientations are offset from the average fault trends in the respective subregions by at most 15°, considerably less than the ideal ~30° needed for faults to slip under typical tectonic conditions. Detailed analyses involving stress inversions are underway to further assess slip susceptibility of Rome Trough faults. Our seismicity observations in and around the trough and the results of the stress inversions and fault slip potential analyses will be presented.

Analyses of Balanced Rocks to Constrain Ground Motions in the Eastern U.S.

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Although analyses of fragile geologic features, and specifically Precariously Balanced Rocks (PBRs), have been used to constrain the strength of ground shaking in the western U.S. and elsewhere, the method has not been used in the eastern U.S. However, the latter region is especially amenable to such studies because: 1) there are many glacial erratics placed in precarious positions when the continental ice sheet melted in the northeastern U.S., and there are a number of PBRs in the Appalachians that were formed by erosion; 2) PBRs in the northeastern states have the advantage of reliable age estimates because of placement following the last glacial maximum, with glacial striations beneath some of the PBRs confirming that they were deposited after the glaciers scoured the landscape; and 3) relatively low seismic attenuation means that PBRs are sensitive to earthquakes over larger areas than in the western U.S. We are beginning studies of eastern U.S. PBRs, with initial efforts in New England, the Adirondack Mountains of New York, and the Blue Ridge Mountains of Virginia. Studies so far have focused on refinement of methodologies, including comparisons of 3-D models made from photogrammetry (structure-from-motion) and terrestrial lidar, with each showing some advantages over the other. We also installed temporary seismometers on top of the rocks, and then pushed them gently to characterize the rocking after small perturbations. We compare the likely toppling accelerations computed using several different methods to accelerations in hazard curves at the PBR sites, and we use a ground motion model to estimate the magnitudes of nearby earthquakes that likely would topple the PBRs. Preliminary results show promise for using PBRs to provide insights to past ground motions in the region.

Long-Lived Aftershocks in the New Madrid Seismic Zone and the Rest of the Stable North America

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Seismicity in the New Madrid seismic zone and the rest of the stable North America has been intensively studied and debated. Some workers view present-day earthquakes there as long-lived aftershocks of historical mainshocks, while others think that they are background earthquakes concentrated in weak zone. Separating aftershocks from background seismicity, however, can be challenging. Here, we used the nearest-neighbor method to identify aftershocks. This method calculates the distance between pairs of events in the space-time-magnitude domain. If the distance is too close to be expected for independent background events that follow the Gutenberg-Richter law and Poisson distribution, they are taken as clustered events (aftershocks). Our results suggest that, depending on the size and location of the 1811-1812 New Madrid mainshocks, 10.7% - 65.0% of the $M \geq 2.5$ earthquakes in the New Marid region between 1980 and 2016 are long-lived aftershocks. Similarly, most present-day earthquakes in South Carolina are long-lived aftershocks of the 1886 Charleston earthquake. On the other hand, most contemporary seismicity in Charlevoix, Québec are background seismicity. These results reaffirm the existence of long-lived aftershock sequences in stable North America and suggest that, in stable continents, present seismicity usually includes both background earthquakes and aftershocks. Identifying long-lived aftershocks from background seismicity is important for assessing seismic hazard in the stable North America and other intraplate seismic zones.

Machine-Learning Detection and Waveform Correlation to Probe New Madrid Seismogenesis

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Decades of research has failed to determine the physical mechanism(s) leading to reactivation of the New Madrid Seismic Zone nor resolve the long-term deformation and earthquake clustering history expected for the broader Central US. As in areas associated with induced earthquakes, where some but not all intraplate faults have become active under very small changes in subsurface stress, in New Madrid, seismic reflection data has revealed faults with Quaternary deformation that do not currently host earthquakes. Here, we focus on providing fundamental new earthquake datasets through application of state-of-the-art improvements in detection, association and location, including waveform correlation to improve relative location. We show preliminary results from the application of a machine-learning (ML) approach (easyQuake - https://github.com/jakewalter/easyQuake) to build out a detection catalog extending from the mid-1990s to present applied to all permanent (Cooperative New Madrid Seismic Network) and high-quality temporary seismic networks (ie., Transportable Array, NELE, OINK). EasyQuake includes an associator and earthquake location algorithm and we explore how to best associate earthquakes with multiple ML algorithms (PhaseNet, EQTransformer, GDP) and training datasets applied to the same continuous waveform data. In parallel, we update the event-to-event waveform correlation datasets for the New Madrid area from 2008-2022 using the New Madrid Cooperative Network phase and waveform catalog to understand if highly similar (swarms) or repeating earthquakes have continued since initially reported (Bisrat et al., 2012). Ultimately the ML and correlation data will be combined to update and expand a high-resolution New Madrid seismic zone earthquake catalog, which in turn will allow for updated earthquake statistics, identification of repeating and clustered earthquakes, and improved earthquake source characteristics and focal mechanisms.

Update on the Seismicity and Tectonics of the 2021-2022 Elgin-Lugoff, South Carolina Earthquake Sequence

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On December 27, 2021 a M=3.3 earthquake started a nearly year-long swarm of felt events centered near the towns of Elgin and Lugoff, South Carolina, ~30 km NE of Columbia, the state capital. Prior to December 27, 2021 event, we can find no evidence of previously reported earthquakes in this area. As of December 10, 2022 there have been 82 events (80 felt) in this swarm, including five M 3+ events widely felt in the Midlands of South Carolina. These events appear to be associated with a reactivated cross fault within the Paleozoic Eastern Piedmont Fault System (EPFS). In this region the EPFS is recognized via magnetic anomalies as it is covered by a thin veneer of coastal plain sediments (0-150 feet thick). The initial events of this sequence are relatively poorly located, with the closest seismic station being >30 km away. Soon after the start of the sequence (December 31, 2021) a new station (BARN) was installed 3-5 kilometers SE of the swarm. In addition, on April 17, 2022 a Raspberry Shake 3D station (R3A5D) was installed ~10 kilometers WSW of the swarm. We have begun analyzing this earthquake sequence in more detail, especially for events occurring after April 17, 2022 when both new stations were operating. Our initial attempts at relocating events in the swarm suggest it is more spatially concentrated than the network solutions suggest; in particular, the two events offset to the south relocate within the main swarm. We also note that there are many smaller events clearly recorded on the nearest station (BARN), some of which are potentially locatable. We will present our latest results on the number, location, and geometry of the Elgin-Lugoff earthquake sequence.

High-Resolution Imaging of the Elgin-Lugoff Earthquake Swarm Sequence in South Carolina Using a Dense Seismic Nodal Array

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Earthquake swarms are characterized by closely-clustered seismic events in space and time, without a single main shock, and they often occur along plate boundaries with ample volatiles or fluids. In comparison, swarms at intraplate regions are rather unique, especially in the Southeast United States where background seismicity is typically low. A prolonged earthquake swarm sequence started on December 27, 2021, beginning with a magnitude 3.3 earthquake near Elgin and Southwest Lugoff in South Carolina (SC). Up to now, 81 microearthquakes have been located in this region, with the largest magnitude of 3.6 occurring on June 29, 2022. These earthquakes occurred near the Eastern Piedmont Fault System (EPFS), but upon closer examination, most events were found to occur across rather than along the EPFS (Howard et al., 2023). This swarm sequence was widely felt in the broader region of SC, and offers a rare opportunity to study physical mechanisms of earthquake swarms in intraplate regions. In October 2022, 86 SmartSolo nodes were deployed in a 7 km x 7 km area right on top of the swarm sequence, with one site co-located with a broadband seismometer JKYD. This deployment aims to capture near-field observations of the sequence in high definition for up to 4 months. The data collected from this deployment can be used to detect additional smaller earthquakes not listed in the existing catalog, and the relocated catalog can reveal spatial-time evolution of the swarm and underlying forces driving this swarm. Preliminary results from this nodal deployment, including comparisons of the nodal recordings and the co-located broadband recording, will be presented in the meeting.

Exploring Rupture Models for the 1 September, 1886, Charleston, South Carolina, Earthquake

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The 1 September 1886 Charleston, South Carolina, earthquake was one of the largest pre-instrumental earthquakes in eastern North America for which extensive contemporaneous observations were documented. The source zone has, however, remained enigmatic, with evidence of the rupture and faulting obscured by saturated Atlantic Coastal Plains sediments. We considered detailed archival accounts, including documented disruption to railroad lines through the epicentral region. The most severe disruptions of the tracks occurred south of the town of Summerville. The railroads have long since been repaired and are now generally straight to within 30 cm over distances of tens of km. However, GPS measurements reveal the railroad alignment south of Summerville has a ≈3 m dextral offset that is reasonably interpreted as a quantitative measure of coseismic surface deformation. We use these data together with present-day surface morphology and other constraints to develop elastic deformation models based on previously proposed faults in the region. Of possible scenarios, evidence favors >4 m of reverse slip on a ≈30-km-long blind rupture parallel to the North Woodstock fault (*Talwani and Dura-Gomez*, 2009) but with ≈45° westward dip similar to the reverse fault proposed by *Chapman et al.* (2016), intersecting the surface near the east-facing Summerville scarp. In our model, dextral slip occurs on secondary shallow faults above this thrust plane. A common feature of models for the 1886 earthquake is the absence of significant coseismic rupture south of the Ashley River. In the near-field region, from Summerville to Charleston, damage was exacerbated by extensive liquefaction on saturated fluvial, barrier sand, and marsh facies. Our preferred scenario implies a moment magnitude of M 7.1, consistent with estimates from previous studies. Given the strong dependence of radiated energy on stress drop, however, any intensity-based magnitude will provide at best a weak constraint on M.

Tectonics and Seismicity of Stable Continental Interiors [Poster]

Poster Session • Wednesday 19 April

Conveners: Will Levandowski, Tetra Tech, Inc. (bouldergeophysics@gmail.com); Zhigang Peng, Georgia Institute of Technology (zpeng@gatech.edu); Miguel Neves, Georgia Institute of Technology (mjgfgn3@gatech.edu); Anji Shah, U.S. Geological Survey (ashah@usgs.gov); Jessica T. Jobe, U.S. Geological Survey (jjobe@usgs.gov); Oliver S. Boyd, U.S. Geological Survey (olboyd@usgs.gov)

Australia's AUS8 Seismotectonic Model – A Product of 30 Years of Continuous Improvements of Earthquake Hazard Data, Concepts and Techniques

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A seismotectonic model for Australia, developed in the 1990's, has been continually modified and updated as more information and better techniques become available to estimate seismic hazard in this intraplate setting. Since the last iteration was described in 2016, we have incorporated significant changes resulting in current model, AUS8, namely, i) previously we assumed an equivalence between the magnitudes calculated for the original earthquake catalogue (often M_L) and the Moment Magnitude (M_W) values used by various ground motion models. Current practice is to transform the original magnitude values, using M_W magnitude conversion factors, prior to ground motion recurrence values being computed; ii) activity rates have been updated using recent seismicity data leading to a refinement in A0 and b-values; iii) calculations at a site using the AUS8 model now includes, as independent seismic sources, all active and neotectonic faults within 70 km as well as all large bedrock faults that are aligned with the current crustal stress regime within 40 km. In an attempt to model the episodic nature of fault activity, we assign three varying factors and give appropriate weights to the uplift rate for each fault to reflect periods of activity and quiescence; iv) maximum magnitude (M_{max}) values assigned to a source zone were previously based on the number of active or neotectonic faults located within that zone, whereby all large earthquakes were assigned to the fault(s). This methodology is still used for zones nearby to the site under consideration, but for distant zones without fault sources (i.e. all zones beyond 70 km) the fault earthquake activity and the zone earthquake activity is modelled together and the zone is assigned a M_{max} of 7.3; v) source zone boundaries in the AUS8 model have also changed considerably. These changes contribute towards improved earthquake hazard estimates within Australia.

Detection of Seismic Events Near the Southern Anninghe Fault Using a Local Dense Array

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The Anninghe fault (ANHF) is one of the major faults on the southeastern margin of the Tibetan Plateau and has produced a few large earthquakes in history (e.g., the 1536 Xichang M7.5 earthquake). Seismic quiescence for M4 events in the recent 40 years and high interseismic locking degree near the southern segment of ANHF emphasize the high seismic hazard of this region.

To better assess the recent fault behavior of ANHF, we used a dense temporary seismic array consisting of 132 three-component instruments to detect local seismic events near its southern segment. After detection with a machine-learning phase detector (EQTransformer), phase association (REAL), and absolute location (Hypoinverse), we obtained an initial catalog with more than 400 events. The matched filter detection method was also applied to array waveform data to detect potential hidden events. Finally, our relocation results reveal five clusters of events around the array, and after both waveform characteristic and spatiotemporal distribution analyses, four of which are probably attributed to mining blasts while the remaining one consists mainly of natural earthquakes that occurred northwest of the main fault. We detected a small number of on-fault earthquakes down to 15 km beneath our array, which is further compared with the existing catalogs and the previously inverted interseismic locking models. We suggest that there might exist some smaller but currently more active faults around the highly locked southern Anninghe fault, and dense array recordings could help increase both the completeness and accuracy of the seismic catalog over our study region.

Investigating the Seismicity of Yucatan, Mexico, Using Machine Learning Techniques

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The Yucatan Peninsula is the subaerial portion of a carbonate platform deposited on the Yucatan Block unit, a continental microplate that covers southeastern Mexico, northern Guatemala and Belize. It has generally been considered tectonically stable, while on a broader time scale it has been interpreted to have been subsiding since the early/middle Eocene. In this study, we use machine learning techniques to investigate seismicity in Yucatán, southwestern Mexico. In this region, seismicity appears to be extremely low compared to the rest of the country. The coverage of seismic stations is also very poor, which could be one of the reasons for the unusual lack of reported earthquakes in this region. We employed the ConvNetQuake and EQTransformer neural network algorithms to identify and locate small earthquakes, not recorded in the catalogs, but hidden in the seismograms. We identified an average of 637 seismic events per year occurring in the studied region between 2007 and 2021. In addition, we investigate the possible relationship between some of these newly detected earthquakes and some of the 23 oil wells drilled in the Yucatan Peninsula since 2003. Our preliminary results show that the Yucatan Peninsula has a low seismicity, but contrary to national catalogs there are seismic events that have not been reported due to a significant lack of instrumentation. These events reflect important characteristics of the stress state of this region and we can use this information to study the orientation of the principal stresses and induced seismicity associated with oil and gas exploitation.

Mapping b-Values Based on Background Seismicity in the Korean Peninsula

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The b value of the Gutenberg and Richter relationship, one of the parameters indicating seismicity, is crucial to seismic hazard assessments and understanding the stress state of regions of interest. We built b-value maps of the Korean Peninsula that belongs to an intraplate region to identify spatial and temporal variations in seismicity, based on the earthquake catalog (1998 to 2022) of the Korea Institute of Geoscience and Mineral Resources. Non-natural or dependent events typically produce high b-values; therefore, we attempted to eliminate non-natural events, such as quarry and mine explosions, by applying the daytime-to-nighttime ratio proposed by Wiemer and Baer (2000) to cataloged events with local magnitudes less than 2.5. We then declustered seismicity to obtain only independent events, by identifying dependent events, such as after- or foreshocks, using the window method proposed by Gardner and Knopoff (1974). The magnitude of completeness (M_c) for the determination of the b-value was estimated using the goodness-of-fit test proposed by Wiemer and Wyss (2000), and the b-value was calculated using the maximum likelihood method proposed by Aki (1965). We mapped the M_c and b-values at nodes generated by dividing the Korean Peninsula into grids of 0.1° x 0.1°. The b-value maps based on background seismicity in the Korean Peninsula showed characteristic temporal and spatial features. Here, we discuss the implications of the low b-values observed, especially around Baekryoeng Island, and examine the changes in b-values after the 2011 Tohoku and 2016 Gyeongju earthquakes.

Southwest Australia Seismic Network (SWAN): Recording Earthquakes in Australia's Most Active Seismic Zone

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The geological structure of southwest Australia comprises a rich, complex record of Precambrian cratonization and Phanerozoic continental breakup. Despite the stable continental cratonic geologic history, over the past five decades the southwest of Western Australia has been the most seismically active region in continental Australia though the reason for this activity is not yet well understood. The Southwest Australia Seismic Network (SWAN) is a temporary broadband network of 27 stations, deployed since July 2020, designed to both record local earthquakes for seismic hazard applications and provide the opportunity to dramatically improve the rendering of 3-D seismic structure in the crust and mantle lithosphere. Such seismic data are essential for better characterization of the location, depth and attenuation of the regional earthquakes, and hence understanding of earthquake hazard and in addition, an improved understanding of the long tectonic history of the Australian continent.

Preliminary results from the deployment include a new machine learning based catalogue that has located 5000+ earthquakes and an ambient noise tomography model. Using ~20 months of continuous data recorded by SWAN stations, we have produced a 3-D Vs model of the crust and uppermost mantle with ambient noise tomography. Our images show distinct low-velocity anomalies beneath the Perth Basin and relatively high-velocity anomalies in the Yilgarn Craton separated by the N-S trending, inactive Darling Fault. In the center of the Perth Basin that is characterized by low velocities, we observe a small-scale high-velocity anomaly. Within the Yilgarn Craton, we detect a prominent structural contrast in the lower crust to the uppermost mantle along the boundary of the South West Terrane and the Youanmi Terrane. Included in the new catalogue, this array captured a significant earthquake swarm in the Arthur River region, located within the south-central part of the Yilgran craton, which began in early 2022 and to date has recorded 1850+ earthquakes, the largest with a MLa magnitude of 4.8 (MLv 5.1).

Structural Setting and Seismogenesis Mechanism of the 16th September 2021 Luxian Ms6.0 in the Southern Sichuan Basin, China

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The Ms6.0 earthquake occurred in Luxian, Sichuan Province, on September 16, 2021, breaking the largest magnitude ever recorded in the inner Sichuan Basin. The epicenter of the earthquake is located in a syncline of Huayingshan thrust-fold belt in southern Sichuan and southern Sichuan's important shale gas mining area. Using two high-resolution seismic reflection profiles passing through the epicenter of the Ms6.0 earthquake, combined with regional geological and drilling data, the geological structure model of the earthquake area is established. Based on the focal mechanism solutions of this earthquake and adjacent area, the analysis of the seismogenic structure and the seismogenic mechanism is carried out.

The results show that the structural styles are decoupled vertically. The gypsum layer of the Middle Cambrian Gaotai Formation and the Silurian shale are typical detachment layers. NE, NE, and NEE striking blind salt-related detachment anticlines and thrust faults are widely developed from the Cambrian gypsum layer to the Silurian shale, indicating the characteristics of multi-directional structural superposition. The buried depth, attitudes, and properties of this fault system in the north of Luxian are consistent with the coseismic fracture surface of shallow earthquakes, indicating that the Cambrian gypsum layer to the Silurian shale should be the main seismogenic layer in the sedimentary cover, and its blind structures strongly susceptible on the local stress field. The Luxian Ms6.0 epicenter is stuck in the triangle area where NE, NNE, and NEE striking faults converge, and its strike of coseismic rupture surface and the direction of principal stress is very different from that of regional faults and principal stresses. We suggest that under the conditions of regional stress slow loading and local stress disturbance, the Middle Cambrian gypsum layer and its complex blind fault system interacted with each other, forming local stress concentration, resulting in Ms6.0 seismic activity in the syncline region.

Understanding the Focal Mechanism Distribution of Microseismicity in the Source Region of the 1886 M 7 South Carolina Earthquake

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In Late August 1886, the East Coast of United States suffered the largest and most damaging magnitude ~7 earthquake near Summerville in South Carolina. However, there remains no evidence of surface faulting, leading to the puzzling nature of the fault mechanism responsible for this important event. Presently, the neighborhood near Summerville still experiences ongoing microseismicity, which has been inferred as the aftershock sequence of the 1886 main shock. Therefore, monitoring modern seismic activities can help to better define the source fault for the 1886 event, and allow for better evaluation of the seismic hazard in this region, as well as serving as a potential analogue for east coast intraplate seismicity. Previous studies (Dura-Gomez and Talwani, 2009), give an inference to the existence of multiple faults within this region. However, results from a 2011-2012 deployment of an 8-station seismic network (Chapman et al., 2016) hypothesized a southwest striking and west-dipping zone of modern seismicity. Starting from May 2021, a temporary 19-station short-period network deployment was deployed in Summerville to better analyze spatial variations in microseismicity (Jaume et al., 2021). Preliminary results from microseismicity relocation revealed a south-striking west-dipping zone in the southern seismicity cluster and a north-south striking near-vertical plane further north, indicating complex patterns of stress and faulting styles in the region (Chen et al., 2023). In this study, we apply a newly developed deep-learning polarity picker (Zhai et al., 2021) to measure the P-wave first motion polarities of 181 events detected from one year of continuous data from this deployment. Consequently, these polarity results will be combined with the measured S/P amplitude ratios to determine their focal mechanisms. In addition, we plan to re-analyze the events recorded by the previous deployment (Chapman et al., 2016), with the expectation of better quantifying the fault structures and subsurface stress fields in this region.

Transforming our Seismological Community through Inclusive Mentorship and Diverse Narratives

Oral Session • Tuesday 18 April • 02:00 PM Pacific

Conveners: Richard A. Alfaro-Diaz, Los Alamos National Laboratory (raalfarodiaz@lanl.gov); Kevin Kwong, Los Alamos National Laboratory (kbkwong@lanl.gov); Esteban J. Chaves, Volcanological and Seismological Observatory of Costa Rica (esteban.j.chaves@una.ac.cr); Katherine Scharer, US Geological Survey (kscharer@usgs.gov); Aaron A. Velasco, University of Texas at El Paso (aavelasco@utep.edu)

Geophysical and Sea Level Monitoring in Puerto Rico, an Inclusive Experience

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The Puerto Rico Seismic Network (PRSN) and the Puerto Rico Strong Motion Program (PRSMP) conform the PR network which is the regional authority for monitoring ground shaking and tsunamis in Puerto Rico and Virgin Islands. The mission of the PR is to monitor and rapidly determine the parameters of all earthquakes and support the Tsunami Service Provider (TWC) to determine the Tsunami alert level in the Area of Responsibility, and to immediately disseminate this information to concerned agencies and stakeholders. The PR compiles the microseismic catalogue, continuous waveforms, and earthquake effects which serve as a foundation for basic and applied earth science & oceanography research in Puerto Rico and the Caribbean. The PR net also promote the education and preparedness of our population to mitigate the effects of a significant earthquake or tsunami, working together with local, commonwealth and federal partners.

As part of the University of Puerto Rico at Mayaguez (UPRM) and belongs to the Geology department (PRSN) and Civil Engineering (PRSMP), the PR network is an equal opportunities institution, serving to the population of Puerto Rico and Virgin Islands (primarily), and nearby Latin America and Caribbean countries. Being part of the UPRM allows the PR network hire undergraduate and graduate students, who are trained in all areas of the network from the monitoring to the public service, including research. As part of our goals, the PR network seeks to sponsor and welcomes students from different backgrounds and provides a valuable job opportunity for alumni in their early careers. In this paper we want to describe the mission and vision of the PR network as well as the services and experiences as an University dependency.

From Academia to Industry: How an Underrepresented Seismologist Became a Data Scientist

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The transition from academia to industry is often nonlinear and full of uncertainty. It is a nuanced and stigmatized process driven by culture, finances, geography, and opportunity. Here, I will discuss the tools that facilitated my transition from a seismology postdoc in a Bridge to Faculty Program to an Associate Data Scientist at KoBold Metals, an AI-driven mineral exploration start-up focused on the discovery of critical metals used in electric vehicles and other renewable energy applications. This talk is intended to provide insight into the transition from academia to industry through the lens of my lived experience as an afro-latina, with the ultimate goal of conveying what it means to be a data scientist.

The presentation will be a 5-part chronology: I will discuss (1) my graduate research and the skills I gained and leveraged during my time in academia; (2) the factors that influenced my decision to pursue industry jobs; (3) my job search, including self-promotion strategies and application response timelines; (4) reflections and advice based on my interview experience, as well as the general structure of data science interviews; (5) my daily routine as a data scientist, including skills learned and tools used, analyzing sediment-hosted ore bodies in Zambia, collaborating with geologists and engineers, and contributing to KoBold's numerous exploration projects.

Trying. Failing. and Trying Again. and Again. An Informal Case Study on the Path to Figuring Out What You Want to Do for a Job and Help Others Do the Same.

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Some people know what they want to do for a job from when they are very young. "I want to be a veterinarian" or a football player or a teacher. Maybe somewhere out there is at least one child who said "I want to be a seismologist!" But what does that *actually* mean and what about the wide range of people who don't know until high school, or college, or graduate school, or even later? What shapes our perspectives of employment opportunities? What role models are we exposed to via home life, school, tv and movies, etc. *What do you want to do when you grow up?* I will present one tale about one person who didn't know what she wanted to do when she grew up (have I ever actually grown up?) and how she found employment in a role outside of the "normal" tenure-track faculty path. The path leads from one earth science class in high school and dropping out of college as a math major and currently ends with an enjoyable project management position in network operations, happy to help others find their own path.

Perspectives on the Inaugural Resess Satellite Program at University of Washington

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The RESESS (Research Experiences in Solid Earth Science for Students) Program, which focuses on research and professional development for undergraduates, has been operating for over 15 years. The program aims to increase representation in the geosciences by focusing on students from historically underrepresented groups. Traditionally housed in Boulder, Colorado at the UNAVCO, Inc. facility and the University of Colorado at Boulder, in the summer of 2022, an initial cohort of 4 students were hosted by the University of Washington in Seattle in the RESESS Satellite program. While the original RESESS program in Colorado generally only hosted semester students, the Satellite program opened up the internship pool to quarter system students, expanding the availability of the RESESS program. The Satellite cohort participated virtually in the professional development activities with the group based in Boulder while they performed their research projects in-person over 6 weeks in June-July. Satellite students had a generally positive experience in the program but found areas for improvement. For example, future students may benefit from a longer in-person component and closer alignment in timing of writing activities, which are completed on a separate time-table from the Boulder interns. Broadly, the RESESS Satellite program successfully opened up RESESS to quarter-based undergraduates and will continue with minor adjustments.

Evolving NOAA's Tsunami Warning Center Workforce Towards Improved Service Equity

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Establishing trust is essential to effective communication of emergency information, and evidence supports the idea that trust is more easily built when the receivers are able to relate well to the communicators. The U.S. National Weather Service, parent agency of the two U.S. Tsunami Warning Centers within NOAA, is making a great effort to improve the diversity of its workforce as well as its culture of belonging and inclusion. These changes are aimed at building a workforce that better reflects the communities we serve, and supporting greater service equity, including more effective reach to underserved communities.

Here, we aim to connect with the research community by demystifying the careers of operational tsunami duty scientists as well as drawing connections between research and real-world impacts. Tsunami monitoring is fast-paced multidisciplinary and interdisciplinary work that incorporates seismology, oceanography, volcanology, landslide science, and others as well as requiring good communication skills. We will highlight the wide swath of potential career paths that might lead to our centers, and the importance of having varied expertise and experience in tsunami staff members. Importantly, we also seek input from the science community to better identify and remove barriers to understanding and entering this exciting career path.

Transforming our Seismological Community through Inclusive Mentorship and Diverse Narratives [Poster]

Poster Session • Tuesday 18 April

Conveners: Richard A. Alfaro-Diaz, Los Alamos National Laboratory (raalfarodiaz@lanl.gov); Kevin Kwong, Los Alamos National Laboratory (kbkwong@lanl.gov); Esteban J. Chaves, Volcanological and Seismological Observatory of Costa Rica (esteban.j.chaves@una.ac.cr); Katherine Scharer, US Geological Survey (kscharer@usgs.gov); Aaron A. Velasco, University of Texas at El Paso (aavelasco@utep.edu)

An Online "Careers Module" to Recruit Undergraduate Students Into the Geoscience Workforce With Universal Design for Learning Approaches

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Future career aspirations are often a critical element in the engagement and recruitment of geoscience majors, yet people with marginalized identities face barriers to success. Formal learning spaces seldom incorporate geoscience career information and how to integrate important aspects of one's identity. However, many instructors face the challenge of curating career content in their courses because commonly available materials either highlight a narrow band of job functions or showcase only a limited range of people as interested and able to do the work. To address these issues, we developed an asynchronous online "Careers Module" to increase representation of marginalized groups through introducing geoscience to first-year and sophomore level undergraduate students. The module frames geoscience and geophysics concepts by their impacts on society, highlights diverse role models in professions, and illustrates how different social identities can connect to specific career pathways. The module features videos about geoscience concepts that use inclusive language and diverse representation, skill-building activities such as active bystander intervention techniques, and discussion forums about diversity, equity and inclusion (DEI) topics, such as addressing impostor syndrome. Faculty who use the module with their existing curriculum will be given access to supplementary resources to help facilitate discussions about geophysics, geoscience careers, and the role that DEI plays in our discipline.

We piloted the module with 10 students located at a Historically Black College and University to gauge the effectiveness of the content on learning outcomes. We use pre- and post-surveys, self-reflection assessment questions, and discussion forum responses to evaluate the module. Preliminary data show that we help students to think critically about how their experiences relate to the geosciences and also help them to apply DEI topics to school and the geoscience career content. As a result, 2-3 non-geoscience majors have cited increased interest in the discipline and are considering pursuing a major or minor in the future.

Three Years In: Reflections on Successes, Challenges, and Next Steps for an Employee-Led Diversity, Equity, and Inclusion Working Group at a National Lab

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Along with many scientific organizations, the Earth and Environmental Sciences Division at Los Alamos National Laboratory (LANL) spearheaded a diversity, equity, inclusion, and accessibility working group in 2020 called Geoscientists United for Diversity Equity and Inclusion (GUIDE). We are volunteer-led and open to all employees in our division; our membership includes ~10% of our division employees as well as our division leadership. The goals of GUIDE are to recruit and retain a more diverse staff by building a more inclusive and accessible workplace, community building, and outreach. In this presentation, we share successes that include collaborations with employee-organized affinity groups across the lab, examples of resources we have developed and distributed, and initiatives we recommend implementing elsewhere. We will share challenges that provide learning opportunities for others and encourage broader community feedback that we can implement locally. The strength of our organization lies in community-building activities and the active engagement of management. Our membership skews more early-career than our division as a whole; and those of us with typically underrepresented identities in the geosciences (by race, gender, disability, sexual orientation, religion, and intersections thereof) are overrepresented within our membership. Much of our learning comes from our dynamic group discussions that are informed by a common code of conduct and the experiences of our members. We both mentor and learn from GUIDE members and external resources to advocate for our colleagues and strive to create structural changes within our division, the National Laboratory system, and the geosciences more generally. We plan to initiate more public outreach through this presentation, involve underrepresented institutions, and encourage participation by current LANL staff, external collaborators, and others interested in applying for opportunities at LANL.

Understanding and Managing Induced Seismicity

Oral Session • Wednesday 19 April • 08:00 AM Pacific
Conveners: Ryan Schultz, Stanford University (rjs10@stanford.edu); Ruijia Wang, Southern University of Science and Technology (ruijia.wang@ualberta.ca); Margaret Glasgow, University of New Mexico (mglasgow@unm.edu); Mohammad J. A. Moein, Freie Universität Berlin (mohammad.moein@fu-berlin.de)

Early Oil Production in Oklahoma and California and Its Possible Relationship to Local Earthquake Activity

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During the late 1800s and early 1900s there were discoveries of significant underground oil reserves beneath both Oklahoma and California, and immediately following these discoveries production of the oil started to take place. In this study, a search of existing earthquake catalogs, of published literature and of early newspapers was carried out to look for associations of earthquakes with some early oil production. In Oklahoma the search for earthquakes focused on the El Reno area, just west of Oklahoma City. Early earthquakes were reported there in 1908, 1910, 1918, 1929 and 1933. A major oil find took place in Oklahoma City in 1928, and this find was located about 30 km east of El Reno. Another oil find took place in 1917 about 70 km northeast of El Reno in the Cement oil field. In California, oil was discovered in 1900 between the towns of Los Alamos and Orcutt. A well hit an oil gusher in October 1901. Newspaper accounts indicate that a swarm of earthquakes took place at Los Alamos in July 1902, and the UCERF3 earthquake catalog reports two earthquakes of Mw 5.8 somewhere near Los Alamos in July 1901. In both cases studied, earthquake activity was reported within months of the first oil production, although in Oklahoma the oil production took place several tens of kilometers (or more) from the possibly related earthquake epicenters. In Gazli, USSR it appears that strong earthquakes were triggered at epicentral distances of 20 km or more from the active wells. Perhaps some of these early historical earthquakes took place near the early oil fields and are mislocated due to poor historical data, or it may be possible that oil extraction can induce earthquakes at several tens of kilometers from the production sites.

Integrating High Resolution Crustal Stress Maps and Seismicity Catalogs to Study Injection-Induced Earthquake Sequences in Oklahoma

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Combining a detailed understanding of the stress field with high quality seismicity data is essential for anticipating which pre-existing faults are most likely to fail due to fluid pressure perturbations or poroelastic stressing resulting from fluid injection. In the case of induced seismicity, high-quality stress data enables retrospective analysis of earthquake sequences, including evaluating causal mechanisms and estimating the spatial and temporal evolution of pore pressure changes at seismogenic depths. In this presentation, we show the new generation stress map that we recently published for North America, which includes the first quantitative map of the style of faulting (relative stress magnitudes) across the continent, as well as hundreds of new orientations of the maximum horizontal principal stress (S_{Hmax}). We apply this dataset to study earthquake sequences that occurred in Oklahoma and southern Kansas over the past decade. Of particular interest are remarkable improvements of the seismic catalog by Park and others, who identified over 300,000 events using deep learning methods. This catalog enables improved understanding of earthquake sequences and the geometry of the causative fault networks within the stress field. Across this area, the orientation of S_{Hmax} varies modestly (ranging from ~N060°E to ~N100°E) but is mostly ENE–WSW, and the style of faulting transitions from normal/strike-slip in southern Kansas to nearly pure strike-slip in central Oklahoma. The orientations of active faults, as indicated by earthquake focal mechanisms and groups of earthquake locations defining fault planes, are generally near-optimal for failure within the mapped stress field; we find that most faults likely required 2 MPa or less to fail. In addition to its utility for understanding and managing induced seismicity, we discuss potential applicability of the improved stress mapping for characterizing natural seismic hazards.

Cooperative Seismic Monitoring & Earthquake Response for Saltwater Injection Operations in Texas

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Saltwater disposal needs in Texas saw tremendous growth since 2007 due to the success of new drilling and fracturing techniques undertaken in the Dallas/Fort Worth area. Seismic activity in that area increased soon after. Elevated seismicity was also observed in South Texas during the completion of oil gas wells as early as 2011. The Permian Basin saw even more dramatic increases in activity, with the frequency and magnitude of basement-depth earthquakes accelerating in 2019 when deep injection was increasing, culminating with two magnitude 5.4 earthquakes in late 2022.

The State of Texas established funding for TexNet in 2015 to improve the state's seismic network, growing from 18 stations to nearly 150 stations by mid-2020, increasing resolution and accuracy to help characterize seismic activity near wells in the vicinity of faults.

The Texas oil and gas regulator introduced an incentive program to allow operators to maintain higher daily injection volumes by installing seismic stations to feed additional data to TexNet, and by developing an earthquake response plan for their area of interest.

This cooperative industry-funded seismic monitoring approach is how the Seismology Research Centre (SRC) established its network since the late 1970s. Individual water authorities, who could not afford to fund a network to monitor their areas of interest, were brought together and contribute proportionately to the operation of a broader network. The data was centrally processed by SRC, and the authorities are provided with bespoke information in near real-time for emergency response.

The SRC's local seismic monitoring workflow and data management system lent itself perfectly for operators in Texas to establish and manage private seismic arrays to determine earthquake locations and magnitudes. The data from these operator-managed networks is also streamed to TexNet's public network in real time as a permit condition of the regulator's incentive program. Between 40 and 50 stations have been added to TexNet through this program, providing greatly increased capabilities for seismic event management and emergency response.

En Echelon Faults Reactivated by Wastewater Disposal Near Musreau Lake, Alberta

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We use machine learning and cross-correlation techniques to enhance the earthquake detectability by two magnitude units for the earthquake sequence near Musreau Lake, Alberta, which is induced by wastewater disposal. This deep catalogue reveals a series of *en echelon* ~N-S oriented faults that are favorably oriented for reactivation as strike-slip events. These faults require only ~0.6 MPa overpressure for triggering to occur. A temporal increase in seismicity response is caused by sequential reactivation of these faults. Episodes of fault activity tend to have earthquakes progressing towards nearby injectors. Together, these findings suggest pore pressure diffusion as the triggering mechanism. Analysis of the "next record-breaking event", a statistical model that forecasts the sequencing of earthquake magnitudes, suggests that the next largest event would be M_L ~4.3. The seismically illuminated length of the largest fault suggests potential magnitudes as large as Mw 5.3.

Causative Fault and Seismogenic Mechanism of the 2010 Suining M5.0 Earthquake in Sichuan Basin (China) from Joint Modeling of Seismic and InSAR Data

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Although the Sichuan basin in western China is a stable block with low historical seismicity, the Suining M5.0 earthquake on January 31, 2010 occurred near center of the basin, causing casualty and substantial damage. Previous studies have shown that the earthquake is very shallow and may occur in the sedimentary cover rocks, but its causative fault has not been identified. Based on local broadband seismic waveform data as well as a pair of ALOS PALSAR ascending orbit data, we exploresthe seismogenic mechanism via further constraining the source depth and the ruptured faul. The earthquake caused ground uplift in the southeast of the epicenter area, with maximum line of sight displacement of about 13.6 cm, much larger than the displacement caused by a M5 earthquake at typical depth of 10 km, which indicates that the earthquake is very shallow. Through joint inversion of seismic waveform and InSAR data, we obtain the moment magnitude of Suining earthquake as Mw4.5, with the strike, dip and rake of its fault plane as 17°, 66° and 90° respectively, and the centroid depth less than 1 km, supporting that the earthquake occurred at the shallow part of a high angle thrust fault dipping to southeast. It is further confirmed that the earthquake may be triggered by the diffusion of high-pressure fluid migrating from the underside gas reservoir.

Seismogenic Fault Characterization of the Quinton Sequence in East Oklahoma

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Over the last several years, we have recorded 1309 earthquakes ML 0.2-3.7 over the time period, near Quinton, OK. The seismic activity temporally coincides with the both the injection of wastewater from a single disposal well and adjacent hydraulic fracturing activity. The catalog locations suggest seismicity occurs around two parallel NE striking faults. However, due to the sparse regional seismic network in the area with poor azimuthal coverage, the seismicity hypocenters are poorly constrained for them to map onto the seismogenic faults or provide a conclusive spatiotemporal occurrence pattern. We re-analyze the seismicity by augmenting the regional broadband sensor network, operated by the Oklahoma Geological Survey, with two seismic arrays each composed of 15 3-component nodes recording for 35 days in July 2021 to assist in constraining the hypocenters. We relocate 1,300 earthquakes of magnitude ML0.2-3.7 using a double-difference scheme and a local 1D velocity model to unravel the seismicity patterns, delineate the seismogenic faults and perform source characterization. Preliminary analysis indicates clustering of earthquakes in three main fault segments, oriented in a NW direction, that linearly align to form an apparent NE striking fault zone. The spatiotemporal evaluation of seismicity indicate seismicity begins at the central fault segment that underlies the lateral positioning of the hydraulic fracturing wells and begins in a period when both hydraulic fracturing and waste fluid disposal activities occurred concurrently. Upon suspension of hydraulic fracturing activities, the seismicity then expands to the SW fault segment and later extends to the NE fault segment. Two earthquake swarm in the later period of the waste fluid disposal occur on the NE and SW fault segments respectively, reversing the spatial migration of seismicity with respect to the beginning of the sequence and coinciding with a period of reduced injection rates. We will present updated analysis that could highlight possible linear fault structures within the seismogenic fault zone.

How Comparable Are Frequency-Magnitude Variations of Natural and Induced Seismic Sequences? A Comparison for the Tectonic Gyeongju and Induced Pohang Earthquake Sequences.

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Induced seismic events are driven by anthropogenic, external forcing that increases stress and/or reduces the strength on seismogenic faults. One of the main processes inducing earthquakes are elevated fluid pressures related to industrial fluid injection. In contrast, natural events are the result of stationary plate tectonic motions causing constant stressing of a seismogenic fault. Though the stressing history of induced seismic sequences are fundamentally different from tectonic, the fluids predominantly trigger the release of preexisting tectonic stress. Hence, an important question from a seismic hazard point of view is the extend to which the evolution of the seismic sequences is set by the elevated fluid pressures.

To gain insight into the fundamental impact of the physics controlling the evolution of natural and induced seismic sequences, we assess the observed spatial and temporal patterns of faulting and the frequency-magnitude distribution evolution of the fore- and aftershock sequence of the 2016 M_w5.4 Gyeongju tectonic earthquake and the 2017 M_w5.5 Pohang induced event. We particularly concentrate on the spatio-temporal evolution of the foreshock sequence, as the identification of a fundamental influence of the elevated fluid pressures could provide important indications for early mitigation of potential future induced events due to fluid injection.

Annual Seismic Hazard and Risk Forecasting for the Groningen Gas Field: Public Domain SHRA by the Geological Survey of the Netherlands

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The Groningen gas field (Europe's largest gas field) is being shut down in the near future due to ongoing societal concerns about the seismicity that has been induced by the gas production. Current gas production levels are at ~5% of the historical peak and are fully determined by the Dutch government based on security of supply. The Geological Survey of the Netherlands has been tasked with providing an annual update of the public Seismic Hazard and Risk Analysis (pSHRA), based on the forecasted production strategy for the envisioned end-of-production and beyond. This pSHRA includes a spatiotemporally varying seismicity rate model and associated magnitude distribution, hazard calculations based on location-specific Ground Motion Model (GMM) with a high-resolution site-response model, and a Local Personal Risk calculation for the 150,000+ buildings in the area. These calculations include a logic tree that currently has 1008 unique paths and will likely expand to 9072 unique paths for the upcoming pSHRA calculation due to the introduction of a new GMM. The (anonymized) results of the annual pSHRA are published and are legally required to be considered in determining the gas production levels. To ensure complete traceability and reproducibility of the pSHRA results, every run of the software is stored and backed up including all input files, configuration settings, and a reference to the version control system of the source code. In this presentation, we discuss the role of a Geological

Survey in such a societally debated context and share lessons learned about different facets of public SHRA, ranging from QA/QC and software design to the importance of (national) safety norms and an integrated model view in a modular chain of models. Finally, we look ahead, both to the Groningen case and to applications beyond, such as Geothermal and CCS.

Evolution of Short-Term Seismic Hazard in Alberta, Canada, From Induced and Natural Earthquakes: 2011–2022

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During the last decade, there has been an increase in seismic activity in the province of Alberta, Canada. This rise in seismic activity has mainly resulted from induced earthquakes related to particular hydraulic fracturing and water disposal injection wells operating in the development of shale oil and gas plays. The seismic hazard related to induced seismicity could be higher than the natural seismic hazard, especially in areas with small-to-moderate natural seismicity. To properly characterize the seismic hazard resulting from incorporating induced earthquakes, we generated short-term seismic hazard maps from 2011 through 2022 for the province of Alberta. We adapted the traditional Probabilistic Seismic Hazard Analysis, which is typically designed for long time frames (for instance, 50 years), to generate annual seismic hazard maps that can be used to better capture the shorter-scale human-induced seismicity. We found that the seismic hazard maps have been dominated by induced seismicity cases, including hydraulic fracturing activities in the Duvernay Fm., near Fox Creek, and water disposal activities near the Musreau Lake. Short-term retrospective seismic hazard maps provide an instrument to quantify and report changes in the seismic hazard at a regional scale, which is especially important considering past and emerging induced seismicity cases related to the energy industry in Alberta.

Lessons Learned From Monitoring of Reservoir Triggered Seismicity in Tectonically Stable and Seismically Active Areas of Vietnam

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Water reservoirs play important role in energy production in Vietnam. Numerous dams were designed and built for hydropower plants and water storage. We conducted seismic monitoring and research on two sites: first, the tectonic active area of Lai Chau (North Vietnam) and the relatively stable area of Song Tranh in Central Vietnam. We observed different seismicity patterns in these areas. The area of Lai Chau was less active in terms of reservoir triggering, while the almost aseismic area of Song Tranh was highly active after reservoir impoundment. The latter activity was related to seasonal water level changes in the reservoir. Moreover, a low water period during service works was proved to be more active and with significantly higher seismic hazard than during the production regime. It suggests that a decrease in water level and following pore-pressure change destabilize minor faults being closer to failure than main faults in the area. It is confirmed by finding multiplets triggered on minor normal faults. Seismic activity in the area of Lai Chau was observed on both existing active strike-slip faults and minor normal faults. However, the difference between seismic activity parameters before and after impoundment except for spatial distribution directly after the first filling didn't differ substantially. Moreover, the influence of the reservoir filling was very limited in short distances from the reservoir in terms of Coulomb stress changes due to water level variations. We can conclude, that in a stable tectonic setting triggering effect is clear and related to pore-pressure changes caused by reservoir water level fluctuations. On the other hand in active seismic area reservoir influence seems to be too small to significantly change seismic activity in the long term.

This work was supported by the research project no. 2021/41/B/ST10/02618, funded by the National Science Centre, Poland under the agreement no. UMO-2021/41/B/ST10/02618.

Fluid Injection Induced Seismic and Aseismic Slip From a Coupled Poroelastic Stress Change and Rate-State Fault Model

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Fluid injection in unconventional hydrocarbon resource exploration can introduce poroelastic stress and pore pressure changes, which in some cases may lead to aseismic or seismic slip on pre-existing fractures or faults. In this study, we examine the relative roles of the above processes in triggering earthquakes by coupling poroelastic stress changes with the rate-state friction framework to simulate slip evolution on a pre-existing fault under stress perturbations.

Assuming an injection source of constant rate and finite period at depth, a receiver fault at distance experiences an initial clamping phase (effective normal stress increase) followed by unclamping (effective normal stress decrease) resulting from fluid diffusion. We then introduce the stress perturbation, including pore pressure, normal and shear stresses, onto a fault governed by rate-state friction, and characterize fault response by the maximum rate and timing of the triggered slip event. Our preliminary results show that higher-amplitude perturbations generally trigger events with higher slip rates and earlier occurrences with respect to the unperturbed reference slip cycle. However, seismic slip rate is always reached when the receiver fault is in the unclamping phase, suggesting the importance of pore pressure increase in destabilizing faults. Stress perturbations (tested up to 30% of background normal stress) introduced early or late in the reference cycle result in aseismic slip; only those introduced in the middle of the cycle can trigger seismic slip, which may reflect the interaction between the timescales of stress perturbation and fault frictional processes. Finally, the receiver fault with a larger influenced area can develop into a seismic event, whereas the fault with smaller influenced areas may remain aseismic despite increasing perturbation amplitudes. Our modeling results suggest optimal design of injection parameters could be critical for preventing the onset of seismic slip.

Combining 3D Dynamic Rupture Modeling and Thermo-Hydro-Geomechanical Modeling Towards Physics-Based Induced Earthquake Simulations

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Geothermal systems, offering sustainable sources of energy, are important building blocks of climate change mitigation strategies, but are challenged by the possible occurrence of induced earthquakes of potentially large societal and economic impact. Hence, the operational success of geothermal systems depends on the development of effective strategies to mitigate the hazard of induced earthquakes. Physics-based numerical modeling can allow a holistic understanding of injection and production operations, earthquake nucleation, propagation, and arrest, and complement empirical guidance, e.g. provided by traffic light systems. However, the physical processes associated with cold water injection and earthquakes occur on vastly different time scales and are governed by distinct physics, challenging numerical models. Here, we demonstrate the feasibility of linking complex 3D thermo-hydro-geomechanical (THM) and dynamic earthquake rupture models. We model exemplary pore pressure, temperature, and stress evolution during injection over decades using the open-source THMC sImulator for GEoscience Research (TIGER), which solves the THM coupled processes in geothermal reservoirs. Our model results suggest that stress can deviate significantly from the background stress at the reservoir scale. Specifically, a localized pore pressure increase of several MPa builds up near the injection well, which results in a sizable effective normal stress change, able to nucleate an earthquake. Using the dynamic rupture and seismic wave propagation code SeisSol, we initialize 3D dynamic rupture simulations from the stress state of the geomechanical models. Depending on the assumed friction law parameterization, a wide range of rupture behavior, including spontaneously arrested or runway ruptures, are modeled. We discuss how geomechanically constrained dynamic rupture simulations can address key problems, such as the maximum physi-

cally plausible earthquake magnitude in a georeservoir, and coupling strategies for multiple events towards digital twins of geothermal systems.

Modelling Induced Seismicity in the Hengill Geothermal Field

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The Hengill Geothermal Field is located in Southwest Iceland and hosts the Hellisheiði and Nesjavellir power plants. The area is characterized by a complex triple junction between three tectonic features: the Reykanes Peninsula rifting, South Iceland Volcanic Zone and West Volcanic Zone. The geothermal field comprises 60+ production wells and 17 injection wells. Significant seismicity, both natural (volcanic uplift event in the 1990s) and production/injection induced is recorded. The beginning of the reinjection in the Húsmúli area in 2011 was associated to a seismic crisis. A high resolution catalogue covering the first nine months of injection allows us to have a look at the dynamics of the seismicity and to characterise the fractures and state of stress of the area. We attempt to model this onset of induced seismicity using a hybrid coupled hydro-geomechanical model (TOUGH2-Seed). In the framework of the Geothermica project COSEISMIQ (http://www.coseismiq.ethz.ch/en/home/), a dense temporary network was installed to monitor the seismicity in the Hengill region between December 2018 and August 2021. With this enhanced network, novel analysis and relocation techniques, a high resolution relocated catalogue was curated and comprises around 8500 events in the Hengill area. We use a Seismogenic index type model and different flavours of Epidemic Type Aftershock Sequence (ETAS) to model the natural and induced seismicity during the two and a half year period. We employ a pseudo-forecasting approach and compare models performances and fit to the recorded seismic data to assess the strengths and weaknesses of the different models.

Deep Learning Phase Pickers: How Well Can They Detect Induced Seismicity?

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Deep learning phase picking models can efficiently process large volumes of data typically produced during microseismic monitoring. These models have detected earthquakes not cataloged by existing traditional methods (e.g. STA/LTA, autocorrelation). Additionally detected earthquakes can affect the statistical properties of a catalog (e.g. b-value) which is important for seismic hazard assessments. Deep learning enhanced catalogs may help us study different driving mechanisms of hydraulic fracturing induced seismicity (HFIS) by observing the spatiotemporal evolution of HFIS in greater detail. We compared four existing models (GPD, U-GPD, PhaseNet and EQTransformer) pre-trained on large volumes of regional earthquakes recorded on surface station datasets (100 Hz) and investigated how well they identify seismic phases in high-frequency (2000 Hz) borehole array data. The PNR-1z dataset comprises continuously recorded injection operations at a hydraulic fracturing site in Preston New Road, UK, where operators cataloged >38,000 events using the Coalescence Microseismic Mapping (CMM) method. We generated earthquake catalogs for the PNR-1z dataset to compare (benchmark) against this initial catalog.Results show that some models, particularly PhaseNet, detects seismic phases robustly within our data: they recover up to 95% of the initial catalog and detected >15,800 additional events (36% increase). PhaseNet's robust application on our dataset could be due to its exposure to different instrument data during training, as well as its comparatively small model size which likely reduces overfitting to its initial training set. The GPD, U-GPD and EQT models require fine-tuning or re-training to detect more microseismic events. We conclude that PhaseNet can be applied off-the-shelf to detect HFIS in high frequency borehole data. The newly detected events could reveal new insights into the mechanisms controlling the spatiotemporal evolution of seismicity during fluid injections.

Shake, Squeeze, and Rumble: Geophone, Hydrophone, and Microphone Observations and Physics of Engineered Geothermal System-Induced Hhz Microearthquakes.

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Three seemingly independent observations of 200-800 Hz signals from an EGS stimulation in Finland basement rock have a common source. The observations come from: a 1.9-2.4 km deep geophone array; a hydrophone array in a nearby shallow bay; and microphones at several places around the bay, all with sampling rates at or above 2 kHz. The common source is 5-6 km deep injection induced microearthquakes directly beneath these sensors. (An audible rumble was produced by wave energy trapped in the bay.) The full-duration spectra of these events appear as a symmetrical hill centered on 500 Hz, declining to 200 and 800 Hz on its flanks. Superimposed on the spectral hills are rapidly changing fluctuations originating in the ~4-second codas following the direct waves. Coda fluctuations are absent from the spectra of the direct P-wave displacement waveform. For those familiar with the empirical Green's functions of multiplet earthquakes, the MEQ spectra can be understood as the result of a sequence of closely spaced impulse emissions – the Shah Function of signal analysis. However, the actual source physics of induced hHz displacement signals is more novel: the displacement motions of the P wave arising from bi-directional slip in ambient crustal fractures - as initiated by EGS fluid injection. In other words, the initial radial source-volume dislocations are followed in a few milliseconds by reverse-direction radial source-volume dislocations. Here 'ambient' means fractures unrelated to planer faults – i.e., fractures in country rock far from active faults. The borehole array first motion P-wave displacement can be fit with a Haskell's model of far-field displacement by summing over volumetric source dislocations. The hHz event-versus-size distribution follows the lognormal distribution of ambient crustal fractures. We suggest these events form a new class of fracture-permeability-related seismicity highly relevant to the development of Engineered Geothermal Systems.

Understanding and Managing Induced Seismicity [Poster]

Poster Session • Wednesday 19 April

Conveners: Ryan Schultz, Stanford University (rjs10@stanford.edu); Ruijia Wang, Southern University of Science and Technology (ruijia.wang@ualberta.ca); Margaret Glasgow, University of New Mexico (mglasgow@unm.edu); Mohammad J. A. Moein, Freie Universität Berlin (mohammad.moein@fu-berlin.de)

Adaptive Spectrum Analysis for a Precise Attenuation Parameter Estimation on the Induced Seismicity Recorded at Puerto Gaitán (Colombia)

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In the last few years there has been a growing interest in the seismicity within the intraplate settings caused by natural processes and anthropogenic activity. Since 2013 a significant increase in seismic activity has been detected and associated to reinjection of wastewater of ~477000 m^3 a day at Puerto Gaitán. The operator installed a local seismic network composed by 22 broadband triaxial stations surrounding the injection wells. Through this network, more than 7000 shallow earthquakes were recorded between 2013 and 2016. We are interested in estimating seismic attenuation and its temporal variations, but before being able to do an attenuation tomography, our main objective is to focus on robustly determining: (1) hypocentral parameters and (2) source spectra and other spectrum characteristics to better select the optimum band range for studying attenuation properties. To achieve this, the processing flowchart implemented here involves a precise earthquake locations and spectral methods to determine earthquake source and attenuation parameters using a proposed adaptive window analysis. In this work, we will present the processing techniques carried out as inputs of the tomography study.

Controlled-source Seismic Imaging of McMurdo Ice Shelf Near Williams Airfield

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Understanding the structure and thickness of the McMurdo Ice Shelf and the ocean environment below is important from an operational as well as a scientific perspective. The McMurdo Ice Shelf is part of the Ross Ice Shelf, and ice shelf mass loss has been observed due to warming ocean conditions in the Ross Sea. During December 2021, the Thwaites Interdisciplinary Margin Evolution (TIME) project team collected a controlled-source seismic survey along an 1150-meter-long line near William's Airfield on McMurdo Ice Shelf. We deployed twenty-four Magseis Fairfield, Z-Land Generation 2, 5-Hz, 3-component seismic nodes at 50-m spacing for 30 days. During one day, we used a 12-lb sledgehammer as a seismic source at 23 locations, with 3 hammer strikes at each location to stack and enhance the signal. The seismic nodes also recorded a variety of passive seismic sources, including icequakes and anthropogenic seismic sources like vehicle and airplane traffic. We process the controlled-source refraction data to develop a velocity model of the ice shelf and environment below. We use Python ObsPy tools to visualize the seismic data and make observations about the data quality and wave propagation. The survey was also a methods test for the use of seismic nodes for ice shelf (and glacier) imaging with controlled sources, and we discuss lessons learned for future deployments such as those planned by the TIME project for Thwaites glacier in 2022-23.

Data Mining Microseismicity Associated to the Blue Mountain Geothermal Site

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Induced seismicity in geothermal sites seems to be strongly correlated to changes in energy production rates. Interestingly, evidence of increasing microseismicity during geothermal power plant outages has been observed worldwide. Seismic studies in these areas provide several hypotheses mostly based on fault slip induction by changes in pore pressure. However, geological dissimilarities between regions halt assumptions of a unique stress mechanism for this phenomenon. Past methods like microearthquake location mapping have proved useful in delineating subsurface structure in these systems and understanding pathways for injection flow. Nevertheless, the stress changes triggering these events remain unclear in some cases. We apply PageRank, a data mining technique, to assess microseismic event connectivity and evolution at the Blue Mountain geothermal site during the 2017 and 2018 stimulations to understand the origin of increased seismicity on-site during annual power plant shutdowns (September 2017 and May 2018) and other power plant operations. We use directly (CC >= 0.67) and indirectly (CC < 0.67, linkage stations >= 6) links events to a reference event, a high PageRank event leading a seismic cluster. Cluster characterization from 2017 resulted in six unique families comprised of three or more microseismic events with similar waveform topology, with one of these families related to the September outage. For 2018, six unique families were identified comprised of two or more events. Four of these families are related to the May outage. In addition, for both years, indirectly links events within our identified unique families show a similar waveform pattern, confirming their belonging to the cluster. Event relocation within clusters will show a more clear picture of stimulation changes, and will help understand why large numbers of events are happening during the power plant shutdowns.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-ABS-843429

High-Resolution Induced Earthquake Catalogs Reveal Non-Planar Faults Near Hydraulic Fracturing Wells in Canada and China

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The development of portable nodal arrays in recent years greatly improved the seismic monitoring ability across multiple scales. The dense arrays also directly benefit microseismic monitoring, providing relatively low-cost surface recordings. In this study, we utilized a machine-learning based workflow to investigate the M<3 events during hydraulic-fracturing (HF) stimulations. Two datasets are analyzed: (1) 33-day recordings from 69 shallow-buried nodes within 5 km of an HF well in the Western Canada Sedimentary Basin (i.e., Toc2ME, 2016); (2) one-weak recordings from up to 85 surface nodes within 10 km of an HF well in the Sichuan Basin, China (i.e., WYC, 2021).

As a result, we detected ~20000 and ~3000 events from the two datasets with relative location errors constrained to meter scale. The event magnitudes range from -2 to 3 for both cases, consisting of both microseismicity and induced earthquakes. Correspondingly, our high-resolution catalogs reveal both the fractures and unmapped short fault segments (i.e., length < 1 km). The structures show strong heterogeneities and non-planar features. A large number of detected events in the high-resolution catalog also permit a detailed investigation of the statistical behavior of different clusters. As expected, we observed higher b-values and lower temporal Cv (coefficient of variance) from fracture-hosted microseismicity. Our comparisons revealed similar and distinctive features from the two HF sites. Aside from the results, we summarized our experience and provided recommendations for applying similar approaches to other local-scale, surface microseismic monitoring. The presented results will benefit induced seismicity regulation by filling the gap between microseismic monitoring and independent case studies of larger events.

Induced Seismicity in Southeastern New Mexico

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Since 2015, the Permian Basin in southeastern New Mexico and western Texas has experienced a surge in seismicity that is continuing to rise. In 2022 the rate of M3+ earthquakes in the Permian was higher than in California. Most of the seismicity lies within the Texas portion of the Basin, including the three M5+ earthquakes that have occurred to date. While the seismicity rate in the New Mexico of the basin is lower than Texas, significant seismicity has been occurring the area, including a M4 earthquake. In response to the growing seismicity southeastern New Mexico, the USGS in collaboration the New Mexico Bureau of Geology deployed a 14-station seismic network in the region. With this network, we have detected and manually located over 1400 earthquakes, many of which lie in New Mexico. Machine learning methods have also been used to generate a catalog of earthquakes, increasing the number of events detected by an order of magnitude. Here we will present analysis of this seismicity, including a new velocity model, a fault map, and stress inversion.

Investigating Complex Triggering in the Midland Basin, Texas, Using Converted Phases

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Intraplate seismicity in previously aseismic areas within the Permian Basin, Texas, has steadily increased since 2009 (Frohlich et al., 2020) and now outpaces California. The Midland Basin, the eastern lobe of the Permian, has experienced multiple moderate magnitude earthquakes (M4-6), including the recent 2023 M5.4. While it is generally accepted that oil and gas development is linked to the seismic activity, and saltwater disposal (SWD) is a significant triggering mechanism in the Midland basin, understanding if it is the shallow (<1.5 km subsurface) or only the deep (2.3-3.4 km subsurface) injection practices that require mitigation remains an open question. The problem is complicated by uncertainties in earthquake depth of +/-3 km that reflect changes in network geometry in space and time and complicated basin geology. Here, we use body wave conversions common for shallow earthquakes in the sedimentary basins that can be extracted as a third arrival for constraining epicentral depths. We present a series of synthetic seismograms used to investigate depth to conversion interfaces and gain an intuitive understanding of the subsurface. This study utilizes REFSEIS, a reflectivity based program designed to generate synthetic near and far field seismograms over prescribed event-station distances; flexible 1D Vp, Vs, density, Qp and Qs; and moment tensors. We explore Midland Basin specific velocity models and moment tensor solutions to generate a suite of synthetic seismograms to forward model how the waveform is influenced when the source depth and source to receiver

distance changes. The synthetic dataset then guides analyst identification of converted phases for use in relocation studies.

Investigating the Triggering Mechanism of the 2019 Mw 5.0 Earthquake in the Weiyuan Shale Gas Field, China

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Understanding the triggering mechanism of damage earthquakes related to hydraulic fracturing (HF) is critical for seismic hazard mitigation, which highly relies on high-resolution earthquake catalogs and detailed production data. To address the triggering mechanism of the largest earthquake (Mw 5.0) in the Weiyuan shale gas field, Sichuan, we conduct an earthquake relocation and template-matching study. We first refine the local 1-D velocity model and absolute earthquake locations using phases recorded by the five closest stations that are within 10 kilometers of the Mw 5.0 event. We then conduct double-difference earthquake relocation to improve the catalog. Our results show that the Mw 5.0 event nucleated at a depth of 4.5 km, which is 1.8 km below the fracking layer. To identify more earthquakes, we conducted template-matching detection using 334 templates in the vicinity of the Mw 5.0 event. We find 40 times more events with the lowest magnitude of $M–_L$ -1.4. We observe plenty of earthquakes on the NE-striking Mw 5.0 fault plane in the depth range of 3.0-4.5 km that occurred 6 months to 1 month before the mainshock. After a quiescent period with no on-fault earthquakes from -30 to -8 days and few earthquakes since -8 days, the Mw 5.0 occurred as a sudden shock. Analysis of earthquake catalog and injection data support our inference that pore pressure increase due to fluid diffusion contributed to the weakening of the fault plane and the Mw 5.0 event is a delayed triggered earthquake. Our study emphasizes the importance of identification of basement faults and monitoring hydraulic fracturing activities to avoid potential destructive earthquakes.

OhioNET: A Decade of Induced Seismicity Monitoring in Ohio

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Since the development of the OhioNET seismic network in 2012, there have been numerous induced seismicity cases identified across Ohio. To cope and prepare for the increased need for regulatory oversight, much of the work done with OhioNET focuses on generating high quality seismic data to guarantee the ability to accurately evaluate seismic events in or near real-time for both wastewater disposal areas and unconventional oil and gas producing zones in Ohio. As induced seismicity has evolved as a field of study over the last decade, there have been many challenges posed to regulators, industry, and academia on how to best manage, mitigate and take proactive steps to build a culture of safety surrounding oil and gas extraction. By implementing best practice strategies developed through collaborations, ODNR has demonstrated improvements in regulatory policies and framework for oil and gas operations in the Utica shale and contributed to an overall seismic risk reduction for the state.

Optimising Earthquake Detection Methods in Delaware Basin, Southeastern New Mexico

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Recent increases in seismicity due to anthropogenic activities in southeast New Mexico have demonstrated the need for timely earthquake detection and updated catalogs of seismicity in this region. Previously earthquake detection and location in this region was performed manually; automated methods can improve efficiency, accuracy, and completeness of earthquake catalogs, which is essential to understanding and reacting to induced seismicity. This study aims to test several existing automated earthquake detection tools such as the template matching technique and the Earthquake transformer machine learning tool to assess the efficiency of these tools in event detection within our seismic network in southeast New Mexico. The template matching tool uses a cross-correlation based scanning algorithm that compares known earthquake events to continuous time series data at a given station. The study will incorporate continuous waveform data of several seismic stations from multiple seismic networks such as New Mexico Tech seismic network, USGS, Nanometrics research network and Texas seismological network for the year 2021 and evaluate the detections from multiple stations to generate an earthquake detection catalog. We will also test a global deep leaning tool, the EQTransformer which simultaneously detects earthquakes and picks P and S phases on single station data at local epicentral distances using neural network mechanism on the same dataset. These automated detections from the two methods will then be compared with an earthquake catalog derived for the study period through manual analyst review. We will use these catalog comparisons, specifically the numbers of missed and false detections, in conjunction with ability to implement the automated tool within our routine network operations to select an appropriate automated tool for the network. This automation will advance our ability to provide the timely earthquake detection and location that is needed in this important region of the Delaware basin.

Signatures of Congregated Injected Fluid in Weiyuan Shale Gas Field, Sichuan, China

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Hydraulic fracturing (HF) is a viable technique to stimulate the productivity of unconventional hydrocarbon resources. However, the mobility of injected fluid in HF plays a critical role in controlling fault reactivation and consequently induced seismicity. Yet tracking the injected fluids underground remains challenging because of the limited resolution in traditional approaches. In this study, we attempt to investigate the possible controlling mechanisms of induced seismicity in the Weiyuan shale gas field in Sichuan, China using a dense temporary seismic network that was deployed between April to June 2020. We apply the frequency index and template matching technique to analyze the impact of injected fluid on event waveforms and classify them based on the low/high-frequency components. We assess the potential controlling mechanism of these waveforms, including source, path, or injected fluid, and evaluate with waveform analysis. Our results reveal that low-frequency waveforms (LFW) are prominent in a certain azimuth range which rules out the possibility of source effects. Meanwhile, most of these LFW are constrained temporally and spatially and unlikely to be path effects. Furthermore, waveforms from nearly collocated earthquakes at different depths have distinct frequency contents. P phases are relatively unaffected, compared to highly attenuated S phases which suggest that absorption might be a key factor, instead of scattering. We identify a zone with congregated fluid near a few hydraulic fracturing platforms which might be responsible for LFW when ray paths encounter. Such fluid may trigger delayed seismicity or upward fluid migration which poses challenges to establishing an effective mitigation strategy for potential seismic risk.

Time-Space Evolution of the Groningen Gas Field in Terms of b-Value: Insights and Implications for Seismic Hazard

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The Groningen gas field, located in the north-east of Netherlands, is the Europe's largest onshore gas field. It was discovered in 1959 and production started in 1963: continuous production leads to reservoir compaction and subsidence, gradually loading pre-existing fault and induced seismicity started about 30 years into the production. The seismic hazard and risk related to the induced seismicity is determined not only the rate of activity, but it is equally influenced by the relative size distribution of the seismicity, the b-value. I re-analyze the spatial and temporal evolution of the b-value in the field using an alternative approach to overcome magnitude in completeness heterogeneity and link it to the evolution of fault loading and subsidence. Spatial variations of b-values are found to vary between 0.61 and 1.3, with lowest observed values observed in the location of the 2012 Huizinge M3.6 earthquake. In the last 10 years, the mapped b-value are more homogeneous throughout the field.

The spatial and temporal evolution of the b-value in the field is shown in this study to be quite complex and systematically linked it to the evolution of fault loading, absolute compaction and the rate of compaction, an important finding that offers new insights into hazard reduction and mitigation strategies of extraction relation induced seismicity. Compaction rates below 2 mm/year are not correlated to seismicity above M 2.0 in the history of the field, suggesting that low volume production may be safer than previously assumed.

Variation of Earthquake Nucleation Length of Injection-induced Seismicity Under the (Aging) Rate and State Friction Law

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Earthquake nucleation length, a critical length characterizing the transition from the quasi-static propagation to the rapid dynamic rupture process of the nucleation zone, is reported to reduce with the elevated loading rate. Recently, laboratory injection experiments showed that injection can also be regarded as a kind of "loading" condition and high-rate injection would reduce the nucleation length of injection-induced seismicity. Motivated by this, in this study, we systematically explored the variation of the nucleation length of injection-induced seismicity under various conditions (different hydraulic diffusivity and injection rate) with the 2D and 3D injection-induced seismic simulations based on the (aging) rate and state friction law. Interestingly, similar to previous work, nucleation regimes of injection-induced seismicity can also be classified into two regimes based on the value of Ω ($\Omega = V\theta/Dc$, i.e. the ratio of the weakening to healing rates) in the center of the nucleation zone. When $\Omega >> 1$, or, in the "no-healing" regime, nucleation length seems to be smaller for seismic events associated with higher injection rate or lower hydraulic diffusivity. However, its evolution would be different when the value of Ω is close to 1. When $\Omega \approx 1$, or, in the "constant weakening" regime, nucleation length is affected by how long the state of the fault stays in this regime. In our study, the nucleation length is smaller for seismic events related to higher hydraulic diffusivity, and shows no correlation with increasing injection rate (but still smaller than the theoretical upper limit derived based on the fracture energy balance theory). Our study shows the similarity between injection-induced seismicity and natural earthquakes in the nucleation process and preliminarily explains the underlying reason for the variation in nucleation length of the injection-induced seismicity.

Understanding and Modeling the Uncertainties in Earthquake Ground Motions

Oral Session • Thursday 20 April • 10:00 AM Pacific

Conveners: Morgan P. Moschetti, U.S. Geological Survey (mmoschetti@usgs.gov); Grace Parker, U.S. Geological Survey (gparker@usgs.gov); Fabrice Cotton, GFZ Potsdam (fcotton@gfz-potsdam.de); Olga-Joan Ktenidou, National Observatory of Athens (olga.ktenidou@gmail.com)

Between and Within-Site Variabilities: How Large Are They? How Far Can We Reduce Them?

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An important component of the variability of seismic motion is related to the effect of surface layers. This site variability has two components: the between-site variability and the within-site variability.

The between-site variability is the spatial variability in the average site response (over multiple events) across many sites in a data set. The between-site variability is mostly epistemic means that its value is equal to zero if the amplification is known at all sites ("non-ergodic" case with many recordings at the considered sites). For sites where no or few records exist, we will never be able to perfectly reproduce the full complexity of real amplifications. The reduction of the between-site variability is then depending on the method used to derive the amplification (1D modelling, empirical prediction based on proxies like vs30, machine learning). We will show a recent compilation of observed between-site variabilities in Japan and Europe and compare the "corrected" between-site variabilities obtained by various site-amplification prediction methods. In particular, we will show the limits of classical 1D models to reproduce site-amplifications and reduce the between site variability at high frequencies (>3Hz). We will also discuss the added value of new methods (new proxies or Machine Learning).

In contrast to the between-site variability, the within-site variability is defined as the randomness in site response from event to event at a single site, and it is considered to be aleatory. Quantifications of this within-event variability show that the within-event variability is much lower than the between-event variability. We will show that it is difficult to identify the geological/geotechnical factors controlling this variability, and we will finally discuss and illustrate new working hypothesis (e.g. time-dependencies of kappa) that may explain part of it.

The Influence of Impedance-Ratio Distributions on 1D Linear Site Response Proxies

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Ground-motion site response is inherently site specific since it depends on in situ dynamic parameters, particularly shear-wave velocity, *Vs*. Thus, identifying the best proxies to predict site-response remains a challenge. Using *Vs* profiles developed at 193 central and eastern U.S. sites with underlying lithologies ranging from bedrock to deep (>100 m) soils, we investigated the influence of impedance ratio, *IR*, distributions on 1D linear site responses at the first peak frequencies, f_0. We categorized each site as "gradient", "single-layer", or "multilayered", depending on the number of *Vs*-profile interfaces with $IR \geq 3.0$, where gradient sites lack any such interface. We then evaluated correlations between various *Vs*-profile attributes with f_0 and corresponding amplifications, A_0, both calculated from 1D linear site-response analyses. Depth-based attributes, $Z_{1.0}$, $Z_{2.5}$, and Z_{IRmax}, the depths to velocities of 1.0 km/s, 2.5 km/s, and the maximum *IR*, IR_{max}, respectively, correlate well with f_0 at single- and multilayered sites, whereas *Vs30*, the average *Vs* in the upper 30 m, is the only strong predictor of f_0 at gradient sites. *Vs30* also correlates with f_0 at other site types but is unreliable at low frequencies (≤~3 Hz) and slow *Vs* (≤~300 m/s). IR_{max} correlates with A_0 for all site categories with the strongest correlation at single-layer sites and the weakest at gradient sites. Average *Vs* to $Z_{1.0}$ correlates marginally (r<0.6) with A_0 at single-layer sites as does *Vs30* at gradient sites. These results suggest: 1) the most appropriate site response proxies depend on the distribution of strong *IR*s beneath a site, 2) no single proxy has skill to predict both f_0 and A_0, 3) IR_{max} and its depth are the most versatile and useful attribute pair, and 4) *Vs*-profile characteristics may contribute to variability in ground-motion model residuals.

Constraining Between-Event Variability of Kinematic Rupture Scenarios: A Case Study of an Mw6.2 Earthquake in Central Italy

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The region of Central Italy is well known for its moderate to large normal-fault earthquakes and motivated ground motion modeling to provide insights on source-related complexities. We utilize a hybrid integral-composite kinematic rupture model by Gallovič and Brokešová (2007) to simulate the 2016 Amatrice earthquake (M 6.2) and perform ground motion prediction for other hypothetical Amatrice fault rupture scenarios (scenario events). The synthetic seismograms are computed in 1D crustal velocity models, including site-specific 1D soil profiles for selected stations up to 10 Hz. We optimize the input source parameters using a grid-search method to minimize the spectral acceleration bias between synthetic and recorded near-source strong-motion data at reference rock stations with negligible site effects. Then, we create up to ten thousand rupture scenarios by varying source parameters. The resulting distributions of synthetic spectral accelerations at periods 0.2 - 2 s agree with the empirical nonergodic ground motion model of Sgobba et al. (2021) for Central Italy in terms of the mean and total variability. However, statistical mixed-effect analysis of the residuals indicates that the between-event variability exceeds the empirical one significantly. We quantify the role of source model parameters in the modeling and demonstrate the pivotal role of the so-called stress parameter that controls high-frequency radiation. We suggest narrowing down the variability of the stress parameter to constrain the scenario variability within the empirical values. The presented validation of the scenario variability can be generally utilized in scenario modeling for physics-based seismic hazard assessment.

Physics-Based Broadband Ground Motion Simulations of M6.5 Scenario Earthquakes in Central and Eastern US, Including Surface Topography: Ground Motion Variability Related to Earthquake Rupture Characteristics

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We are developing a validated and computationally efficient simulation capability that can provide representative synthetic ground motions from crustal earthquakes in the Central and Eastern US, using high performance computing. The main objective is to provide constrains to refinements of existing ergodic Ground Motion Models (GMMs), for large magnitude earthquakes and near-fault distances, for which these models are less reliable. We used physics-based broadband (0-5Hz) ground motion simulations to estimate the ground motion amplitude and within event and between-event variabilities associated with fault rupture characteristics. First, as part of a strategy for selecting a reginal velocity model and validation of our rupture modeling technique, we simulated ground motion from the Mw5.0 2016 Cushing and Mw5.8 2016 Pawnee OK earthquakes. The successful simulations of both earthquakes demonstrated the reliability of our deterministic simulation approach while emphasizing the importance of including small-scale variability in the regional velocity model needed to reproduce the observed high-frequency wave scattering effects. Additional validation analysis, based on comparisons with GMMs for CEUS region and for a Mw6.5 earthquake, resulted in a very good match between the simulations and GMMs predictions.

Our initial investigation of within-event and between-event ground motion variabilities for M6.5 scenario earthquakes on a strike-slip fault, suggests that they are strongly related to spatial slip and slip rate variations, rupture velocity, rupture area and rupture initiation location. We found that the ground motion variability observed at near-fault distances (< 5 km) also persists at longer distances. Regardless of the rupture scenario, the simulated ground motion tends to fully saturate at short distances and for all periods. Analysis of effects of rupture initiation location suggest that PGV and SA can be quite variable due to rupture directivity effects. Such effects are stronger at periods longer than 1s.

Epistemic Uncertainty in Ground-Motion Prediction in the Indian Context: Evaluation of Ground-Motion Models (GMMs) for the Himalayan Region

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Empirical ground-motion models (GMMs), the essential element of probabilistic seismic hazard analysis (PSHA), exhibit two types of uncertainties for a given rupture scenario: aleatory and epistemic. The former is captured by the residual standard deviation (σ) of GMM, whereas the actual epistemic uncertainty associated with ground-motion prediction is unknown. Epistemic uncertainty increases significantly with less recorded data in magnitude and distance ranges that dominate hazards at a particular location. In the Indian context (mainly along the Himalayan arc), constraining epistemic uncertainty poses a major challenge due to less recorded data. The present study investigates two components of uncertainty in ground-motion prediction in the Indian context. We use a recently compiled strong-motion dataset to evaluate the published GMMs for the active crustal regions, mainly across the Himalayas. First, we provide a brief review of the GMMs developed, followed by statistical analysis. The inherent uncertainty, due to regional variations and incorrect parameter estimates, is also explored. The residual analysis involves decomposing the total residuals into between and within-event components using a mixed-effects regression algorithm. For evaluation, 13 GMMs with 519 records for distance ≤ 300, magnitude ≥ 3, years 2005-2017, were utilized. For most GMMs, the current functional form can't capture the observed magnitude and distance scaling exhibiting a significant bias. The residual analysis indicates that GMMs performance decreases with increases in periods, particularly beyond T ≥ 0. 8s and total aleatory variability, σ is lower at shorter periods but increases at higher periods. Our analysis shows that a large aleatory and epistemic uncertainty is associated with the Indian GMMs. Further studies are required to better understand different uncertainty sources with more recorded data to provide constraints on the developed GMMs along with ground-motion simulations.

Understanding and Modeling the Uncertainties in Earthquake Ground Motions [Poster]

Poster Session • Thursday 20 April

Conveners: Morgan P. Moschetti, U.S. Geological Survey (mmoschetti@usgs.gov); Grace Parker, U.S. Geological Survey (gparker@usgs.gov); Fabrice Cotton, GFZ Potsdam (fcotton@gfz-potsdam.de); Olga-Joan Ktenidou, National Observatory of Athens (olga.ktenidou@gmail.com)

Capturing Epistemic Uncertainty in Site Amplification Models with Different Site Proxies, Including Geomorphological Sediment Thickness

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Local geological features can have a strong impact on earthquake ground shaking. Especially sites with softer sediments, which are expected to amplify the recorded ground motion. However, estimating this site amplification at new sites and sites without any direct geotechnical measurements of site parameters remains a large challenge in seismic hazard assessment. In this study we propose adopting a geomorphological model for inferred sediment depth (Pelletier et al., 2016), as an alternative site proxy to predict ground motion site-amplification on a regional or global scale. Though originally developed as an input for hydrology and ecosystem modeling, the global inferred sediment depth model is is based on a combination of data including topographic slope, geological maps and water table depth, which correlate with geotechnical soil conditions known to yield seismic amplification.

To test the suitability of the geomorphological model for ground-shaking prediction, we compare the ability of the new proposed proxy and common site proxies to predict site amplification using empirical site amplification derived for sites in Europe at regional scale. We find that the geomorphological sedimentary thickness performs better than or equally well as the traditional regional-scale proxies, such as VS30 inferred from topography. We therefore argue that the inferred geomorphological sedimentary thickness from the Pelletier et al. 2016 model is a promising new alternative for predicting site amplification on a regional or global level. Furthermore, the differences in the predicted site amplification maps from different proxies captures the epistemic uncertainty associated to the site amplification models used in large scale seismic hazard or risk studies. This result has important implications for the development of new generation of ground-shaking models used for shake maps and regional seismic hazard and risk models.

Determination of Seismic Intensities From Seismic Microzoning Results for the Xalapa Conurbation Zone, Veracruz, México

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The effects of earthquakes in México have caused great disasters, which are accompanied by economic and human losses;in the State of Veracruz, throughout its history, important damages have been manifested due to earthquakes of great intensity. The State occupies the second and third place in the number of fatalities at the national level, with the Xalapa earthquakes of 1920 and the Orizaba earthquake of 1973, only after the Mexico City earthquake of 1985.The objective of this study was to create seismic intensity maps in terms of maximum accelerations for the metropolitan area of Xalapa, using the results of environmental vibration studies in the area. The seismic records obtained from the non-permanent seismic monitoring network of the Veracruz University in the Xalapa area, and the results of the environmental vibration analysis obtained for more than 500 vibration points taken in the seismic microzonation of the metropolitan area were used.A one-dimensional propagation methodology of the signal of the earthquakes recorded in the seismic monitoring stations of the metropolitan area was proposed, from

the rock to the surface using a convolution operator, related to the empirical transfer function obtained from the seismic noise. This study used acceleration records from various stations, within the earthquake catalog of the seismic monitoring network, both to validate the methodology and to generate seismic scenarios for each of the earthquakes under study.The maps were created for earthquakes of various magnitudes and seismogenic sources, to obtain maps of maximum amplification of the terrain in the metropolitan area, and thus establish areas of greater acceleration of the terrain and therefore of greater danger. The aforementioned methodology will be applied to obtain maps of the maximum accelerations in a practical and efficient way, which will serve to delimit the areas with the greatest danger, with which the population and decision makers, will be able to take immediate actions after the occurrence of an earthquake and orient them where to direct the aid after the earthquake.

Implication of Rupture Model Parameterization Uncertainty in Simulated Ground Motions From the Mw 6.2, 24 August 2016 Amatrice, Italy Earthquake

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The Amatrice, Italy earthquake occurred on 24 August 2016, with Mw6.2, and started a long seismic sequence dominated by three Mw≥6.0 events in the Central Apennines. It destroyed the historical center of Amatrice town, causing 299 fatalities, and induced spread damage in villages nearby as an effect of the causative fault's proximity and the high vulnerability of old buildings in the area. The ground shaking was severe and much larger than the expected value from the Italian ground motion model (GMM). Several authors have discussed the observed ground motion variability linked by the source rupture propagation and rupture directivity effects, as revealed by the observed data. In this study, we performed physics-based three-dimensional numerical ground motion simulations (up to 3 Hz) of the Amatrice earthquake using a series of rupture models and a well-constrained local 3D velocity model, including the surface topography in the near-source region. The kinematic rupture models are generated using the technique described by Graves and Pitarka (2016). We studied the sensitivity of near-fault ground motion amplitudes, particularly to the spatial slip pattern of the earthquake rupture model and its impact on observed and simulated ground motion amplification. We explored the ground motion variability and the uncertainty raised by the rupture model parameterization for the Amatrice earthquake. Finally, we compared the simulated ground motions with the recorded ground motions and those predicted by the GMMs, ITA18 (Lanzano et al., 2019), to investigate the performance of our simulations. We observed that our synthetic ground motions match well with the observed ones, reproducing the recorded ground motion characteristics in both the time and the considered frequency domains. The simulations' median ground motion intensities are similar to the ITA18 GMMs. However, besides a larger dissipation as a function of distance, our simulations predict higher ground motion amplitudes and higher standard deviations at short distances from the rupture, which can be attributed to fault rupture kinematics effects.

Long-Period Strong Ground Motion Prediction for the Mw7.2 Earthquake Set by the Nankou-Sunhe Fault in Beijing

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The Nankou-Sunhe Fault is located in a potential source zone of high magnitude M7.5 in the geoseismic parameter zoning map of China, although no major earthquakes have occurred in history. Taking into account the statistical relationships between macroscopic dimensions of faults and source parameters by scholars from China, the United States, and the former Soviet Union, 35 models with different rupture directions of single and double Asperity were set, and a three-dimensional crustal and upper mantle structure model of the Beijing basin and its surrounding area was constructed based on the available geological and geophysical sounding results, we performed predictions and statistical analysis, and the results showed that (1) under the strong ground motion effect of unilateral rupture mode from northwest to southeast, the Beijing basin has a large amplification effect, and strong ground motion will be generated in Changping, Beijing Center, Shunyi and Tongxian. The intensity of these areas can reach IX degrees and above, and the engineering structures, especially the high-rise buildings, will suffer serious seismic risks. The intensity VIII degree area includes the southeast suburbs of Beijing, Sanhe, Dafang, Baodi County and other areas, and the impact range is very large, the seismic mitigation situation in this area will be serious. (2) When the earthquake source ruptures in the reverse direction, the influence of the mountain topography and underground structure in the northwest has a significant blocking effect, resulting in the seismic wave spreading instead in an intensity map with the main axis in the northeast-southwest direction, and the intensity curve is nearly perpendicular to the fault direction, and the extreme zone only reaches intensity VIII with a small distribution area, which is low. This result is beyond the conventional understanding. This study provides an important reference for predicting the seismic intensity characteristics of destructive earthquakes in areas with few earthquake records.

Sensitivity Analysis of Conditional Mean Spectrum Ground Motion Selection Procedure

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Assessing the seismic performance of structures requires ground motions as inputs. Ground motion selection is, therefore, a topic of significant interest in dynamic structural analysis and performance-based earthquake engineering. In this vein, the most common approach to selecting ground motions is to select time series whose response spectra match a target response spectrum. The uniform hazard spectrum and the conditional mean spectrum (CMS) are commonly used target spectra. The CMS is taken by conditioning on spectral acceleration at the period of interest, and the response spectra at other periods have variance. The response spectra at these periods are derived using the correlation coefficients between the spectral accelerations at them and the period of interest. Thus, one of the major steps in ground motion selection based on CMS is to parameterize the correlations between the spectral accelerations at various periods. In this study, we perform a sensitivity analysis to ascertain how the selected ground motions' different ground motion intensity measures are affected by uncertainties of the model inputs when the CMS ground motion selection model is utilized. Moreover, it investigates the importance of the various input parameters for different ground motion intensity measures. For this purpose, we use an efficient information theoretic that utilizes the concepts of entropy and mutual information. The major advantages of the information-theoretic approach are the fast computational time and its ability to generalize to stochastic simulation models, such as ground motion selection procedure based on CMS, compared to the traditional methods, such as variance-based global sensitivity analysis methods.

Spatial Changes in Earthquake Generated Ground Motion Observations: An Examination of Data From Four Small Aperture Arrays in Southern California

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Ground motions recorded at one location are often extrapolated to nearby regions within a given radius. Here, we explore alternatives to simple extrapolation methods, accounting instead for the proximity of a station to primary fault zones. We use data from four small aperture seismic network deployments in southern California. Three of these deployments span, or are near, the San Jacinto fault zone and are linear arrays (YN.JF*, N=9, aperture 0.4 km; YN.RA*, N=9, aperture 0.25 km; and YN.TR* N=4, aperture 3 km) and one is a 2D array at Pinyon Flats Observatory (PF.BPH*, N=13, aperture = 1.2 km). To build robust catalogs an automated method is used to remove data with clipped waveforms and temporally overprinted waveforms from events in quick succession. All data are filtered 0.5-25 Hz. Using these refined waveform catalogs, peak ground acceleration (PGA) and peak ground velocity (PGV) are derived individually for each of the 3-component waveforms (vertical, north-south, and east-west) using one-minute waveform snippets. Associated metadata are stored in a data structure for additional analysis. These ground motion results are compared with theoretical estimates from Abrahamson et al., 2014. Generally, we find the PY.BPH* array data produce ground motions most similar to the theoretical values. The YN.JF* and YN.TR* array data produce smaller-than-expected ground motions and the YN.RA* array data produce larger-than-expected ground motions. We attribute these overall differences to site conditions. Results from array YN.JF* indicates that ground motions within the fault zone can be elevated in comparison with ground motions ~0.2 km off fault.

When the Acquisition Conditions and Processing Procedures of Seismic Data Increase the Ground Motion Model Uncertainties: Example of the Impact of Obspy and of the Sensor Installation Choices

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Understanding and reducing the epistemic uncertainties in earthquake ground motions models is currently one of the main challenges in probabilistic seismic hazard assessment. It is generally done by improving the earthquake source models, the seismic wave propagation representation or by relaxing the ergodic assumption by accounting for site effect. The quality of the data acquisition condition and the data processing are generally not questioned. The data-driven ground motion models implicitly assume that the ground motion used to derive the models have been measured at the free surface of the earth, that the sensor installation conditions and the seasonal effects can be neglected, and that open access instrumental correction tools such as Obspy can be used blindly. In practice, many seismic stations are posthole station or are installed in tunnel. The soil-structure interaction effects of the station are generally underestimated. The existence of very short wavelength topographic features (such as scarps of a few meters in height) should also be considered. In some cases, seasonal variations in soil moisture can make the site response variable over time. We show here some examples of effects that have been observed on the stations of the French RESIF network and on temporary arrays deployed on the island of Cephalonia (Greece). These effects can lead to de-amplifications of a factor more than 10 at certain frequencies (in the case of deep stations) or to amplifications of the same order of magnitude (in the case of sensors on pillar). We also present an issue on the way the instrumental correction is performed on Obspy. The main objective here is to inform the ground motion modeler on the potential impact of these effects. The next step will be to quantify the epistemic uncertainties related to the acquisition and processing of the seismic data.

Understanding Earth Systems with Fiber-optic Cables

Oral Session • Wednesday 19 April • 08:00 AM Pacific

Conveners: Brad Lipovsky, University of Washington (bpl7@uw.edu); Ettore Biondi, California Institute of Technology (ebiondi@caltech.edu); Loïc Viens, Los Alamos National Laboratory (lviens@lanl.gov); Xiaowei Chen, Texas A&M University (xiaowei.chen@tamu.edu)

Temperature Sensing With DAS for Fiber-Optic Oceanography

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Although typically used to measure dynamic strain from seismic and acoustic waves, Rayleigh-based distributed acoustic sensing (DAS) is also sensitive to temperature, offering longer range and higher sensitivity to small fluctuations than conventional Raman-based distributed temperature sensing. In this presentation, we demonstrate that ocean-bottom DAS on pre-existing fiber-optic cables is sensitive to, for example, both large-amplitude internal waves propagating on the near-surface thermocline as well as the intensified internal tide at sloping bottom boundaries, which are regions of enhanced ocean mixing but scarce observations. In particular, we interpret temperature transients up to 4 K (equivalent to 40 microstrain) along a power cable in the Strait of Gibraltar, associated with passing groups of internal solitary waves in water depth <200 m. We then show how temperature variability of about 2 K at 1-km depth decreasing to 0.2 K at 2.5-km depth on the slope of Gran Canaria, an island off the coast of west Africa, reveals the bore-like propagation of the nonlinear internal tide at locations where the slope is near critical. While the temperature sensitivity of DAS opens new frontiers in fiber-optic oceanography, it also presents a significant challenge for long-period seismology and seafloor geodesy with fiber-optic strainmeters, as temperature fluctuations associated with internal waves and boundary-layer flows may overprint elastic strain from fault creep or slow earthquakes.

Potential of Ocean Bottom Distributed Acoustic Sensing for Seismic Ocean Thermometry

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The ocean absorbs >90% of the excess heat and plays a key role in the climate system. However, an accurate estimate of global ocean temperature changes is still challenging. Seismic ocean thermometry (SOT) using T-wave from repeating earthquakes has proven an accurate remote-sensing method complementing existing temperature measurements. Nonetheless, current high-quality T-wave stations are sparsely distributed, limiting the spatial resolution of global SOT. Distributed acoustic sensing (DAS) can provide an affordable and scalable solution for long-term submarine array observation and therefore significantly enhance a global SOT capacity. Here we systematically investigate T-wave detectability of ocean bottom DAS (OBDAS) and explore its potential for SOT using the OOI (Ocean Observatories Initiative) OBDAS experiment offshore central Oregon as an example. During the four days, T waves from multiple distant earthquakes, most of which are missing in current catalogs (i.e., ISC), are detected at OOI DAS. To further enhance the signal-to-noise ratio, we use a curvelet-based denoising algorithm to extract the coherent T-wave from noisy data. After denoising, we explore the SOT feasibility using T waves from pseudo repeating earthquakes, which are generated using the realistic T-wave from a Mw5.2 Aleutian earthquake and noises at OOI OBDAS. Benefitting from the ultra-dense array, we find that OBDAS can use T-wave from small repeating events for SOT while data at a co-located OBS from similar magnitude events would be too noisy. Still, some other challenges (e.g., a possible temporal change of cable response to T-wave) affecting SOT awaits further studies.

High-Resolution Imaging of Submarine Structures and Ocean Microseism Sources With Distributed Acoustic Sensing

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Ocean-generated microseism is a predominant source of seismic noise on Earth. It reflects the dynamics of ocean waves and Earth's shallow structures and has been commonly used for studying both of them. However, quantitative understanding of such noise and its applications for seismic purposes are still limited by the sparsity of submarine seismic instrumentations. Distributed acoustic sensing (DAS) is offering a cost-effective solution to this limitation by converting submarine fiber-optic cables into dense seismic arrays.

In November 2021, a 4-day submarine DAS experiment was conducted in offshore Oregon. In cross-correlations of ambient noise records, Scholte waves are clearly observed in the frequency band of 0.1-1 Hz. The precise Scholte wave phase velocity dispersion is inverted for a high-resolution subsurface shear velocity model. The result reveals several sediment basins whose depths and shapes are consistent with interfaces in previous seismic survey profiles. We also measure landward/oceanward signal amplitude ratios in cross-correlations for different channel pairs and implement a Bayesian inversion for the spatial distribution of microseism sources. While the deep ocean produces strongest sources for long-period microseism (< 0.2 Hz), coastal sources become dominant for short-period microseism (> 0.2 Hz) and the location is shallower when the frequency is higher. The retrieval of high-resolution noise source spatial variations provides new insight into ocean wave and microseism noise models.

We successfully used signal travel times to image subsurface velocity structures and amplitude asymmetry to unravel the distribution of microseism sources along the DAS array. The local noise field can be reconstructed by considering both site effects of sediments and sources related to ocean waves. The findings greatly advance our knowledge of the ambient noise field and how it can be employed to investigate the marine environment.

Observing Slow-Slip Fault-Activation Processes Using DAS

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Recent models have postulated that aseismic slip could play an important role in the initiation of injection-induced seismicity. Distributed fiber optic sensing, especially distributed acoustic sensing (DAS), is being increasingly used to monitor hydraulic fracturing operations. We show several examples of DAS-recorded M < 2 induced events that show near-field signatures of aseismic slip before or during seismic slip. In one example, we model and interpret a strain pattern observed using DAS at low frequency (< 1 Hz) to represent initial fault tensile opening followed by aseismic shear slip over several hours. In several other cases, low-frequency DAS data indicate aseismic fracture growth that correlates with measured pressure and/or temperature perturbations. In one such case, a M1.8 induced event occurred within the depth range of the aseismic slip, with a time lag of less than one day. Modelling of these signals using a modified displacement discontinuity method is providing new insights into the possible role of aseismic slip in earthquake nucleation following fluid injection.

Measuring Instrument Response and Self-Noise Level of Telecommunication-Fiber-Optic DAS Arrays

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Distributed acoustic sensing (DAS) is an emerging technology that converts an optical fiber into a dense array of strain sensors. It is essential to quantify its technical performance to ensure the accuracy of DAS recorded phase and amplitude information. Recent studies show that the accuracy of phase information (e.g., travel time measurements) recorded by DAS is comparable to broadband stations. However, DAS's amplitude response and self-noise level have not been fully quantified, especially for dark fiber experiments which use pre-existing telecommunication cables with less available fiber-ground coupling information. Without the coupling information, it is a challenge to calculate the amplitude response of DAS theoretically. Using the co-located conventional seismometers, we empirically measure the amplitude response of telecommunication-fiber-optic DAS arrays. We systematically perform the measurements on multiple DAS arrays using the body wave and surface wave of teleseismic and local earthquakes spanning the 0.01 to 10 Hz frequency range. Our preliminary results based on the DAS arrays in Ridgecrest and Long Valley show that the array-average amplitude response is around 0dB with about 10 dB fluctuation depending on frequency. The amplitude response information will help determine the ground motion's absolute amplitude and earthquake magnitude. In addition, we also quantify the self-noise level of these DAS arrays. The noise level information is essential for evaluating the detection ability of DAS for weak signals. The methodology proposed in this study can be used to quantify the instrument performance of future DAS experiments.

Strategies for Passive DAS Data Analysis at the Edge

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A significant advantage of distributed acoustic sensing (DAS) is that only a single power source needs to be maintained, and an interrogator can be connected to a fiber-optic cable to continuously collect data for months or years with little human intervention. This makes DAS an appealing tool for seismic data acquisition in remote areas, particularly for studying fine-scale processes across long distances. However, remote areas often have limited data transfer capabilities, sometimes orders of magnitude smaller than DAS data collection rates. These data transfer limits have pushed us to increase the amount of automated analysis and quality control carried out by limited computing resources in the field, particularly for long-duration experiments in remote areas. To achieve this goal, we are investigating the use of lossy compression of passive DAS data, increased use of data products for initial analysis of passive seismic data, and algorithms that directly rely on these compressed data and data products. For multiple types and levels of compression, we have quantified the lossy compression errors through multiple metrics. We also quantify errors as they propagate through common workflows for small seismic event detection and cross-correlation. Additionally, we have released open-source software for real-time data product computation that can be carried out continuously on the computer of a DAS interrogator. The methodology developed in this research is intended to impact cost-effective DAS monitoring in a wide range of applications.

Fiber-Optic Monitoring of the Vadose Zone

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The vadose zone is an unsaturated superficial layer of the subsurface that precipitation must typically pass through before it can reach groundwater. As a result, modifications to the physical properties of this shallow layer may modulate groundwater recharge and discharge, as well as affecting vegetation. In-depth investigation of the vadose zone is often limited by the paucity of instrumentation. A tool that may achieve this objective with high temporal and spatial resolution as well as extensive regional coverage is distributed acoustic sensing (DAS). By repurposing fiber-optic cables into seismic sensors with meter-spacing, DAS offers unprecedented spatial density for high-frequency wavefield recordings that are sensitive to water in the shallow layers. With ambient noise interferometry, we can track ~2% seismic velocity changes in the vadose zone, including the seasonal variation from thermal effects and the transient changes from soil moisture. The results highlight the potential of using seismic velocity changes to study soil moisture and its response to climate changes.

Lighting Up Down Under: Passive Imaging of Urban Melbourne Shallow Subsurface Using Distributed Acoustic Sensing

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Distributed Acoustic Sensing (DAS) provides a new, non-invasive means for high resolution subsurface imaging in urban, developed environments by repurposing existing telecommunication cables, which has many important geophysical and seismic hazard applications including measuring Vs30. However, urban fibre optic networks, which are designed around telecommunication needs, introduce unique challenges to passive seismic imaging including complicated array geometry and non-uniform seismic noise. A 25-km long DAS array was deployed along a telecommunication fibre that spans across metropolitan Melbourne, Australia for a duration of 3 months (December 2021 to March 2022). This dataset provides an ideal test case to address the challenges of using urban dark fibre and establish an effective workflow for ambient noise correlation with DAS recordings in urban settings. Traffic noise from vehicles and trains are the dominant signal at a frequency range of 1-30 Hz. Ambient noise correlation is performed using NoisePy, a high-performance python tool specifically designed to deal with large data volume. Cross-correlation functions (stacked over a day) show clear surface wave dispersion up to 15 Hz. Acausal move-out times are also observed, indicating strong scatterers off the fibre array and varying fibre coupling condition to the ground. The subsurface velocity model obtained from ambient noise correlation reveals strong structural variations at 10-m scale up to 1 km depth across Melbourne and shows good correspondence with the mapped geological boundaries including an 800 kyr basalt flow and Miocene marine and terrestrial sediments. The exciting results from the Melbourne experiment demonstrate that DAS can be used to build high-resolution shallow subsurface models for metropolitan areas with high seismic hazard risk that may be poorly instrumented with inertial seismometers.

Near-Surface Characterization Using Distributed Acoustic Sensing and Ambient Seismic Noise in an Urban Area: Granada, Spain.

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The Granada Basin in the southeast of Spain is an area of moderate seismicity. Yet, it presents some of the highest seismic hazards with a soft sedimentary layer amplifying local ground motion in the Iberian Peninsula. In urban areas, ground motion measurements often suffer from sparse instrumentation. An enticing alternative to conventional seismometers is the novel Distributed Acoustic Sensing (DAS) technology that can convert telecommunication fiber-optic cables into dense arrays of seismic sensors. In this study, a field test of DAS array is conducted in Granada city on 26 and 27 Aug 2020 using a telecommunication fiber. We utilize the dataset to extract surface wave information from ambient seismic field (ASF) and obtain nine shear-wave velocity (Vs) profiles under different sections of the cable. The shallow Vs structure shows a good agreement with the geological conditions of different soil deposits. This study demonstrates that ASF monitoring using DAS could provide insights into soil characterization and seismic microzonation in urban areas, which helps to understand local site response to ground motion.

Love Wave Ambient-Noise Imaging of Urban Subsurface Velocity Structures: Exploiting the Potential of Horizontally Orthogonal DAS Array

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Recent advances in Distributed Acoustic Sensing (DAS) technique significantly benefit urban seismology by transforming pre-installed telecommunication fiber-optic cables into dense arrays of seismic sensors. Interferometry of DAS-recorded seismic ambient noise wavefields has been widely applied to analyze surface wave dispersion and thus image seismic velocity structures of the shallow subsurface (~ several hundreds meters) in urban areas. Many previous studies only focused on Rayleigh waves within linear fiber segments to avoid the ambiguity of mixed surface wave modes induced by complex local fiber orientations. However, as more and more two-dimensional dense grids of fiber-optic cables in cities are exploited by DAS technique, ambient noise interferometry that takes advantage of complex DAS array geometry can provide new opportunities for seismic monitoring of subsurface structures in urban environments. In this work, we perform dispersion analysis of Love waves extracted from ambient noise interferometry using orthogonal branches of fiber-optic cables. Theoretical angular responses of DAS ambient noise cross-correlation, together with numerical experiments, help identify sensor pairs expected to record stronger Love waves than Rayleigh waves. We test our methodology on DAS data recorded under San Jose, California. We successfully obtain three sets of Love wave dispersion maps, including both phase and group velocities, with various channel pair orientations. Phase-matched filtering is applied to clean the waveform and thus smooth the results. Consistency of Love wave dispersions among these three sets indicate the robustness of our analysis. We finally perform inversion of Love wave dispersion relations to obtain depth-dependent subsurface velocity structures of the top ~ 100 m. Our Love wave inversion result is consistent with the model presented by Hayashi & Burns (2020), which is obtained from Rayleigh wave dispersion and H/V spectral ratio. This indicates the potential of surface wave analysis on fiber-optic cables with complex geometry, which can further advance the seismic monitoring of urban areas.

Understanding Earth Systems with Fiber-optic Cables [Poster]

Poster Session • Wednesday 19 April

Conveners: Brad Lipovsky, University of Washington (bpl7@uw.edu); Ettore Biondi, California Institute of Technology (ebiondi@caltech.edu); Loïc Viens, Los Alamos National Laboratory (lviens@lanl.gov); Xiaowei Chen, Texas A&M University (xiaowei.chen@tamu.edu)

Constraining Antarctic Ice Sheet Properties using Distributed Acoustic Sensing Data from the South Pole

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Well-constrained properties of the South Pole subsurface are vital for understanding Antarctic ice sheet dynamics. Estimates of firn, ice, and sediment layer properties in the Antarctic ice sheet exist from traditional active source experiments using geophones, but their spatial resolution and extent are quite limited due to deployment challenges. Distributed acoustic sensing (DAS), a new tool in seismology that transforms fiber optic cables into dense arrays of strainmeters, has high spatial resolution, large spatial coverage, and relatively low-effort deployment, making it a promising tool for glacier seismology. In January 2023, we deployed a DAS unit on a long-range telecommunication cable from the QSPA South Pole station. This experiment allows for the accurate estimation of the ice sheet and bedrock properties from active and passive strain-rate recordings. To calibrate the expected data recordings, we generate a set of synthetic experiments based on three geologic scenarios: 1) ice to bedrock, 2) ice to lithified sediment to bedrock, and 3) ice to dilatant sediment to bedrock. We apply a single-force source estimated from a previous active source experiment in Ridgecrest CA for accurate amplitude and frequency content, and convert the output synthetic displacements to strain-rate for comparability with the DAS data. Our synthetic data suggests the 8 kilometer cable records the triplicated P and S phase, allowing constraint of layer depths and wave speeds. Variations between the three models give insight into which end member case the acquired data likely represents. On the acquired data, we apply a surface-wave inversion strategy to estimate the seismic velocity and attenuation of the subsurface structure . These material properties can be used as a proxy for englacial temperature, which in turn provides insights on ice-sheet dynamics and better constraints for climate modeling.

Earthquake Detection Using a Submarine DAS Array in Monterey Bay, California

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The Seafloor Fiber-Optic Array in Monterey Bay (SEAFOAM) is a year-long Distributed Acoustic Sensing (DAS) deployment project, with a goal of local seismicity monitoring. An interrogator (model QuantX, OptaSense) was connected to a 52-km long submarine cable, turning it into a DAS array of 10245 channels with 5-meter channel spacing. Recording started on July 21, 2022. The region is seismically active because of the nearby San Andreas fault system, and offshore San Gregorio fault system which the cable crosses. The

1989 M6.9 Loma Prieta earthquake occurred just north of Monterey Bay, and a magnitude 7+ earthquake is believed to happen on the San Gregorio fault after 1270 AD. Applying DAS to submarine cables can benefit systems like Earthquake Early Warning (EEW) by increasing warning time and improving accuracy for offshore events.F-K domain filters have been applied to denoise the raw data. P- and S-wave phase picking results with STA/LTA methods show different performance with different background noise (channel water depth, substrate composition, stormy weather etc.), which implies that dynamic parameter selection is needed. The dense spatial sampling nature of a DAS array is used to filter out bad picks and obtain more robust results. A 1D velocity model is used to locate earthquakes with P-wave arrivals. Location results only using the DAS array show expected strong trade-off between earthquake epicenter and origin time, for events outside of the array. On-land stations are added to better constrain the locations. Estimation of magnitude for local earthquakes using peak strain-rate data after 3s of the P-wave arrival shows promising results when using catalog locations. Spatially down-sampled data is streamed in real time to the Northern California Earthquake Data Center (NCEDC). These data are processed together with data from on-land seismic stations using a version of the rapid earthquake source parameter estimation EEW algorithm EPIC. DAS data currently contributes to event location in a very similar way as seismic data does, demonstrating the possibility to increase warning time for offshore events.

Focal Mechanism Inversion With Distributed Acoustic Sensing

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Focal mechanism inversion with distributed acoustic sensing (DAS) has been challenging due to its single-component sensing and low signal-to-noise ratios compared to conventional seismic instruments. However, DAS has several advantages that can be leveraged to improve the inversion accuracy and resolution. Firstly, the widespread deployment of telecommunication (dark) fibers allows for an improvement on the azimuthal coverage in current seismic networks. Secondly, the ultra-dense spatial sampling of DAS can tightly constrain the orientation of nodal planes using P-wave polarity reversals across channels. In this study, we propose a systematic method to convert the DAS array into an ultra-dense polarity discriminator for improving the accuracy of focal mechanism inversions. We test our method on two DAS arrays with 50-km sensing ranges and 10-meter channel spacing and verify the inverted P-wave polarities using catalog focal mechanisms. We show that a joint inversion using P-wave polarities determined from DAS and conventional seismic stations can improve the accuracy and decrease the uncertainty of inverted earthquake focal mechanisms.

How Close Are We to Integrating Fiber-Optic Distributed Acoustic Sensing in Earthquake Early Warning Systems?

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We present a roadmap for the incorporation of fiber-optic distributed acoustic sensing (DAS) in earthquake early warning (EEW) systems. Significant strides have been made in the field of fiber-optic DAS. The technology is being used in seismic and volcanic monitoring, seismic profiling and imaging, and various other geophysical applications. However, operational EEW systems all over the world have yet to utilize DAS arrays for rapid earthquake detection and characterization purposes. Strain (measured by traditional strainmeters) has been recently demonstrated to have the potential to complement velocity and acceleration data for earthquake parameter quantification traditionally used in EEW systems. The incorporation of DAS strain in EEW systems could be a gamechanger through sheer upscaling in sensor coverage, especially for offshore environments where traditional seismic and geodetic instrumentation is sparse and costly to install, but where unlit optical fibers are abundant. As most DAS arrays are not formally coupled installations dedicated to seismic monitoring, there remain technical challenges for a full employment of DAS strains in EEW systems, notably the acquisition of accurate, multi-component strain amplitudes that could be converted to other ground-motion measurements. DAS researchers need a clear understanding of how a typical EEW system works, and especially its data requirements and processing flows. Likewise, the EEW community requires clear demonstrations of the robustness of DAS strains, and evidence of accurate outcomes in either running currently available algorithms with strain-derived data, or in strain-based EEW algorithms. In this work, we present a list of required DAS capabilities and array attributes for EEW and outline a roadmap that would take us from where DAS technology is today to the point where it can be fully utilizable in EEW applications.

Imaging Near-Coast Subsurface With Distributed Acoustic Sensing and Double Beamforming

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An Ocean-bottom Distributed Acoustic Sensing unit collected four-month data from a telecommunication fiber cable in the coastal Oregon region. The energy of the microseisms is concentrated below 2 Hz and is generated by ocean wave-solid earth interactions. We extract clear surface waves propagating both landward and seaward using a cross-correlation scheme. The quasi-linear geometry of the cable enables applications of conventional slant stack and 1D double beamforming to measure phase velocity. We generate dispersion curves from Cross Correlation Functions (CCFs) with 500 virtual receiver channels with slant stack. A continuous phase velocity profile is acquired by moving the virtual source along the array. With 1D double beamforming, we first define source beam and receiver beam pairs along the cable. Presuming phase velocities of both beams, we stack travel-time-adjusted CCFs of all the source-receiver pairs within the beams. Good velocity estimates stack CCFs constructively, and we test numerous pairs of inputs in search of the best velocities in the source and receiver beams respectively, which return the highest CCF amplitude. Repeating the same procedure with different beam pairs along the array and averaging over all the available estimations, we retrieve a 2D velocity profile on the region. Finally, we separately invert both velocity profiles for subsurface shear wave velocity models. By comparing the two models, we find good agreement on submarine structures and anomalies. We combine two models with respect to their uncertainties to present a final model of shear wave velocity.

Imaging the Subsurface of Long Valley Caldera Through Converted Phases Recorded on a Distributed Acoustic Sensing Network

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The volcanic system within the Long Valley Caldera once produced the Bishop Tuff supereruption and remains active today. Thus, the region is of great scientific and societal importance, with the mapping of its subsurface crucial to a broad understanding of the system's behavior. Tomography remains a valuable tool in subsurface imaging, but cannot adequately characterize sharp boundaries in velocity, such as those expected beneath the caldera. An understanding of such boundaries in a magmatic system is crucial both to constraining its true extent and determining changes in structure over time. Sharp features may be characterized by reflected phases, but past work on the subject has been limited by poor spatial coverage, sometimes relying on arrivals at a single channel. The recent deployment of a distributed acoustic sensing array across the caldera provides the opportunity for improved imaging of sharp features through reflection seismology. The array spans the caldera, covering approximately 90 kilometers at 10-meter channel spacing. For certain local earthquakes, the array regularly records a converted phase which has been interpreted by past work as an SP reflection generated by the roof of the large Pleistocene magma chamber located approximately at 10 km depth. Using seismicity in the vicinity of the caldera as a passive source, we image reflectors capable of producing this phase. We jointly consider the results of Kirchoff migration, as well as an inversion based solely on travel time, to delineate the top of the large magmatic chamber of this volcanic system.

Laboratory Study of Coupling and Sensitivity of Optical Fiber Distributed Acoustic Sensing

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Optical Fiber Distributed Acoustic Sensing (OF-DAS) is rapidly evolving as a seismic observation tool. However, installation of OF widely varies. These include pre-installed dark fiber, shallow trenches, directly on ice, or installed in wellbores. The coupling of the OF with its surroundings is known to have a large impact on the instrument response. Most information about how

well OF is coupled and how the OF-DAS instrument response compares to conventional seismometers is through empirical data gathered in the field. To characterize this coupling methodically, we constructed a large container filled with grains, almost 10 meters in length, and placed both OF and seismometers inside and outside of the container. Local, regional, and teleseismic earthquake motions are recorded to understand how factors such as burial depth and grain characteristics affect the received signal. These measurements are not only important for ensuring that accurate amplitude and phase information is obtained on OF-DAS systems, but also help to engineer optimal coupling for a desired application. LA-UR-23-20264

Synthetics for Stress, Strain and Rotation

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The last decade has seen the increased use of DAS (distributed acoustic sensor) and rotational sensor waveforms. To facilitate the interpretation of these data, modifications are made to the wavenumber integration and modal superposition codes of Computer Programs in Seismology (Herrmann, 2013) to compute stress, strain and rotation in a cylindrical coordinate system for 1-D velocity-density models. In addition an auxiliary program is provided to rotate these to a local Cartesian system at the observation point. The complete synthetics permit an evaluation of some deductions about the joint use of rotational and translational instrumentation (6C) to estimate Rayleigh- and Love-wave phase velocities. For a plane waves propagating in the x_1 direction one can show that $c_R = (du_z/dt) / \omega_{13}$ for an observation at the free surface and $c_L = ½ (du_L/dt) / \omega_{12}$. However although $c_R = (du_z/dt) / \omega_{rz}$, $c_L \neq ½ (du_L/dt) / \omega_{r\varphi}$ because the $\omega_{r\varphi}$ contains near both Love and Rayleigh near field terms. Love wave phase velocities can be estimated only when there is no overlapping Rayleigh wave and when wavelengths are small compared to epicentral distance.

Herrmann, R. B. (2013) Computer programs in seismology: An evolving tool for instruction and research, *Seism. Res. Lettr.* 84, 1081-1088, doi:10.1785/0220110096

Understanding the Variability in Earthquake Stress Drop Measurements

Oral Session • Thursday 20 April • 02:00 PM Pacific

Conveners: Colin N. Pennington, Lawrence Livermore National Laboratory (pennington6@llnl.gov); Shanna Chu, U.S. Geological Survey (schu@usgs.gov); Trey Knudson, Stanford University (trey05@stanford.edu); Meichen Liu, University of Michigan (meichenl@umich.edu); Ian Vandevert, University of California, San Diego (ivandevert@ucsd.edu); Rachel Abercrombie, Boston University (rea@bu.edu); Annemarie Baltay, U.S. Geological Survey (abaltay@usgs.gov); Kevin Mayeda, Air Force Technical Applications Center (kevin.mayeda@us.af.mil); Taka'aki Taira, University of California, Berkeley (taira@berkeley.edu); Kilian Kemna, Ruhr University Bochum (kilian.kemna@web.de)

Introduction and Update on the International SCEC/USGS Community Stress Drop Validation Study

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In 2021 we launched the Community Stress Drop Validation Study, focused on the 2019 Ridgecrest earthquake, California, sequence, using a common dataset. The broad aim of the collaboration is to improve the quality of estimates of stress drop and related fundamental earthquake source parameters (corner frequency, source duration, etc.) and their uncertainties, to enable more reliable ground motion forecasting, and to obtain a better understanding of earthquake source physics. Seismological estimates of stress drop from earthquake spectral measurements have become standard practice over the last 50 years, but their wide variability, model dependence and inconsistency between studies have led to controversy and concerns about how to assess and interpret these measurements.

The SCEC/USGS community study has engaged a wide international community focused on improving methods and distinguishing the sources of variability between physical earthquake source variation, and random and systematic scatter and bias. To date, 16 research groups have submitted 21 different measurements of source parameters for earthquakes in the 2019 Ridgecrest sequence, with a focus on 55 events of *M*2 to 5. These approaches include spectral decomposition/generalized inversion, empirical Green's function analysis in both frequency and time domains, and ground-motion and single-station based approaches. Comparison of submitted stress drops reveals considerable systematic and random scatter, but also shows consistency between events; for some events, methods are in agreement on either relatively high or low stress drops. Ongoing focus is on understanding the relative influences of different analysis parameter choices, assumptions about attenuation, frequency range of the data, and the growing evidence of widespread complexity and heterogeneity in even small earthquake ruptures. We welcome new members wishing to observe, learn or more actively participate; more information can be found at https://www.scec.org/research/stress-drop-validation.

Spectral Scaling Comparison and Validation Between Coda, GIT and Finite Fault Spectra for Ridgecrest, CA (3.3 < Mw < 6.9)

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The coda magnitude method of Mayeda and Walter (1996) provides stable source spectra and moment magnitudes (M_w) for local to regional events from as few as one station that are virtually insensitive to source and path heterogeneity. We applied the Coda Calibration Tool (CCT) to the 2019 Ridgecrest sequence and compare against results derived from the data driven, generalized inversion technique (GIT) as well as from results derived from finite-fault inversion. We find excellent agreement over a broad range of event sizes and also confirm CCT provides stable M_w, eliminating the need for empirical magnitude relationships that tie M_L to M_w. Coda has the advantage of requiring much fewer events and stations for calibration and routine measurement. Additionally, we use independent ground-truth source spectra constraints from coda spectral ratios to break the path and site trade-off, as well as *not* imposing a regional source scaling assumption or assuming a fixed stress drop for Green's function events. The GIT and CCT approaches show an increase in apparent stress with increasing magnitude to roughly M_w 5.5, then becomes constant. Furthermore, finite fault average apparent stress estimates are also in good agreement with common events, further validating the GIT and CCT results. CCT stems from a multi-year collaboration between the US NDC and LLNL scientists, as well as collaboration with other institutions who are helping to evaluate and test the code with the goal of developing a fast and easy Java-based, platform independent coda envelope calibration and processing tool. CCT is freely available to the public on GitHub (https://github.com/LLNL/coda-calibration-tool). The tool can be used in routine processing to obtain stable source spectra for M_w, radiated seismic energy, apparent stress, corner frequency, and source discrimination on event type and/or depth.

Multi-scale Analyses of Ridgecrest Earthquake Stress Drop

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The Ridgecrest earthquake sequence was well recorded by the Ssouthern California earthquake Seismic Nnetwork (SCSN) and rapid response arrays. These dense observations provide an excellent opportunity to better understand the variabilities and uncertainties of earthquake source parameters. In this study, using the seismic network, we apply a stacking-based spectral analysis with depth-dependent attenuation corrections, and an empirical-Green's-function (EGF) method in both frequency and time domain to the Ridgecrest earthquake sequence. We also apply the EGF method to a Distributed

Acoustic Sensing (DAS) array with 1250 channels that recorded many aftershocks to measure the spectral ratio and relative source time function (RSTF). The 10-km long EW oriented DAS array is located to the Southwest of the Ridgecrest earthquake and recorded many aftershocks.

Systematic comparison of spectral ratio using from the seismic network shows overall consistency between different methods., Hhowever, we found that the time window and low-frequency bandwidth strongly influence the measured spectral ratio and corner frequencies. Events that show rupture complexity have larger discrepancy than simple events.

Comparison between DAS array and nearby seismic station SRT found good agreement in the shape of the spectral ratio. The RSTFs source time function resulted from complex spectral ratio shows good agreement., However, the time-domain deconvolution of DAS array data shows high degree of complexity, which is possibly from overfitting, and may need improvement. Our approach directly applies EGF analysis to the strain data recorded by DAS array without converting to velocity or acceleration. T, and the agreement from spectral analysis demonstrates the potential of directly using DAS for earthquake source parameter studies.

Assessing the Accuracy of Earthquake Stress Drop Estimation Methods for Complex Ruptures Using Synthetic Earthquakes

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We evaluate how well simple, commonly used stress drop estimation methods are able to recover the known stress drop of synthetic, complex ruptures, constructed by combining multiple simple kinematic source models. Earthquake stress drop is a commonly estimated parameter that can provide insight into both earthquake source physics and the resulting ground motion. Stress drop methods usually assume that earthquakes are a symmetric circular crack which release their energy in a single pulse with a simple, symmetric source time function (STF). Real earthquakes, however, often have complex source time functions with multiple pulses of seismic moment release. Because recent studies have shown that stress drop estimates contain significant uncertainties, and independent analyses of the same earthquakes often produce conflicting estimates, we seek to identify how different methods perform on the known, synthetic, complex events.

In this study, we create a synthetic catalog of complex rupture earthquakes by combining multiple simple, circular-crack spectral models to create complex STFs with known static stress drops. We then apply time-domain methods (i.e., rupture duration) and frequency-domain methods (such as corner frequency) to estimate stress drop. Our results suggest that the frequency-domain method performs better than the time-domain method when applied to complex earthquakes. However, frequency-domain stress drop estimates more strongly correlate with the stress drop of the largest moment pulse rather than the average stress drop of the entire rupture area. Identifying which stress drop estimation methods (or combination of methods) perform best under which circumstances will allow us to reassess prior stress drop studies to determine whether observations reflect real tectonic trends or are simply artifacts of the methodology. This analysis will help lead to new insights into earthquake source processes and more accurate assessments of future earthquake hazards.

Apparent Stress of Moderate Sized Earthquakes in Southern California

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Using S-wave records at epicentral distances less than 60 km we determine the apparent stress for 62 Mw≥4.5 earthquakes in southern California since 2000. All earthquakes have reliable network moment tensor solutions. We compute seismic radiated energy with two methods: a time domain method by Kanamori et al. (2020) and a frequency domain method by Boatwright et al. (2002). The Kanamori approach (GR) is a modified Gutenberg-Richter in which attenuation and near surface effects are not considered. The Boatwright method uses path attenuation, near surface kappa0, and a station specific radiation pattern. With Boatwright we compute seismic energy 1) with an average radiation pattern (F0) and 2) with station specific radiation pattern (F1). The geometric means of apparent stress are 0.48, 0.40 and 0.57 MPa for GR, F0 and F1, respectively. Apparent stress is independent of seismic moment for these earthquakes. Converting apparent stress to Brune's stress drop (Andrews, 1986), we find stress drops of 2.1, 1.7 and 2.5 MPa for GR, F0 and F1, respectively. From the perspective of seismic radiated energy, a Brune stress drop is nearly the same as that when using Madariaga (1976) and Kaneko and Shearer (2014) models (Ji, Archuleta and Wang, 2022). The standard deviation of stress drop (log10) is 0.35—almost the same for GR, F0 and F1. Cotton et al. (2013) show the standard deviation from stochastic vibration theory used in ground motion prediction equations is 0.15 for Mw>5.5 earthquakes. Seismic moment/corner frequency methods produce a standard deviation of 0.61, though the magnitude range is larger in some studies. Apparent stress (and consequently stress drop) shows a statistically significant depth dependence (~0.05 MPa/km).

Understanding the Variability in Earthquake Stress Drop Measurements [Poster]

Poster Session • Thursday 20 April

Conveners: Colin N. Pennington, Lawrence Livermore National Laboratory (pennington6@llnl.gov); Shanna Chu, U.S. Geological Survey (schu@usgs.gov); Trey Knudson, Stanford University (trey05@stanford.edu); Meichen Liu, University of Michigan (meichenl@umich.edu); Ian Vandevert, University of California, San Diego (ivandevert@ucsd.edu); Rachel Abercrombie, Boston University (rea@bu.edu); Annemarie Baltay, U.S. Geological Survey (abaltay@usgs.gov); Kevin Mayeda, Air Force Technical Applications Center (kevin.mayeda@us.af.mil); Taka'aki Taira, University of California, Berkeley (taira@berkeley.edu); Kilian Kemna, Ruhr University Bochum (kilian.kemna@web.de)

Between and Within Region Comparison of Source Parameters: Applications of the Coda Calibration Tool (CCT)

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Between and within region comparison of source parameters (e.g., seismic moment and stress drop) is hampered by the inconsistencies that arise when different approaches are considered (Baltay et al., 2022). To overcome this problem, we present the application of the Coda Calibration Tool (CCT) to different tectonic settings for closer analysis of the regional variations. CCT implements the empirical methodology outlined in Mayeda et al., (2003), which provides reliable source spectra even for events recorded by sparse local and regional seismic networks (*e.g.*, Morasca et al., 2022). We use independent ground-truth (GT) reference spectra for which apparent stresses are independently calculated through the coda spectral ratio (Mayeda et al., 2007), to break the path and site trade-off. The use of GT spectra eliminates the need to assume source scaling for the region, reducing the impact of *a-priori* model assumptions on the interpretation of scaling laws of source parameters and their variability. The CCT is a freely available Java-based code (https://github.com/LLNL/coda-calibration-tool) that significantly reduces the coda calibration effort and provides calibration parameters for future use in the same region for routine processing.

Recently, several studies applied CCT in very different tectonic contexts, including (1) earthquakes in tectonically active regions (*e.g.*, central Italy, Puerto Rico, southern California, Utah); (2) induced earthquakes in southern Kansas and northern Oklahoma; and (3) moderate-sized earthquakes in stable continental regions such as in Eastern Canada and the United Kingdom. We summarize the results from these studies here, showing that the application of a consistent methodological framework and the robustness demonstrated by the results of the seismic coda analysis, allow comparison of source scaling relationships for different tectonic settings over a wide range of magnitudes.

W.R. Walter and J. Barno's portion prepared by LLNL under Contract DE-AC52-07NA27344

Earthquake Source Parameters and Their Uncertainties Estimated From S-Wave Maximum Amplitudes Using Amplitude Decomposition: Application to the 2019 Ridgecrest Sequence

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Earthquakes radiate a wide spectrum of seismic energy, from which properties like seismic moment and stress drop can be estimated. A common approach to large data sets of local earthquakes with many sources and receivers is spectral decomposition, which first separates event terms from station and other path terms and then solves for a best-fitting source model. A common problem in spectral decomposition is a poor signal-to-noise ratio for smaller earthquakes at low frequencies, which prevents setting the lower frequency limit low enough to accurately measure the moments and corner frequencies of the largest earthquakes. Here we experiment with a new method for amplitude decomposition, which measures the maximum shear wave amplitude of bandpass filtered seismograms as a function of event-dependent effects, station-dependent effects, and path effects. We produce spectra by filtering at different bands and assembling the decomposed results in the frequency domain. The main benefit of this method is that spectra appear reliable at frequencies about an order of magnitude lower than with P-wave spectral decomposition applied to the same events. We estimate source parameters and their uncertainties by applying this method to seismic data generated during the 2019 Ridgecrest earthquake sequence, compare the results to previous spectral decomposition studies, and explore any implications for source-scaling issues.

Measuring Source Parameters With Filtered Peak S-Wave Amplitudes Using the Asymptotic Spectral Ratio Method

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Measuring stress drop, a physical source characteristic that relates the average slip to fault size, is important for ground motion prediction and earthquake source physics. Different studies commonly find strong variability in stress drops within the same datasets, but much of this apparent variability arises due to difficulty in accurately measuring the corner frequency. As part of the community stress drop validation study, we present a method using spectral ratios and apply it to the Ridgecrest sequence. Stress drop ratios remove the common path and site effects from co-located events, to determine stress drop variability without the need to directly calculate corner frequencies. To form the ratios, we first calculate an earthquake's observed frequency spectrum using maximum amplitudes in a series of band-pass filters on a displacement seismogram. Spectra determined this way have shown reliable moments and corner frequencies. From a pair of co-located events, we take the ratio of observed spectra, where the low-frequency asymptote is the ratio of the moments, and the high-frequency asymptote is the ratio of the slips. From these quantities we measure the stress drop ratio between both events. This method doesn't rely on distinguishing corner frequencies, so unlike traditional spectral ratio methods, it can be used on earthquakes of similar size. These measurements will help determine how variable stress drops are, and have the potential to provide particular insight into potential differences in similar-sized events.

Spatial variations in the source spectra of Southern California earthquakes

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We show observed variations of earthquake spectra in Southern California earthquakes which support several physical mechanisms for source-level complexity. The spectrum of seismic radiation from earthquakes are usually fit to a model derived from an analytical crack solution. However, real earthquakes are observed to have complex radiated spectra. This becomes problematic for hazard estimation when parameters related to ground motion, such as earthquake stress drop, cannot be accurately estimated due to this complexity. Complexity of waveform recordings can be attributed to various physical mechanisms in the earthquake source itself. In our recent study, we defined new metrics using fault maps to quantify the complexity of groups of faults within selected polygonal regions, specifically attempting to capture the possibility that faults in a complex network could interact. We found that enhanced high-frequencies in observed earthquake spectra from the broader Southern California region tend to correlate with locally misaligned faults having disordered orientations, suggesting that structural interactions between different parts of the fault system may play a role in generating the ground motions felt during earthquakes. Focusing on a smaller study area of the 2019 Ridgecrest earthquake and its aftershocks, we examine variations in spectral shape that arise from using differential methods to deconvolve source spectra from the observed waveform (which includes effects from the source, wave propagation, and station site response). These variations show that spatial patterns of spectra variability continue from the fault-map scale to a more local scale, and also may have an azimuthal dependence. Our observations support several physical mechanisms of spectral complexity at the source level, such as meter-scale structural collisions or stress heterogeneity, which can affect the amount of high frequencies produced by earthquakes.

Stress Drop Estimates Using the Attenuation Parameter Kappa for Earthquakes in the SCEC/USGS Community Ridgecrest Dataset

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Estimates of earthquake stress release, regional attenuation and site effects are needed for ground motion prediction and are essential to improve our understanding of the factors controlling both the statics and dynamics of the rupture process. The ongoing community stress drop validation study is aimed at improving measurements of these fundamental parameters. Calderoni et al. (2010, 2014) developed a two-step approach to modeling attenuation and then estimating source parameters from individual earthquake spectra. To test and verify this spectral fitting approach we apply it to the common dataset provided by the community study. The dataset consists of 2 weeks of earthquakes in the 2019 Ridgecrest, California, sequence.Following Calderoni et al., 2019 first we calculate the regional kappa attenuation (k) parameter by averaging 6 earthquakes with magnitude from 5.0 to 5.6. We select these large, well recorded events to estimate spectral falloff because they have the best signal-to-noise ratio over the widest frequency range. We correct the spectra using the k parameter and normalize to unit distance. Second, we estimate the site term accounting for attenuation and amplification in the near-surface beneath the station. For each event, we average the attenuation-corrected scaled spectra at available stations and compute the difference from the mean event spectrum for each station. These differences are averaged over the event ensemble to obtain a mean site term for each station. We then correct each recorded velocity spectrum for regional attenuation using the k values and for the site effects calculated at each station. We then fit the resulting source spectra assuming a simple circular source model (e.g., Brune, 1970; Madariaga, 1976) to estimate the corner frequencies and stress drop of each event. We investigate how selection choices used in the analysis including station selection and signal frequency range affect the results and compare our measurements with those of other research groups.

USGS National Seismic Hazard Models: 2023 and Beyond

Oral Session • Tuesday 18 April • 08:00 AM Pacific

Conveners: Peter M. Powers, U.S. Geological Survey (pmpowers@usgs.gov); Jason M. Altekruse, U.S. Geological Survey (jaltekruse@usgs.gov); Sanaz Rezaeian, U.S. Geological Survey (srezaeian@usgs.gov); Kishor S. Jaiswal, U.S. Geological Survey (kjaiswal@usgs.gov); Mark D. Petersen, U.S. Geological Survey (mpetersen@usgs.gov); Emel Seyhan, Risk Management Solutions (emel.seyhan@rms.com)

2023 U.S. 50-State National Seismic Hazard Model

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We are developing the 2023 U.S. National Seismic Hazard Model for all 50 states by applying new seismicity, fault rupture models, and ground motion assessments. We consider two types of models: (1) a public model that guides hazard assessments intended for building code provisions and policy applications and (2) a research model geared towards less formal applications that may be included in future public models. New data and methods will be introduced in the 2023 earthquake source components: earthquake catalogs - excluding induced earthquakes, alternative declustering methods, spatially smoothed seismicity, new geodetic- and geologic-based fault and deformation models, and earthquake rupture forecast models accounting for a more complete representation of potential earthquakes in Alaska, Hawaii, and the conterminous U.S. Improved ground motion models (GMMs) consider new NGA-Subduction, modified NGA-East and NGA-West2. Some GMMs and earthquake source models contain changes in median and aleatory variability that need to be evaluated and weighted. Amplification models will also consider available 3D simulations to supplement the empirical GMMs, and basin specific data in California Central Valley, Seattle Washington, Los Angeles California, and near Portland Oregon. New stress drop, tomographic, and other geophysical models help refine the complex boundary between the tectonically stable and active regions used in assigning GMMs. The research model may incorporate more geological information on timing of past earthquakes for time-dependent assessments and on regional variations in earthquake shaking - accounted for by a partially non-ergodic ground motion representation. Scenarios and population exposure assessments of these models will help users assess impacts of the earthquakes and facilitate risk mitigation measures.

Overview of the Final Earthquake Rupture Forecasts for the 2023 USGS NSHM

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On behalf of a very large group of co-authors, formal reviewers, and other contributors, this presentation provides a summary of the final time-independent Earthquake Rupture Forecasts (also known as seismic source characterizations) for the 2023 update of the USGS National Seismic Hazard Model. The main goals have been a more uniform application of methodologies across the country, a more complete representation of epistemic uncertainties, and establishing a basis for an eventual operational earthquake forecasting capability nationwide. Efforts also include a better representation of multi-fault ruptures and the ability to apply variable degrees of segmentation throughout each fault system (e.g., a wider range of models than applied previously in California). The presentation also summarizes updated geologic constraints, deformation models, statistical seismology components, efforts to operationalize various computer codes, hazard and risk sensitivity analyses (e.g., for logic tree refinement), and priorities for future improvements.

Hazard Implications and Epistemic Uncertainties of the Updated Fault-System Inversion Model for the 2023 U.S. National Seismic Hazard Model

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A 50-state update to the U.S. National Seismic Hazard Model will be released in 2023 (NSHM23). NSHM23 will utilize an inversion-based methodology for active fault systems in the Western U.S., building upon the approach used in the 3rd Uniform California Earthquake Rupture Forecast (UCERF3). The fault-system inversion approach accommodates relaxation of fault segmentation assumptions and inclusion of multi-fault ruptures. Acknowledging scientific disagreement and lack of knowledge related to the propensity of multifault ruptures, connectivity, and MFDs on individual faults, we introduce new constraints to explicitly model a wide range of rupture behaviors. The updated epistemic logic tree contains segmentation branches ranging from fully segmented to fully unsegmented, as well as fault MFD branches ranging from Gutenberg-Richter b=0 to b=1.

We will describe the new model and show hazard comparisons between it and UCERF3, distinguishing between changes resulting from methodological enhancements (i.e., inversion setup and constraint implementations) and ingredient changes (i.e., deformation models and scaling relationships). We will also present branch choice-specific hazard results, highlighting the impact of each epistemic logic tree branch on mean hazard.

A Fault-Based Crustal Deformation Model With Deep Driven Dislocation Sources for the 2023 Update to the US National Seismic Hazard Model

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We apply a fault-based crustal deformation model with deep driven dislocation sources to estimate long-term on-fault geodetic slip-rates and off-fault moment rate distribution in the Western United States (WUS) for the 2023 update to the National Seismic Hazard Model (NSHM). This model uses the method of Zeng and Shen (2017) to invert for slip-rate and strain-rate parameters based on inputs from global positioning system (GPS) velocities and geologic slip-rate constraints. The model connects adjacent major fault segments in California and the Cascadia subduction zone to form blocks that extend to the boundaries of the study area. Faults within the blocks are obtained from the NSHM geologic fault model. The geodetic slip rates are determined using a least-squares inversion with a normalized chi-square of 6.6. We also apply a time-dependent correction called "ghost transient" effect to the data to account for the viscoelastic responses from large historic earthquakes along the San Andreas Fault and Cascadia subduction zone. Major discrepancies between geodetic slip rates and geologic slip rates along the San Andreas Fault, for example, from the Cholame to the Mojave and San Bernardino segments of the San Andreas, are well-resolved after we apply the ghost transient correction to GPS velocities. Off-fault moment rate distribution is consistent with regional tectonics and seismicity patterns with a total rate of 1.6×10^{19} N·m/year for the WUS.

The 2023 update of the Alaska National Seismic Hazard Model

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The U.S. Geological Survey (USGS) is developing a major revision to the Alaska portion of the 2023 National Seismic Hazard Model (NSHM). This update will incorporate new data and models that have been gathered and published since the last update to the Alaska NSHM in 2007. The 2023 Alaska NSHM includes updates to both source, or earthquake rupture forecast (ERF), and ground motion model (GMM) components. The ERF includes updates to the crustal fault inventory and considers both geologic and geodetic rate models. The large-magnitude subduction interface model uses an updated segmentation and structural model (based on the SLAB2 geometry of the Alaska-Aleutian arc) and includes geologic, geodetic, and earthquake catalog-derived earthquake rates. A new catalog that includes earthquakes from 2007 to 2020 has been compiled to inform the rate model for the both the crustal and subduction gridded seismicity components. Calculation of the gridded seismicity rate models considers multiple declustering and smoothing methods and subduction interface (small magnitude) and intraslab sources are modeled at depths derived from SLAB2. For the GMM component, the model uses the new NGA-Subduction GMMs with regionalization for Alaska for both interface and intraslab sources and the NGA-West2 GMMs for crustal sources. Here we present implementation details of the above model components and comparisons to the prior NSHM from 2007.

Towards Regionalized Earthquake Source Models of Subduction Interface Earthquakes

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In Skarlatoudis et al. (2016; Sea16) we developed a set of global scaling relations using seismic moment (M_0) to predict physical source properties such as earthquake rupture area (S), total asperity area (S_a), slip (D), and fault width (W), for large subduction interface events. These relations significantly reduced the aleatory variability in predicting these source parameters. In this work, we present an augmented database of subduction interface events, including 79 additional events with published finite fault solutions that have been catalogued in the USGS Finite Fault database, the Online Database of Finite Fault Rupture Models (Mai and Thingbaijam, 2014), and the Next Generation Attenuation Subduction (NGA-Sub) database. These additional models are used to update the Sea16 set of global scaling relations, further improving the predictions of various source properties and minimizing uncertainties.

For the subduction zones with a sufficient number of earthquakes in our database, we also develop regionalized scaling relations and seek physical explanations for regional differences in subduction interface ground motions by examining correlations with physical parameters, as considered by Schellart and Rawlinson (2013), Heuret et al. (2011) and Schafer and Wenzel (2019). The regionalization terms are estimated as random effect terms in linear mixed models, and the use of Bayesian Analysis with appropriate distributions for the model terms is also evaluated.

Incorporating the M9 Project Simulations Into Non-Ergodic Site and Path Terms for the Cascadia Region Outside the Seattle Region

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Sung and Abrahamson (2022) incorporated the simulations for the Seattle region from the M9 Project (Frankel et al., 2018) into the Abrahamson and Gulerce (2020) (AG20) ground-motion model (GMM), resulting in a partially non-ergodic GMM that captured the long-period site-specific combined site and path effects due to the 3-D crustal model for large-magnitude Cascadia interface earthquakes. The M9 Project also simulated the ground motions for the larger Cascadia region but with sparser spatial sampling of 20 km x 20 km. We use these simulation results to develop the non-ergodic site and path effects for the larger Cascadia region. The average basin-depth (Z2.5) scaling for the larger region has weaker basin effects than for the Seattle region. As a result, extrapolating the Seattle-region non-ergodic GMM outside the Seattle region does not work well for shallow basin sites. The non-ergodic terms for the larger Cascadia region span a smaller range than for the Seattle region. Overall, the non-ergodic aleatory variability for the non-ergodic GMM outside the Seattle region was reduced by 15% compared to the global aleatory variability of the AG20 model. This is similar to the reduction for the global single-station sigma, indicating that the path effects from the 3-D crustal structure are not strong outside the Seattle region. In addition, sites located close to the coastline at rupture distances less than 40 km show a significant increase in both the median and the aleatory variability compared to sites at distances larger than 50 km. This increase in the standard deviation is likely related to the variability of the distances to the main subevents in M9 earthquakes for the same rupture distance. The ergodic and non-ergodic hazards are compared for a suite of site locations. For example, using the non-ergodic GMM for the Portland region, the T=3 sec spectral acceleration with a 10,000-yr return period is a factor of 1.16 larger than the results for the ergodic GMM.

PSHA Study for the State of Hawai'i Based on Regionalized Seismic Source Characterization and Ground Motion Characterization Models

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The State of Hawai'i spans the range from high levels of seismicity and active tectonics located around the island of Hawai'i to more stable and quiescent seismicity located around the island of Kauai. Given the observed active tectonics, volcanism, and seismicity, the area around the island of Hawai'i has some of the highest seismic hazard ground motion levels in the United States. A regionalized probabilistic seismic hazard analysis (PSHA) study was conducted for 81 sites located across the state of Hawai'I using a standard state of practice PSHA methodology.

To support the PSHA calculations, an updated seismic source characterization (SSC) and ground motion characterization (GMC) model were developed. For the SSC model, both crustal faults and regionalized seismicity were included based on previous fault models and an updated seismicity catalog. Given the potential damage significance from mainshocks as well as aftershocks, the rates for the gridded seismicity sources were developed for both a declustered and non-declustered catalog (i.e., including aftershocks) as part of the SSC model. The spatial distribution of events was only based on the declustered catalog. For the GMC, an evaluation with observed strong motion recordings in Hawai'i was performed to select the appropriate ground motion models. As part of this evaluation both current crustal models and subduction models were evaluated given the observed depth of events in Hawai'i, spanning from shallow depths of <20 km to intermediate depths of 20 – 40 km. For the aftershock sources, adjustments were applied to the ground motion models to account for an expected reduction in ground motions from aftershocks relative to mainshocks. We will present the significant SSC and GMC regionalized model features, the deviations from the recently released Hawai'i USGS models, and discuss the overall results from this PSHA study.

Update of NGA-East Database to Include Central and Eastern North America Events Since November 2011

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The NGA-East database was developed as part of a Senior Seismic Hazard Analysis Committee process during the NGA-East Project (Goulet et al. 2021[1]). That database includes data and metadata from events up to November 2011 and was used in the development of ground motion models and site amplification models applicable to stable continental regions. The coverage of seismic instrumentation in the central and eastern portions of North America has increased in recent years and the quality of instruments now provide data over a broader useable frequency range. To leverage this improved information for ground-motion research, while maintaining data quality protocols typical of NGA projects, we have expanded the NGA-East database to include the recent data. Due to the uncertainty of potentially-induced-events in Oklahoma, the data for this region was obtained from Li et al. 2023[2]. This effort has three major components: (1) data processing; (2) consistent metadata compilation; and (3) organization of the data into a relational database. To facilitate efficient data processing while maintaining protocols for human inspection of waveforms to ensure reliability, we worked with collaborators to expand the capabilities of the United States Geological Survey's automated processing code gmprocess (Thompson et al. 2023[3]) to include displacement drift checks in the selection of high-pass corner frequencies. The metadata for newly added events includes moment magnitudes from moment tensor solutions for 76 of 100 events, and estimates provided with uncertainties for the remaining 24 events. Rupture distances are computed from simulated finite faults following standard NGA procedures. Site parameters are derived from V_S profiles where available and the Parker et al. (2017)[4] geology-slope proxy otherwise. The data is archived in a relational database that connects 25 tables of data, metadata and intensity measures. Relative to the original NGA-East database, the dataset grew 72% in the number of recordings, with a significant increase (from 4400 to 10200) in usable records at low periods.

Development of a Site Response and Hazard Model for the U.S. Atlantic and Gulf Coastal Plains With a Geology-Based Shear Wave Velocity Model

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The Atlantic and Gulf Coastal Plains consist of low-velocity sediments and sedimentary rock overlying high-velocity bedrock, which significantly impacts the amplitude and duration of earthquake ground motions. Evaluating seismic hazards in the U.S. Coastal Plains requires a thorough understanding of how both geology and sediment thickness influence seismic wave propagation in the region. Existing site amplification and seismic hazard models for the coastal plains are limited in their characterization and modeling of these factors. Our project seeks to improve the characterization of site response in the coastal plains and incorporate it into probabilistic seismic hazard estimations for the region. In this study, a new grid-based model of site response in the coastal plains has been developed based on an integration of Vs measurements, knowledge of the geology in the region, and a literature review on representative Vs values at reference bedrock conditions. The resulting model was compared to other available amplification models by focusing on the input variables of sediment thickness and ground shaking intensity. Existing measured Vs profiles located throughout the coastal plains were sorted into five geologic groups. A median Vs profile was determined for each geologic group and assigned within the grid-based site amplification model according to the spatial distribution of geologic units at the surface. The modulus-reduction and damping curves used in the site response analyses were also selected on the basis of geology. These critical model updates provide a significant advancement in the characterization of site responses at regional scales and their effective incorporation in seismic hazard maps.

Bias of NGA-East GMMs and Site Amplification Models Relative to Supplemented Cena Ground Motion Database

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In this study we investigate bias in the median ground motion model (GMM) and linear site amplification model created as part of the Next Generation Attenuation project for stable continental regions (NGA-East), and present a bias adjustment term that can be used in forward applications. Bias is anticipated because these models were not developed in an iterative manner and the ground motion data used to calibrate the GMMs were modified to a reference site condition using ergodic site amplification models appropriate for active tectonic regions. Moreover, the F_{760} term in the site amplification model (amplification of sites with V_{S30}=760 m/s relative to the reference of 3000 m/s) carries significant parametric uncertainty in κ_0 (high-frequency spectral decay parameter) due to the lack of empirical data at the reference site condition. Using an expanded version of the NGA-East database (Ramos-Sepulveda et al. 2023) in which potentially triggered events in the Texas-Oklahoma-Kansas region were excluded, we compute residuals from the median versions of the GMM and site amplification models. The residuals were partitioned using mixed-effects analysis to quantify bias, event terms, and within-event residuals. With over 1500 recordings with periods from 0.01 to 3 sec and over 900 recordings from 3 to 10 sec, we find period-dependent bias in 5% damped response spectral acceleration across a wide period range. Results depict a negative bias (indicating over-prediction) at short periods (0.01 to 0.5 sec) and null to positive bias at longer periods. We do not find strong regional trends in event terms, suggesting this bias is not isolated to one region and may be widespread throughout central and eastern North America (CENA). A bias correction factor is proposed for short-term utilization in applications including the National Seismic Hazard Model. In the future, modifications to the GMMs or the site amplification models will be developed to remove this bias.

Evaluating Bias of NGA-EAST GMMs and Site Factors for Ground Motions From Natural and Potentially Induced Earthquakes in Texas, Oklahoma, and Kansas

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To empirically investigate the bias and linear site amplification of the median NGA-East ground motion model (GMM, Goulet et al. 2021) in predicting ground motions from natural and potentially induced earthquakes in Texas, Oklahoma, and Kansas, we developed a database containing ground motion recordings in the study region with moment magnitude greater than 3.5 and rupture distances smaller than 500 km. The same protocols in Ramos-Sepulveda et al. (2023) are utilized to establish the database. A reference empirical approach (Atkinson 2008) is utilized to adjust the magnitude and distance scaling of the NGA-East median GMM based on the observed data, and a GMM for the region is developed. The site amplification model relative to =760m/s developed in this study is compared to the site amplification models for Central and Eastern North America (CENA) from Parker et al. (2019) and Zalachoris and Rathje (2019). The comparisons suggest similar site amplification effects reflected by the dataset used in this study to those in the other studies. However, the overall bias adjustment factor in the GMM shows discrepancies from the simulation-based model suggested by Stewart et al. (2020). The bias is negative at shorter periods of T<0.1 s and is positive at longer periods, reaching values up to 1.0 (in ln-units) at periods longer than 3.0 s. The negative bias at shorter periods may be associated with the choice of value of reference κ when developing the NGA-East GMM, while the large positive bias at longer periods is difficult to explain physically as a site amplification effect. This large bias may be due to issues with assigning moment magnitudes to much of the data or bias in sampling of the ground motion data, where ground motions of smaller amplitudes are more likely to be dropped because of noise at low frequencies.

A Framework for Incorporating Epistemic Uncertainty in Site Effects in National Building Codes

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Probabilistic seismic hazard analysis (PSHA) is the basis for the development of the National Seismic Hazard Maps (NSHM) produced by the USGS. These maps are adopted by building codes for the design of structures. This research intends to provide a framework by which the NSHM can be postulated in terms of a new paradigm: partially non-ergodic PSHA. Within this approach, PSHA analyses are conducted using the so-called single-station sigma, which is the aleatory variability that results after accounting for repeatable site effects at every station. In recent years, seismic hazard analyses that have been conducted for critical facilities, such as Nuclear Power Plants, have been performed within the framework of partially non-ergodic PSHA; the proposed research aims to introduce these advancements into the NSHM and national building codes. The proposed framework for implementing non-ergodic PSHA in building codes builds on the current framework by introducing a correction factor called 'ergodicity factor' that accounts for the inherent ergodic assumptions in PSHA. These factors are postulated as a function of the level of knowledge on site properties reflecting the fact that uncertainty in site effects is considered as epistemic in partially non-ergodic PSHA. The ergodicity factors are computed for NEHRP site classes for varying levels of site characterization. It was observed that the factors increase with increase in uncertainty on the estimates of shear wave velocity at a site, indicating increase in design motions with increase in epistemic uncertainty. Given that lower uncertainty leads to lower design values, the proposed framework incentivizes practitioners for investing more in site characterization in expectation of lower design seismic loads. The resulting reduction in hazard, however, is relatively minor.

An Update to FEMA P366: Estimating Annualized Earthquake Loss Estimates in the United States

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Earthquake risk continues to rise within the United States given the rapid growth in human and economic exposure complemented by the fact that much larger fractions of built assets are located in high earthquake hazard areas. Although modernization of seismic codes and advancements in seismic design, construction, and retrofitting practices have greatly increased life safety over time, the bulk of the earthquake-induced losses is due to damage to nonstructural components and contents. We conduct systematic assessments of earthquake risk by utilizing the latest building inventory, exposure, and earthquake hazard data to evaluate annualized earthquake losses in the United States—a step towards updating the 2017 FEMA P366 study. Specifically, the newly released Hazus 6.0 model is employed that incorporates significant updates to building inventory, demographics, and replacement cost models, resulting in a more than 42% increase in total building replacement value relative to the previous version of Hazus. The hazard data considered are based on the 2018 National Seismic Hazard Model (NSHM) for the Conterminous U.S. and the 2021 NSHM for Hawaii. It should be noted that older data are still used for Alaska (2007), Puerto Rico (2003), and the U.S. Virgin Islands (2003).

Our analysis indicates that annualized earthquake losses have more than doubled across the country to 14.7B USD of which 9.6B is from California alone. This presentation will discuss data enhancements, updates to hazard and exposure mapping, and geographic distribution of earthquake risk in the United States. In addition, we compare the impact on AEL estimates of changing from 2014 to the 2018 NSHM for the Conterminous U.S. The results from the FEMA P366 study are now widely used in a variety of applications supporting earthquake mitigation programs including the distribution of state NEHRP grants.

Earthquake Hazard Prediction Software for South Carolina Considering Local Geology and Seismicity

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South Carolina is one of the seismically active regions in the eastern United States. The 1886 Charleston earthquake (M_w =7) produced damaging levels of ground shaking, and a repeat of such an earthquake can cause catastrophic damage to infrastructures. Seismic site response analysis is conducted to predict the earthquake hazard level at a site for designing infrastructures. An in-house computer program SCENARIO_PC provides SCDOT engineers with ground motions at the hard rock (V_s = 3400 m/sec) and reference outcrop conditions (V_s = 700 m/sec in the Coastal Plain and V_s = 2500 m/sec in Piedmont) for conducting site response analysis. SCENARIO_PC is currently a DOS-based version that uses old attenuation models for generating synthetic ground motions, primarily based on western United States seismic events.In this study, SCENARIO_PC is updated into a Windows-based graphical user interface (GUI) software that generates acceleration design response spectra and time histories for any site in SC. The updated program uses the latest Central and Eastern United States Seismic Source Characterization (CEUS-SSC) and Next Generation Attenuation – East (NGA-East) ground-motion models to construct site-specific uniform hazard spectra (UHS) and deaggregation results for hard rock and new reference outcrop conditions in SC. It is configured to use either real earthquake ground motions from any database or generate a synthetic ground motion using the point-source stochastic model. After having seed time histories, performing spectral matching in the time or frequency domain is implemented in the program. It can spectrally match with UHS at all periods or scales to match a specific period of interest. The baseline correction algorithm is implemented to correct any drift error in generated time histories. The software has a graphical interface to view the results, post-process, and can be exported into any standard format. Hence, this comprehensive software package is a cost-effective solution that is useful in making engineers work more efficiently and less prone to errors in performing the site-specific response analysis.

USGS National Seismic Hazard Models: 2023 and Beyond [Poster]

Poster Session • Tuesday 18 April

Conveners: Peter M. Powers, U.S. Geological Survey (pmpowers@usgs.gov); Jason M. Altekruse, U.S. Geological Survey (jaltekruse@usgs.gov); Sanaz Rezaeian, U.S. Geological Survey (srezaeian@usgs.gov); Kishor S. Jaiswal, U.S. Geological Survey (kjaiswal@usgs.gov); Mark D. Petersen, U.S. Geological Survey (mpetersen@usgs.gov); Emel Seyhan, Risk Management Solutions (emel.seyhan@rms.com)

Analyses and Implications of Deformation Models of the U.S. National Seismic Hazard Model 2023

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Five deformation models were developed as potential inputs for the 2023 update of the National Seismic Hazard Model (NSHM). Four of these models rely on GNSS velocity data as primary constraints (the "Zeng," ShenBird," "Pollitz," and "Evans" models), and one relies on published geologic slip rate information as the primary constraints ("geologic"). The five-model suite seeks to characterize the range of epistemic uncertainties on deformation rates across the western U.S. Given that all five models have different governing assumptions and modeling choices, there is significant variability of on-fault slip rates within the suite for many faults. This variability within the suite presents a conundrum: which deformation model rate is the "right" value for seismic hazard analysis? Here, we present an outlier analysis of the five-model suite, discuss the influence of deformation model assumptions within the fault system solution (inversion) framework, and highlight implications of different branch weight options on hazard metrics. We find that the Evans and Pollitz models account for the most variability within the five-model suite, with these models supplying rates ~5x greater or less than the median rate. In contrast, the Zeng, ShenBird, and geologic models provide the median rate for ~85% of all faults. We show that branch weights for deformation models can locally impact peak ground acceleration (2% in 50 year) by a factor of ~2. Refining existing deformation models, including testing alternative assumptions within each model to provide null space exploration, will be key for defining epistemic uncertainties in future fault system solutions.

Evaluating Spatial Smoothing for the 2023 USGS National Seismic Hazard Model

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A long-term model for earthquake occurrence is a critical component for probabilistic seismic hazard assessments (PSHA). One approach to constructing these models is declustering and spatially smoothing an earthquake catalog in order to forecast the location of future seismicity. Past versions of the U.S. Geological Survey National Seismic Hazard Model (NSHM) relied on spatial smoothing methods using a two-dimensional Gaussian kernel of either fixed or adaptive (variable) bandwidth (Frankel, SRL, 1995; Helmstetter et al., SRL, 2007; Moschetti, BSSA, 2015). These two methods were represented as separate logic tree branches that were weighted and combined for the final hazard model. As the NSHM is updated for 2023, we re-examine these methods and explore different testing strategies to evaluate their performance, which can inform how they will be implemented in future models.

Likelihood-based methods are commonly used for testing spatial earthquake forecasts (e.g., the Regional Earthquake Likelihood Models and Collaboratory for the Study of Earthquake Predictability experiments, Schorlemmer et al., SRL, 2007; Zechar et al., BSSA, 2010). For the NSHM adaptive smoothing, they are used to optimize the nearest-neighbor number (*N*-value) that determines each event's smoothing distance (Moschetti, BSSA, 2015). For 2023, we are re-optimizing the *N*-values for both the western and eastern US because of changes in boundaries between and within the two regions. We explore the effect of choosing different durations of training and testing data sets for that optimization, and what might be most appropriate for a 50-year forecast, given that the data does not yet exist to test such a forecast. We also consider whether the fixed smoothing model, which often requires the use of floor rates in low-seismicity regions, can be replaced by an adaptive smoothing model with an appropriate *N*-value(s).

Evaluation and Integration of Seismic Directivity Models for the USGS National Seismic Hazard Model

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Several directivity models (DMs) have been developed in recent years to describe the near-source spatial variations in ground motion amplitudes related to propagation of rupture along the fault. We recently organized an effort towards incorporating these directivity effects into probabilistic seismic hazard analysis (PSHA), by first evaluating the community's work and selecting an approach that can be readily implemented into the USGS National Seismic Hazard Model (NSHM). Guided by this evaluation and comparison among the considered DMs, we chose to incorporate a computationally simple approach, which provides an azimuthally varying adjustment to the median ground motion and its aleatory variability. This method allows us to assess the impact on hazard levels and provides a platform to test the DM amplification predictions using a generalized coordinate system, necessary for consistent calculation of source-to-site distance terms for complex ruptures.

We give examples of the directivity-related impact on hazard, progressing from a simple, hypothetical rupture, to more complex fault systems, composed of multiple rupture segments and sources. The directivity adjustments were constrained to strike-slip faulting, where DMs have good agreement. We find that seismic directivity adjustments using a simple median and aleatory adjustment approach can impact hazard both from a site perspective and on a regional scale, increasing shaking off the end of the fault trace and potentially reducing it for sites along strike. Statewide hazard maps of California show that the change in shaking along major faults can be a significant factor to consider for assessing long-period near-source effects within the USGS NSHM going forward. Finally, we suggest consideration of minimum parameter ranges and baseline requirements as future DMs are developed to minimize single approach adaptations and enable more consistent application within both ground motion and hazard studies.

Ground Motion Model for Small-to-Moderate Potentially Induced Earthquakes using Machine Learning Algorithms

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Ground motion models play vital roles in probabilistic seismic hazard analyses and seismic uncertainties. New ground motion models (GMM) are developed using non-parametric machine learning algorithms, including neural network, gradient boosting, support vector, k nearest neighbors, and random forest regression techniques. This paper evaluates the different machine learning models in predicting peak ground acceleration (PGA) and 21 spectral accelerations given the moment magnitude (Mw), rupture distance (Rrup) and average shear wave velocity of the upper 30 m of soil (Vs30). A database of 1336 ground motions (with small and moderate moment magnitude) ranging in magnitude from 2.8 to 5.8, recorded within a rupture distance range of 6–500 km in Central and Eastern North America, is used to train the algorithms. Linear regression-based models with predefined equations and coefficients are widely utilized. The requirement for predefined equations can restrict the use of complicated and nonlinear equations to improve performance. Compared to typical regression linear methods, the proposed GMM can increase the accuracy of GMM. Although the conventional regression model is more interpretable, machine learning can achieve a better result if enough training data is available. To evaluate the performance of different regression techniques in machine learning, mean square error (MSE), mean absolute error (MAE), explained variance score (Var), and the coefficient of determination (R2) are considered. Gradient boosting regression offers a better performance according to error metrics.

Furthermore, a machine learning weighted ensemble method is applied to develop the hybrid model. The weighted ensemble method is used to improve the GMM performance by combining the regression results of the algorithms. Based on the evaluation of regression models, the coefficient of determination (R2) increase in the hybrid model compared to different machine learning technique.

Hybrid Empirical Ground-Motion Models with Simulation-based Site Amplification Factors for the Island of Hawaii

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The primary purpose of this study is to develop Ground Motion Models (GMMs) with Site Amplification Factors for the island of Hawaii. We develop GMMs using the Hybrid Empirical Method (HEM) with a companion simulation-based Site Amplification Model for the V_{S30} requirements of the National Seismic Hazard Mapping program (V_{S30} is time-averaged shear wave velocity in the upper 30 m of the site). Stochastically simulated Ground Motion Intensity Measures (GMIMs) in the host and target regions are utilized in HEM to develop adjustment factors that are applied to empirical GMIM predictions in the host region. The island of Hawaii, the target region in this study, has been the site of numerous large earthquakes with a growing database of strong ground motion observations. The crustal earthquakes on the island of Hawaii originate from volcanic activity and include both swarms of small-magnitude volcanic events and larger tectonic events. Ground motion modeling on the island of Hawaii is challenging due to the depth distribution of events and different anelastic attenuation characteristics. In the absence of an amplification model for the island of Hawaii, the proposed simulation-based amplification model can be used not only for the proposed GMMs but for all other previously developed GMMs that will be considered in the upcoming national seismic hazard maps updates. Since the hazard comes both from shallow crustal earthquakes and from deep events for the island of Hawaii, two separate GMMs are being developed. We consider the focal depth of 20 km to distinguish between shallow crustal and deep earthquakes. A moment magnitude range of 4.0 to 7.5 and Joyner-Boore distances of up to 400 km are considered. For the required seismological parameters in WNA, we use Zandieh et al. (2018) results. For the required seismological parameters in the island of Hawaii, we use Wong et al. (2020).

The 2023 Update of the Alaska National Seismic Hazard Model: Overview and Sensitivities

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The 2023 update for the U.S. Geological Survey (USGS) National Seismic Hazard Model (NSHM) for the state of Alaska includes updates to the seismic source model (SSM), or earthquake rupture forecast (ERF), and ground motion model (GMM) components. These updates incorporate new data and models gathered and developed since the previous update in 2007. The SSM is updated with an expanded crustal fault inventory and considers both geologic and geodetic rate models and includes several zone sources in key areas. Crustal and subduction gridded seismicity component rate models, based on an updated earthquake catalog that includes events from 2007 to 2020, incorporate multiple methods for declustering the catalog and smoothing spatial seismicity. Intraslab and small-magnitude interface sources are modeled with depths derived from the Slab2 (Hayes, 2018) geometry for the Alaska-Aleutian arc. The large-magnitude subduction interface model uses updated megathrust segmentation and model geometry (based on Slab2), and includes geologic, geodetic, and earthquake catalog derived earthquake rates. The 2023 NSHM for Alaska incorporates the NGA-West2 GMMs for crustal sources and the NGA-Subduction GMMs with Alaska-specific regionalization for both interface and intraslab sources. We present an overview of the preceding updates in the 2023 NSHM for Alaska, sensitivity calculations, and comparisons to the previous update in 2007.

Updating the Crustal Seismic Sources for the 2023 National Seismic Hazard Model for Alaska

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We present the crustal and intraslab seismic sources for Alaska, based on geologic observations, as a primary input for the 2023 revision of the USGS National Seismic Hazard Model (NSHM). Since the 2007 USGS probabilistic seismic hazard map for Alaska there have been significant improvements to our understanding of active faults across the state. We build on the 2013 Alaska Quaternary fault and fold database (Koehler, 2013) by updating it with recent findings, and new observations from recent high-resolution statewide DEMs. We then simplify that database into a model of 83 fault sections for which we provide basic geometric and rupture parameters including sense-of-offset and slip rate. Significant updates from prior maps include: 1) A slip rate of ~53 mm/yr on the Queen Charlotte fault system inferred from offshore mapping which accommodates all of the plate boundary motion (based on a lack of recognized active structures to the east). 2) Determination of long-term slip rates on megathrust seafloor splay faults in the southern Prince William Sound region and near Kodiak Island derived from seismic reflection and thermochronology studies. 3) Significantly improved details of contractional structures in the Chugach-St. Elias orogen. 4) Recognition that Holocene activity on the Castle Mountain fault is predominantly thrust faulting, not strike-slip. 5) Refinement of interior Alaska tectonic models that clarify the relationships between the Denali fault, Totschunda fault, and thrust faults on both the north and south sides of the Alaska Range. 6) We eliminate two faults in previous compilations: the Chatham Strait fault, and the Togiak-Tikchik sections of the Denali fault. The main unreconciled differences between our model and geodetic data are the lack of geologic evidence for active faulting in western Alaska, southwest of the Denali fault system, and the lack of geologic evidence for faulting to the east of the communities in southeastern Alaska, in the vicinity of the Coast Shear Zone. The revised NSHM could be tested by lacustrine paleoseismic records of strong shaking, such as at Eklutna and Skilak Lakes.

USGS NSHM Hazard Tool

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The U.S. Geological Survey (USGS) earthquake hazards website provides web services and applications that give users access to the National Seismic Hazard Models (NSHMs) for the United States and its territories. The NSHM Hazard Tool (https://earthquake.usgs.gov/nshmp) is the main entry point for end-users to calculate hazard and to query data for various USGS NSHMs. The tool currently supports the 2018 conterminous U.S. NSHM and the 2021 NSHM for the State of Hawaii with additional older NSHMs to be added soon. One advantage of recent improvements to the USGS hazard modeling codebase is that models currently under development (e.g., the 2023 NSHMs for the conterminous U.S. and Alaska) can be deployed to the tool for earlier end-user evaluation and adoption. In addition to providing web applications for hazard calculation and disaggregation, the NSHM hazard tool also provides model analysis applications. Applications for working with ground motion models include the response spectrum plotter and ground motion versus distance or magnitude plotters. Applications for working with source models, or earthquake rupture forecast, include a magnitude-frequency distribution plotter and a source data mapping application. All the web applications are backed by services such that the underlying data may be easily accessed via third-party applications (e.g., MATLAB, R). Moreover, each application provides export options to save any plot data in tabular form. Here we provide an overview of the various NSHM Hazard Tool applications, as well as examples of how to leverage the suite of underlying web services.

Using Geodetically-Derived Strain Rates in Future US National Seismic Hazard Models

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Geodetic data are now being used in developing the US National Seismic Hazard Map (NSHM) to estimate slip rates on crustal faults using various kinematic models that relate long-term fault slip rates to surface velocities. However, best practices for using geodetic data in the hazard models are still under consideration and challenges remain, especially in areas of diffuse faulting and distributed off-fault deformation, in inferring fault slip rates using geodetic data. Due to a lack of confidence in off-fault strain rate estimates generated by models of geodetic data, these off-fault rates were not used in the 2014 or 2023 NSHM hazard calculations. An alternative approach that was not adopted in 2023 NSHM is to use geodetically-derived strain rates directly, without introducing a kinematic model for surface velocities. Such an approach was adopted for the 2022 release of the New Zealand national seismic hazard model in which slip deficit rates on faults were inverted directly from strain rate observations. In this study, we address two major challenges of working with strain rates: 1. Strain rate inferences are non-unique, and the uncertainties are not well understood, and 2. Methods to infer slip deficit rate on faults directly from strain rate are underdeveloped. To address the first problem, we systematically compute and compare strain rate maps and uncertainties in the western US using suites of different methods for computing strain rates from geodetically-derived velocities. The methods include fitting non-parametric basis functions and elastic basis functions to geodetic data. We also conduct inversions of strain rate observations for slip deficit rates on all western US seismic hazard model faults (2023 NSHM fault model) using a viscoelastic earthquake cycle model that accounts for time-dependent viscoelastic mantle flow due to periodic locking and unlocking of the faults. We explore the uncertainty in slip deficit rate estimates introduced by uncertainties in strain rate observations and viscoelastic cycle model parameters.

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