Faculty of Mathematics, Physics and Informatics, Comenius University Bratislava
and
Earth Science Institute, Slovak Academy of Sciences, Bratislava

# Proceedings of the Workshop

## Numerical Modeling of Earthquake Motions: Waves and Ruptures

2024 NMEM
Waves and Ruptures

June 23 - June 27, 2024

Smolenice Castle, Slovakia

# PROCEEDINGS
# OF THE WORKSHOP

## Numerical Modeling of Earthquake Motions: Waves and Ruptures

# NMEM 2024

*June 23 - June 27, 2024,*
*Smolenice Castle, Slovakia*

http://www.nuquake.eu/NMEM2024

We appreciate the financial contribution from the National Science Foundation, Award 2346964, for supporting attendance by US participants in the workshop.

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Editors: Peter Moczo, Jozef Kristek, Martin Galis

Published by Library and Publishing Centre
Faculty of Mathematics, Physics and Informatics
Comenius University in Bratislava

ISBN: 978-80-8147-140-7

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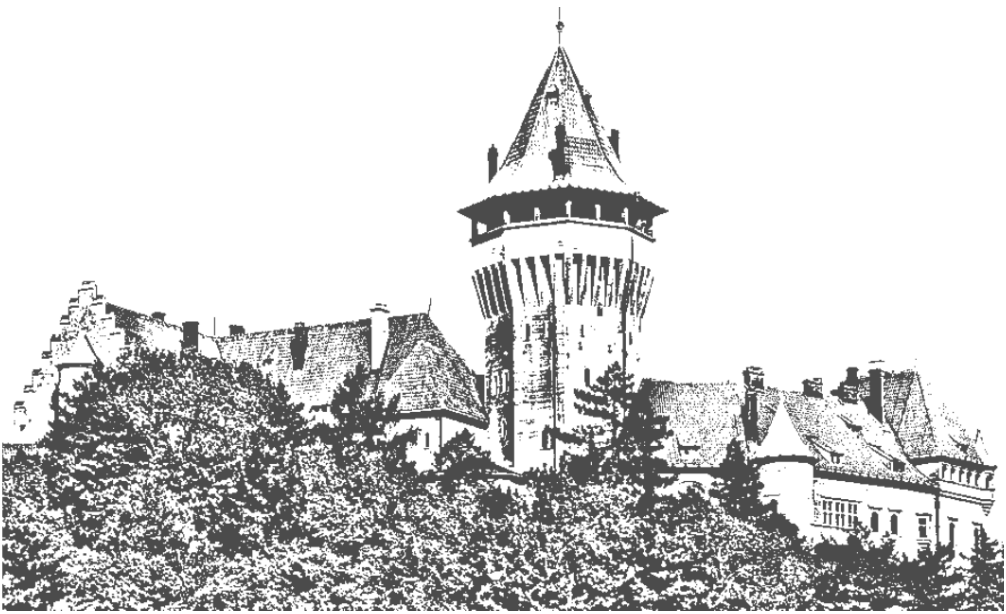

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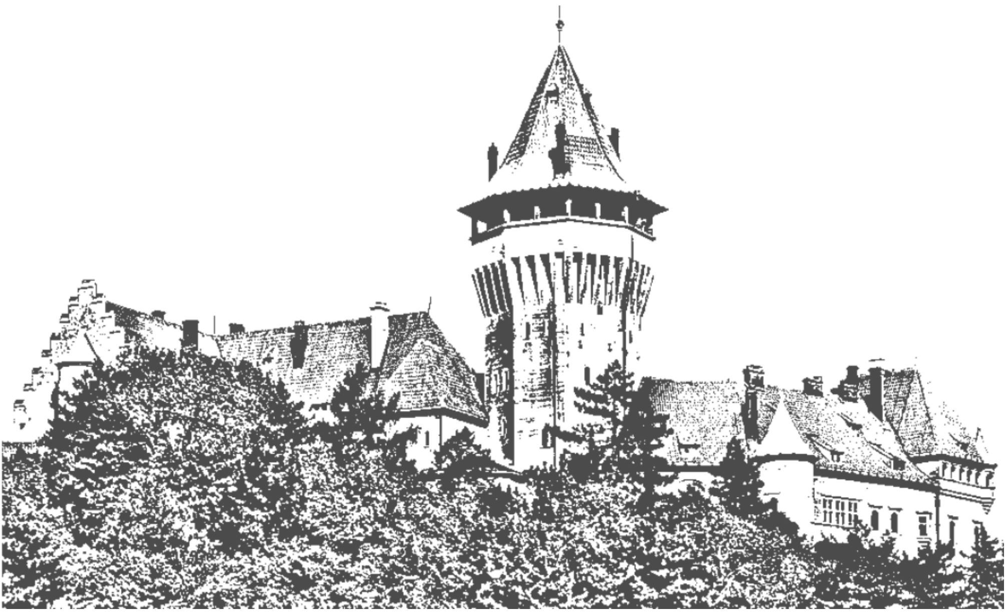

# GROUND-MOTION SIMULATIONS FOR FINITE-FAULT EARTHQUAKE SCENARIOS ON THE HÚSAVÍK-FLATEY FAULT, NORTH ICELAND

***Claudia ABRIL*** [1], ***Alice A. GABRIEL*** [1,2], ***P. Martin MAI*** [3],
***Benedikt HALLDORSSON*** [4,5], ***Sigurjon JONSSON*** [3]

[1] Department of Earth and Environmental Sciences,
Ludwig-Maximilians-Universität (LMU), Munich, Germany

[2] Scripps Institution of Oceanography, University of California, San Diego, USA

[3] Physical Science and Engineering Division,
King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia

[4] Service and Research Division, Icelandic Meteorological Office (IMO), Reykjavik, Iceland

[5] Faculty of Civil and Environmental Engineering, University of Iceland (UI), Reykjavik, Iceland

*contact: claudia.abril@lmu.de*

The Tjörnes Fracture Zone (TFZ) is the largest transform zone in Iceland that connects two spreading centers of the Mid-Atlantic Ridge: the Northern Volcanic Zone and the Kolbeinsey Ridge. Destructive historical earthquakes that occurred in Northern Iceland (the 1755 Ms 7.0 and the 1872 doublet Ms 6.5) have been associated with the Húsavík-Flatey Fault (HFF), which is the central largest linear strike-slip fault in the TFZ. We simulate kinematic fault rupture models for several potential earthquake scenarios at the HFF, and we estimate the ground motion of those scenarios at the main towns in Northern Iceland. Ground-motion predictions at Húsavík town are particularly interesting because of its location atop the HFF. The town is the largest in the area and is subject to the highest seismic hazard in the country. To simulate fault rupture scenarios, we apply the high-order accurate derivative discontinuous Galerkin (ADER-DG) method with SeisSol, and incorporate high-resolution topo-bathymetry and viscoelastic attenuation. Slip distributions are computed using a von Karman autocorrelation function whose parameters are calibrated with slip distributions of Icelandic $M>5.0$ recorded earthquakes. Synthetic ground motion and time histories at low frequencies ($<2$Hz) are estimated for the main towns, and ground-shaking maps are generated for the entire region [$\sim$100 km $\times$ 100 km]. Intensity values estimated from the simulation results are compared with those from the dynamic simulations by Li et al. (2022) and the GMPEs calibrated to Icelandic earthquakes. Directivity effects towards Húsavík town are studied. Our results are expected to complement the available information on seismic hazard in Northern Iceland towards non-ergodic physics-based seismic hazard assessment.

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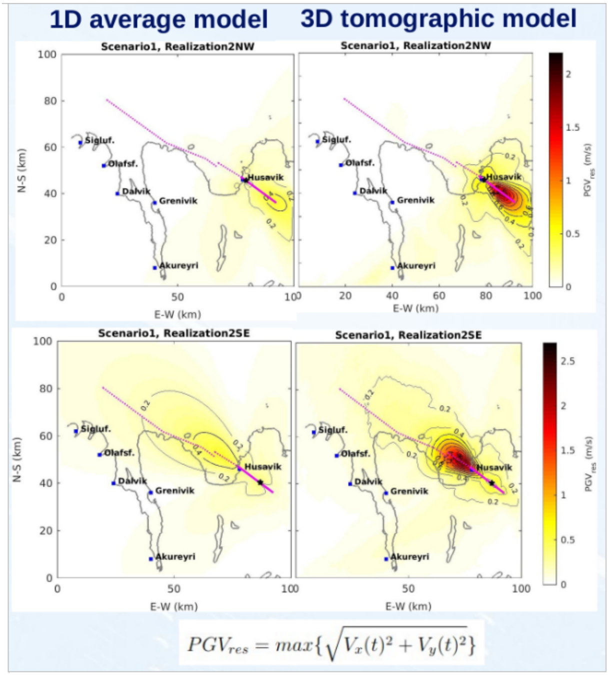


Shake maps generated with SORD code showing the resultant PGV of a simulated scenario of an Mw=6.4 earthquake with two different hypocenters, where we implemented a 1D velocity model (left panels) and the tomographic 3D model by Abril et al. (2021) (right panels).

# KEY OBSERVATIONAL CONSTRAINTS ON DYNAMIC RUPTURE SIMULATIONS: FAULT GEOMETRY AND REGIONAL STRESS TENSOR FIELD

***Ryosuke ANDO***

Department of Earth and Planetary Science, the University of Tokyo, Tokyo, Japan

*contact: ando@eps.s.u-tokyo.ac.jp*

Recent dynamic rupture simulations demonstrate the reproducibility of natural large earthquakes (e.g., Ando and Kaneko, 2018, GRL). We present the analysis results for the 2023 Türkiye-Syria earthquake sequence and the 2024 Noto-Peninsula, Japan earthquake as two new examples, clarifying the importance of the 3D fault geometry and stress tensor that control the dynamic rupture processes. We perform the fully dynamic rupture simulations using the boundary integral equation method accelerated with the fast domain partitioning method (Ando, 2016, GJI). This method is capable of handling non-planar 3-D fault geometries at the time complexity of O(N2M) and the memory use of O(N2). We built models of the fault geometry and regional stress field based on observations. The simulation results (forward models) are compared with the coseismic observations and slip inference (inverse models) in these two cases. The simulations reproduce the primary characteristics of the observed rupture processes and slip distributions. For the mainshock (the first event) of the 2023 event, the simulation reproduces the rupture propagations through the three major segments with the branch and bends. The simulated process includes the observed time delay for the backward branching. The simulation results for the 2024 event basically reproduce the coseismic surface displacement captured by SAR, showing the particular uplift associated with a fault bend. Our results demonstrate the reasonable gain in the forecastability of the dynamic rupture processes with the observational constraints of the fault geometry and stress tensor field. This further suggests the importance of building these structural models beforehand.

# PHYSICAL INTERPRETATION OF SLOW EARTHQUAKE MIGRATION PROCESS BASED ON A FRICTION LAW

***Keisuke ARIYOSHI***

Research Institute for Marine Geodynamics,
JAMSTEC (Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan

*contact: ariyoshi@jamstec.go.jp*

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. 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 $\mu$m and 30 mm; (iv) the stress and strength drops of very low-frequency earthquakes is much smaller than 1 MPa.

# STATIC AND QUASI-STATIC INVERSION OF FAULT SLIP DURING LABORATORY EARTHQUAKES

***Feyza ARZU*, *Cedric TWARDZIK*, *Barnaby FRYER*, *Jean-Paul AMPUERO*, *Yuqing XIE*, *François PASSELÈGUE***

CNRS, Observatoire de la Côte d'Azur, Géoazur, Université Côte d'Azur, Valbonne, France

*contact: feyza.arzu@geoazur.unice.fr*

Inferring from seismological data the spatio-temporal slip distribution during earthquakes remains a challenge due to the large size, non-uniqueness and ill-posedness of the problem; finite source inversion usually relies on simplifying assumptions. Moreover, without ground truth source data, the evaluation of the performance of source inversion is only possible by synthetic tests. To address these concerns and test the viability of the inversion methods used for natural earthquakes, laboratory earthquakes offer a valuable alternative. They enable us to work with simulated real data and provide a relatively well-constrained solution. Here, we employ a biaxial apparatus capable of reproducing shear rupture along a rectangular fault separating two PMMA blocks. Normal and shear stresses are initially increased up to the target normal stress using external pressure pumps, assuming a fixed shear to normal stress ratio of 0.3. Subsequently, the shear stress is increased until instabilities occur at a peak friction of 0.4. During the seismic rupture, we measure the acceleration at 20 receivers along the fault, integrate it twice into displacements. Then we use it to invert the slip history, which is compared to direct measurements using laser sensors placed through the fault. The predicted data is computed using Okada's formulation and the posterior PDF of the slip history is obtained using a Metropolis algorithm. The adoption of a probabilistic approach provided a range of solutions, is essential for assessing the uncertainty in our results and addressing the non-uniqueness issue. Ultimately, the obtained results will offer insights into inversion methods, presenting their strengths and limitations more realistically than when using artificially generated synthetic datasets.

# TEMPORAL CHANGES OF SITE RESPONSE IN THE CENTRAL TOKYO AREA: A POSSIBLE SITE-CITY INTERACTION CASE ?

***Pierre-Yves BARD*** [1], ***Kenichi NAKANO*** [2], ***Eri ITO*** [3], ***Jikai SUN*** [3], ***Ziqian WANG*** [3], ***Hiroshi KAWASE*** [3]

[1] ISTerre, University Grenoble-Alpes, Grenoble, France
[2] Hazama Ando Corporation, Hazama Ando Corporation, Tsukuba, Japan
[3] DPRI (Disaster Prevention Research Institute), University of Kyoto, Uji / Kyoto, Japan

*contact: pierre-yves.bard@univ-grenoble-alpes.fr*

Many cities are established on soft soils, with a high building density. The possible feedback of multiple Soil-Structure Interaction (called ”SCI”, Site-City Interaction) on site response has been investigated over the last 3 decades with various approaches (numerical simulation, reduced scale laboratory experiments, full scale analogs). Their results consistently indicate the plausibility of significant effects on ground motion, with an overall decrease of the average ground motion in specific frequency bands. However, such effects could never be unambiguously proved with real earthquake recordings in real cities. The long collection of strong motion observations in the Kanto area was thus used to investigate possible time changes in site response, using event-specific site terms derived from Generalized Inversion Techniques for 106 KiK-net, K-NET or JMA accelerometric stations in the Kanto area (average of 136 recordings from 1996 to 2018). Most of these sites do not exhibit any temporal change, except those located close to the redevelopment areas of Tokyo, where many new high-rise buildings were recently erected, which exhibit a significant reduction of low-frequency amplification (up to a factor of 3). Considering the correspondence between high-rise building frequencies ($<$ 1 Hz) and site frequencies (fundamental mode $<$ 0.2 Hz in relation with 3 km thick sediments, and largest amplification around 0.5 - 1 Hz in relation to softer soils at shallow depth), such a decrease appears to be consistent with the outcomes of all kinds of SCI investigations carried on the last three decades. The presentation will finally discuss the additional investigations to be performed to confirm (or eliminate) this intriguing consistency with the SCI interpretation.

# MODELS OF INJECTION-INDUCED SEISMIC SLIP WITH PERMEABILITY ENHANCEMENT AND RATE-AND-STATE FRICTION

***Natalia BERRIOS-RIVERA*** [1], ***So OZAWA*** [1,2], ***Eric M. DUNHAM*** [1]

[1] Department of Geophysics, Stanford University, Stanford, USA
[2] Earthquake Research Institute, University of Tokyo, Tokyo, Japan

*contact: nberrios@stanford.edu*

Anthropogenic fluid injections and natural fluid flow in Earth's crust leads to an increase in pore pressure, which can trigger earthquake swarms characterized by a migrating seismicity front. Observations of seismicity expanding with the same diffusive space-time behavior as analytical solutions for aseismic slip have been interpreted as evidence for seismic slip triggered by stress changes from aseismic slip. In some cases, aseismic slip is confirmed from crustal deformation and shear wellbore casing. Our work offers another interpretation of migrating seismicity that may be relevant when there is no independent evidence for aseismic slip. We show that pressure diffusion and elastic stress transfer can independently drive the diffusive expansion of seismicity fronts, and that analytical solutions for aseismic slip can explain this seismicity pattern, even when all slip is seismic. Here we present a 2D earthquake cycle model that simulates constant-pressure injection into the end of a velocity-weakening rate-and-state fault, permeability enhancement with slip, and fluid transport. Our simulations produce microseismicity concentrated along the slip front and large events that rupture back to the injector, with minimal aseismic slip prior to or during the sequence. The fault is planar with uniform friction and stress, likely concentrating seismicity at the slip front. Although we find that simulations for understressed faults have some distributed seismicity behind the slip edge, future work accounting for heterogeneities may produce more realistic spatial distributions of seismicity. Our results suggest that aseismic slip solutions can be used to quantitatively interpret the space-time behavior of migrating swarms, even in cases with negligible aseismic slip.

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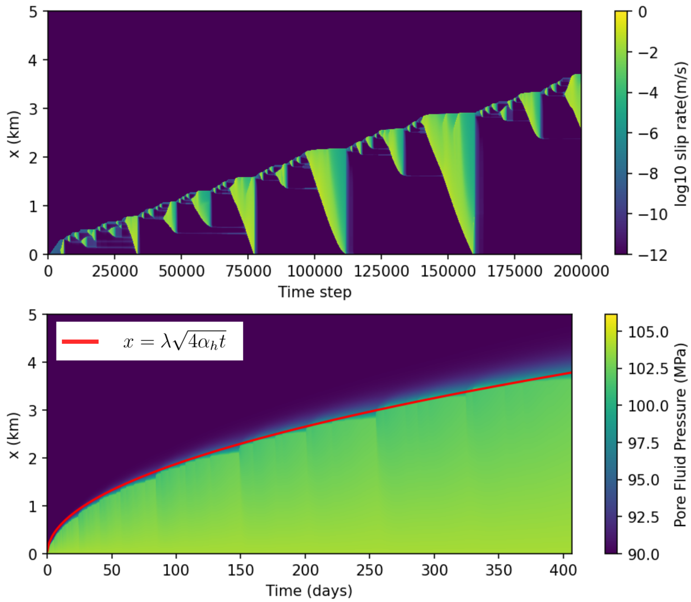
x (km)
Time step
log10 slip rate(m/s)
$x = \lambda\sqrt{4\alpha_h t}$
Time (days)
Pore Fluid Pressure (MPa)

# COMPARISON OF OBSERVED AND SIMULATED GROUND MOTIONS IN THE LOS ANGELES BASIN

***Brianna C. BIRKEL***, ***John E. VIDALE***

Department of Earth Sciences, University of Southern California, Los Angeles, CA, USA

*contact: birkel@usc.edu*

The deep sedimentary basin surrounding Los Angeles is a region of ongoing scientific interest and study, due to its overlying dense infrastructure and tendency to amplify 3-10s period seismic waves. In this study, we evaluate the accuracy of the latest seismic velocity models – CVM-S4.26.M01 and CVM-H 15.1.0 – by comparing observed seismograms from several recent moderate magnitude earthquakes to their synthetic counterparts. These synthetic seismograms are computed via the spectral-element simulation software Salvus. In the Los Angeles basin, we see significant differences between observations and predictions, even at long period (above 3 seconds). These differences are quantified using the Anderson 2004 goodness-of-fit metrics, as well as via direct waveform comparison. Our results suggest that earthquake hazard estimation in the Los Angeles basin will benefit from specific, focused improvements of the velocity models in this region.

# CHARACTERIZATION AND ANALYSIS OF A POTENTIAL HIDDEN GEOTHERMAL RESOURCE IN THE JERSEY SUMMIT AREA, NORTH-CENTRAL, NEVADA

***Quentin P. BURGESS*** [1,2]

[1] Great Basin Center for Geothermal Energy, University of Nevada, Reno, Reno, Nevada, USA
[2] Nevada Bureau of Mines and Geology, University of Nevada, Reno, Reno, Nevada, USA

*contact: quentinpierceburgess@outlook.com*

The Great Basin region (GBR) in western North America has substantial geothermal resource potential due to its favorable tectonic setting; however, most of the geothermal systems in this region are hidden, with no surface manifestations such as hot springs or steam vents. For this study, we aim to better characterize hidden geothermal systems in the GBR using detailed structural analyses of designated field sites. Here, we focus on the Jersey Summit area in north-central Nevada. This site has been identified as having high potential for a hidden system based on the presence of a major Quaternary accommodation zone between the southward terminating, east-dipping Buffalo Valley normal fault zone and northward terminating, west-dipping Jersey Valley normal fault zone. Our objectives are to integrate multiple geological, and geophysical datasets to establish the stratigraphic and structural framework of the Jersey Summit area, delineate the geometry and kinematics of the Quaternary fault systems, identify particularly favorable structural, define locations of thermal anomalies, and assign the most favorable targets for future temperature gradient drilling. Detailed geologic mapping, geophysical potential fields surveys (i.e., gravity, magnetic, and magnetotelluric), structural analysis, and shallow 2-m temperature surveys were employed to identify the most highly prospective areas. These data suggest two particularly promising areas: 1) a broad left step-over in the southern part of the Buffalo Valley fault zone, and 2) a complex fault intersection between terminating strands of both the Buffalo Valley and Jersey Valley fault zones as well as a major east-striking, down-to-the south fault that transects the Tobin Range and projects into the accommodation zone.

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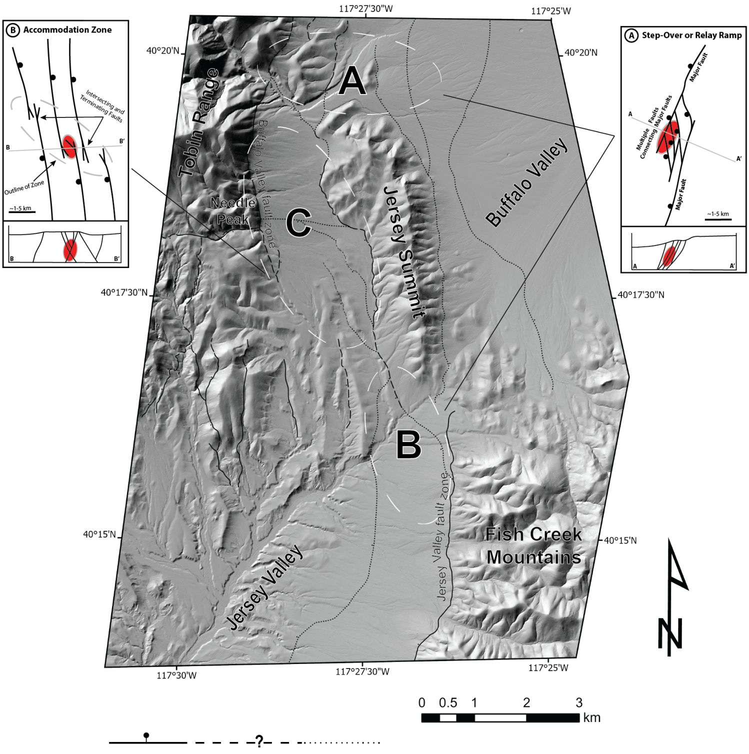



**Normal Fault** Solid where certain, dashed where approximately located, dotted where concealed; queried if identity or existence uncertain. Ball on downthrown side.

# SLIP DEFICIT RATE INVERSIONS IN THE WESTERN U.S. INCORPORATING VISCOELASTIC EARTHQUAKE CYCLE EFFECTS

***Nicolas CASTRO-PERDOMO***, ***Kaj JOHNSON***

Department of Earth and Atmospheric Sciences, Indiana University, Bloomington, USA

*contact: jcastrop@iu.edu*

This project addresses three fundamental challenges in working with strain rates: The non-uniqueness of strain rate estimates and the lack of clarity regarding their uncertainties, the underdeveloped methods for directly inferring slip deficit rates on faults from strain rates, and the quantification of off-fault deformation in areas of distributed deformation. To tackle these challenges, I employ a systematic approach to compute strain rate maps and their uncertainties across the western U.S., using various methods to derive strain rates from GNSS velocities. Additionally, I invert surface strain rates for slip deficit rates on faults included in the 2023 U.S. National Seismic Hazard Model (U.S. NSHM), leveraging a viscoelastic earthquake cycle model that incorporates time-dependent mantle flow due to the periodic locking and unlocking of faults. The inversion is performed using least squares coupled with a Monte Carlo procedure to construct the posterior distribution considering truncated Gaussian priors on slip deficit rates based on the preferred slip rate values in the U.S. NSHM.

Our preliminary results suggest that elastic and viscoelastic models explain 60-70 percent of the observed strain rates. However, there remains 30-40 percent of the strain rates that cannot be accounted for by coupling on faults in the 2023 NSHM fault model, highlighting areas for future investigation, particularly determining the nature and origin of off-fault deformation. Also, my analysis has identified the northern San Andreas, along with the Carrizo and Mojave segments of the San Andreas Fault, as regions with the highest slip deficit rates, where depth-averaged rates exceed 15 mm/year.

# PROPAGATION OF EXTENDED FRACTURES BY LOCAL NUCLEATION AND RAPID TRANSVERSE EXPANSION OF CRACK-FRONT DISTORTION

***Thomas CHOCHARD*** [1,2], ***Ilya SVETLIZKY*** [2], ***Gabriele ALBERTINI*** [3], ***Robert C. VIESCA*** [4], ***Shmuel M. RUBINSTEIN*** [5], ***Frans SPAEPEN*** [2], ***Congcong YUAN*** [6], ***Marine DENOLLE*** [7], ***Yi-Qiao SONG*** [2,8], ***Lizhi ZHAO*** [1], ***David A. WEITZ*** [2,9,10]

[1] National Key Laboratory of Petroleum Resources and Engineering, China University of Petroleum, Beijing, China

[2] School of Engineering and Applied Sciences, Harvard University, Cambridge, USA

[3] Faculty of Engineering, University of Nottingham, Nottingham, United Kingdom

[4] Department of Civil and Environmental Engineering, Tufts University, Medford, USA

[5] Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem, Israel

[6] Department of Earth and Planetary Sciences, Harvard University, Cambridge, USA

[7] Department of Earth and Space Sciences, Harvard University, Cambridge, USA

[8] Athinoula A. Martinos Center for Biomedical Imaging, Department of Radiology, Massachusetts General Hospital, Charlestown, USA

[9] Department of Physics, Harvard University, Cambridge, USA

[10] Wyss Institute for Biologically Inspired Engineering, Harvard University, Boston, USA

*contact: robert.viesca@tufts.edu*

Fractures are ubiquitous and can lead to the catastrophic material failure of materials. Although fracturing in a two-dimensional plane is well understood, all fractures are extended in and propagate through three-dimensional space. Moreover, their behaviour is complex. Here we show that the forward propagation of a fracture front occurs through an initial rupture, nucleated at some localized position, followed by a very rapid transverse expansion at velocities as high as the Rayleigh-wave speed. We study fracturing in a circular geometry that achieves an uninterrupted extended fracture front and use a fluid to control the loading conditions that determine the amplitude of the forward jump. We find that this amplitude correlates with the transverse velocity. Dynamic rupture simulations capture the observations for only a high transverse velocity. These results highlight the importance of transverse dynamics in the forward propagation of an extended fracture.

# CONDITIONS FOR SLOW-TO-FAST SLIP IN A SINGLE-ASPERITY STRIKE-SLIP FAULT

***Federico CIARDO*** [1], ***Robert VIESCA*** [1], ***Dmitry GARAGASH*** [2]

[1] Department of Civil and Environmental Engineering, Tufts University, Medford, USA
[2] Department of Civil and Resource Engineering, Dalhousie University, Halifax, Canada

*contact: federico.ciardo@tufts.edu*

Numerical models are typically invoked to predict if and where slow (aseismic) or fast (seismic) slip occurs on a fault over geological time scales. However, results are problem-dependent: predictions cannot be obtained without prior numerical simulations. Here, we provide a mechanistic approach that allows to predict a-priori and accurately whether a finite fault governed by rate-and-state friction and loaded by steady creep at its extremities is expected to give rise to seismic slip, aseismic transients, or simply steady creep. We focus on a vertical strike-slip fault with a rate-weakening asperity embedded within an otherwise stable, rate-strengthening surface. We leverage linear and non-linear stability analyses of slip to define semi-analytically the critical asperity size that could lead to an earthquake or simply a transient acceleration of creep, as a function of governing dimensionless parameters.

Our results, supported by elasto-dynamic numerical simulations, show that, for a given rate-strengthening condition surrounding the asperity, its critical size above which slip rate becomes linearly unstable to tiny perturbations decreases non-linearly with decreasing values of a/b ($< 1$) characterizing the asperity, with b and a being the phenomenological parameters of rate-and-state friction. Also, when this size is much smaller compared to the total fault length, we show its value agrees well with the calculated critical size of a single asperity within an infinitely long fault, whose value is shown to increase logarithmically the less pronounced rate-strengthening condition is around the asperity. Finally, when the asperity size is large enough for slip rate to be both linearly and non-linearly unstable, seismic events nucleate, and inertia is mobilized.

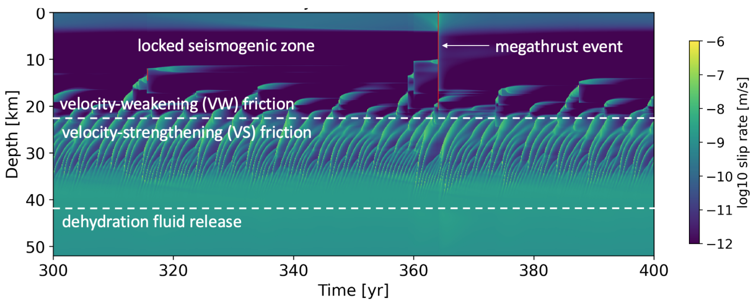
# FAULT-VALVE INSTABILITY: A MECHANISM FOR SLOW SLIP EVENTS

**Eric M. DUNHAM** [1], **So OZAWA** [1,2], **Yuyun YANG** [3]

[1] Department of Geophysics, Stanford University, Stanford, USA
[2] Earthquake Research Institute, Tokyo University, Tokyo, Japan
[3] Earth and Environmental Sciences Programme, Chinese University of Hong Kong, Hong Kong, China

*contact: edunham@stanford.edu*

Geophysical and geological studies provide evidence for cyclic changes in fault-zone pore fluid pressure that synchronize with or at least modulate seismic cycles. A hypothesized mechanism for this behavior is fault valving arising from temporal changes in fault zone permeability. In our study, we investigate the coupled dynamics of rate and state friction, along-fault fluid flow, and permeability evolution. Permeability decreases with time, and increases with slip. Linear stability analysis shows that steady slip with constant fluid flow along the fault zone is unstable to perturbations, even for velocity-strengthening friction with no state evolution, if the background flow is sufficiently high. We refer to this instability as the "fault valve instability". The propagation speed of the fluid pressure and slip pulse can be much higher than expected from linear pressure diffusion, and it scales with permeability enhancement. Two-dimensional simulations with spatially uniform properties show that the fault valve instability develops into slow slip events, in the form of aseismic slip pulses that propagate in the direction of fluid flow. We also perform earthquake sequence simulations on a megathrust fault, taking into account depth-dependent frictional and hydrological properties. The simulations produce quasi-periodic slow slip events from the fault valve instability below the seismogenic zone, in both velocity-weakening and velocity-strengthening regions, for a wide range of effective normal stresses. A separation of slow slip events from the seismogenic zone, which is observed in some subduction zones, is reproduced when assuming a fluid sink around the mantle wedge corner.




Subduction zone earthquake sequence simulation illustrating slow slip events in the velocity-strengthening region below the seismogenic zone caused by the fault valve instability.

# NEAR-FAULT AND SITE EFFECT PHYSICS-BASED GROUND MOTION MODELLING FOR BETTER UNDERSTANDING OF HISTORICAL EARTHQUAKES: THE CASE OF MUGELLO BASIN

***Christine EL KHOURY*** [1], ***Sebastien HOK*** [1], ***Céline GÉLIS*** [1], ***Hervé JOMARD*** [1], ***Hélène LYON-CAEN*** [2], ***Maria LANCIERI*** [1]

[1] Seismic Hazard Team (BERSSIN), IRSN, Paris, France
[2] Laboratoire de Géologie, ENS, Paris, France

*contact: christine.elkhoury@irsn.fr*

The Mugello basin, located in the north of Florence, Italy, is a sedimentary basin with a thickness of several hundred meters, bordered by two fault systems. The region has witnessed significant seismic events in the past, notably in 1542 (M 6) and 1919 (M 6.3), leading to extensive damage throughout the area. Particularly, these events caused disorders, repairs, and restorations to bell towers located in the region. These historical buildings serve as important indicators of past seismic events and can be used as ”stone seismometers” to analyze the ground motions that caused damage or repairs to the structures. It is important to note that there is an ongoing debate regarding the specific fault system accountable for the 1542 and the 1919 earthquakes.

The primary objective of the project is to reconstruct the seismic ground motion associated with these earthquakes. To achieve this goal, numerical modeling of the seismic ground motion is conducted, considering the complexity of source rupture and wave propagation in a 3D sedimentary basin. Many rupture scenarios are created by investigating the physical parameters of the fault model, primarily focusing on fault geometry, the fault position, and the fault kinematic parameters such as the slip distribution, the rupture velocity, and the hypocenter position with respect to the fault asperities which controls directivity effects. Ground motions produced by the selected rupture scenarios and propagating within the area including the basin are computed, with a particular focus on the studied bell towers. The site effects, essential to consider for earthquake damage assessment, are found to be highly dependent on the rupture scenario.

# FAULT-SIZE DEPENDENT FRACTURE ENERGY AND RUPTURE DYNAMICS OF CASCADING EARTHQUAKES IN MULTISCALE FRACTURE NETWORKS

***Alice-Agnes GABRIEL*** [1,2], ***Dmitry I. GARAGASH*** [3], ***Kadek H. PALGUNADI*** [4,5], ***P. Martin MAI*** [4]

[1] Scripps Institution of Oceanography, UCSD, La Jolla, USA
[2] Department of Earth and Environmental Sciences, LMU Munich, Munich, Germany
[3] Department of Civil and Resource Engineering, Dalhousie University, Halifax, Canada
[4] Physical Science and Engineering, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia
[5] Swiss Seismological Service, ETH Zurich, Zurich, Switzerland

*contact: algabriel@ucsd.edu*

Earthquakes vary in size over many orders of magnitude, often rupturing in complex multi-fault and multi-event sequences. However, the scaling of the earthquake energy budget remains enigmatic. Here, we propose that fundamentally different fracture processes govern small and large earthquakes. We combine seismological observations with physics-based models, finding that both dynamic weakening and restrengthening effects are non-negligible in the energy budget of small earthquakes.

New analytical descriptions of crack-like circular dynamic ruptures with flash-heating friction and co-seismic restrengthening, as well as bilaterally expanding kinematic pulse-like ruptures with co-seismic stress recovery allow us to derive physics-based corrections and estimate the total earthquake fracture energy across scales of global seismological observations of small and large earthquakes. We add newly measured total fracture energy from thirteen realistic 3D rupture simulations of past small repeating and large well-recorded earthquakes spanning magnitudes 1.9 – 9.2.

Our analysis reveals a linear scaling relationship between fracture energy and fault size and a break in scaling with slip. Our proposed minimum fracture energy may reflect a local fault property, which can be explained by a well-localized near-front process zone that depends on fault size. We apply this scaling using supercomputing and unveil large dynamic rupture earthquake cascades involving over 700 multi-scale fractures within a fault damage zone. Our results provide a simple explanation for seismicity across all scales with implications for comprehending earthquake genesis and multi-fault rupture cascades.

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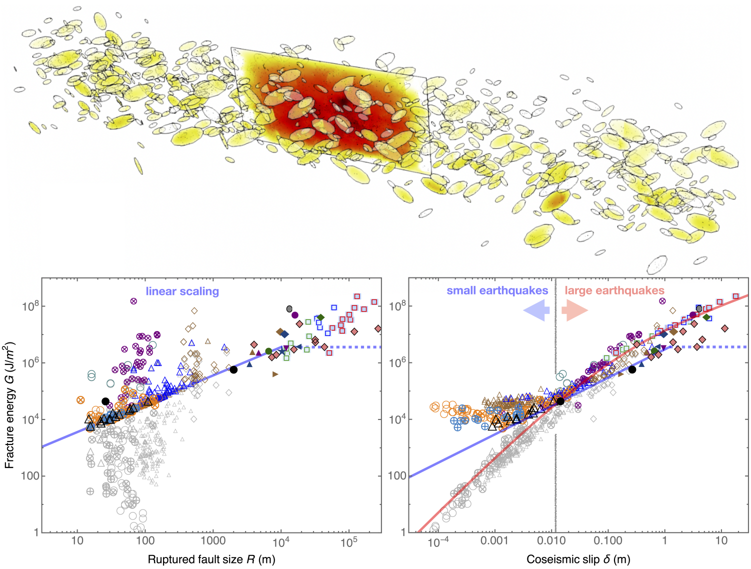
linear scaling
Fracture energy G (J/m²)
Ruptured fault size R (m)
small earthquakes
large earthquakes
Coseismic slip δ (m)

# DYNAMIC RUPTURE INVERSE MODELING ACROSS BROAD SPATIAL AND TEMPORAL SCALES

***František GALLOVIČ***, ***Ľubica VALENTOVÁ KRIŠKOVÁ***

Department of Geophysics, Faculty of Mathematics and Physics,
Charles University, Prague, Czech Republic

*contact: frantisek.gallovic@matfyz.cuni.cz*

Inference of earthquake source parameters from observational data can be constrained by dynamic rupture modeling, combining an assumed friction law with the elastodynamic equation. We present techniques for dynamic rupture inversions and selected applications, including low-frequency waveform inversions for slip-weakening friction parameters of the 2016 Mw6.2 Amatrice, Italy, and the 2020 Mw6.8 Elazığ, Türkiye, earthquakes. We also introduce recently developed dynamic inversions of i) apparent source time functions of a deep-focus earthquake in Eastern China and ii) apparent source spectra of a Mw4 event in Central Italy. Finally, we present dynamic source inversions with rate-and-state friction law of seismic and geodetic data, inferring jointly parameters corresponding to co- and post-seismic slip and thus bridging time scales from seconds to weeks.

Smooth planar dynamic rupture models tend to underestimate the high-frequency content of observed ground motions. To remedy this issue, we introduce small-scale random fractal perturbations of initial stress and fracture energy, while keeping the efficacy of planar fault simulations. For a generic elliptical Mw6.3 dynamic model and a low-frequency inverted dynamic model of the 2016 Mw6.2 Amatrice, we demonstrate that the random perturbations preserve large-scale characteristics of the original models and introduce small-scale abrupt changes in rupture velocity (undetectable by the low-frequency inversion). The latter improves the fit to the recordings of the Amatrice earthquake and Central Italy ground motion model up to 5-10 Hz. Such physically constrained broadband rupture models will guide further research toward realistic dynamic rupture scenarios for seismic hazard assessment.

# STICK-SLIP INDUCED COLLECTIVE RESPONSE IN SHEARED GRANULAR FAULT

***Ke GAO*, *Zhuan DAI***

Department of Earth and Space Sciences,
Southern University of Science and Technology, Shenzhen, China

*contact: gaok@sustech.edu.cn*

Granular gouge is commonplace in natural faults. Revealing the particle motion and rearrangement inside the granular gouge during stick-slip cycles can help better understand the mechanism of tectonic earthquakes. Here, the microscopic kinematics and collective response of a granular gouge during the two distinctive states – stick and slip phases – are analyzed based on a numerically simulated sheared granular fault system using the combined finite-discrete element method (FDEM). During stick phases, the gouge locks the fault plane like a solid, but a few tiny active particle clusters exist due to scattered local contact failures between particles. When slips occur, part of the gouge flows like a liquid, and the particles in the principal slip zone are the most chaotic. The correlation of the collective response of granular particles is weak during stick phases, and the particles barely rearrange themselves, which gives opportunities for storing potential energy in the system. However, when fault slips, the gouge particles' collective response is strongly correlated, and the stored energy is released, indicating that the particles are effectively rearranged. The rearrangement of the gouge can be explained by the stress chain structures. These stress chains make the slip tend to cascade, which reveals why granular gouge inhibits pre-slips. This study shows how the granular gouge reacts and rearranges during stick-slip cycles from a microscopic viewpoint and may shed light on the dynamic nucleation process of natural earthquakes.

# RUPTURE DYNAMICS ON FAULTS WITH CONTINUING SLIP WEAKENING: DOES THE TAIL WAG THE DOG?

***Dmitry GARAGASH*** [1], ***Martin GÁLIS*** [2],
***Jean-Paul AMPUERO*** [3], ***David KAMMER*** [4]

[1] Civil and Resource Engineering, Dalhousie University, Halifax, Canada

[2] Faculty of Mathematics, Physics and Informatics,
Comenius University, Bratislava, Slovak Republic

[3] Geoazur Laboratory, Université Côte d'Azur, Nice, France

[4] Department of Civil, Environmental and Geomatic Engineering, ETH, Zürich, Switzerland

*contact: garagash@dal.ca*

Continuing fault weakening with co-seismic slip has been inferred from seismological observations of earthquakes [Abercrombie and Rice 2005] and laboratory quakes [Paglialunga et al 2022]. Thermal pressurization (TP) of pore fluids by shear heating has shown to be a possibly ubiquitous mechanism leading to continuing fault weakening in agreement with the observations [Viesca and Garagash 2015].

Continuing co-seismic weakening implies that the breakdown of fault strength is not localized near the rupture front, contrary to classical earthquake source mechanics models, while the associated energy dissipation (breakdown work) is accrued over the entire slipping fault. A related fundamental question is to what extent the rupture-wide energy dissipation governs the dynamics of the rupture front propagation.

We address this question by numerical simulations of ruptures driven by continuous weakening, and analytical modeling using an approximately equivalent Linear Elastic Fracture Mechanics (LEFM) framework. We use a proxy slip-weakening law $\tau \propto \delta^{-1/3}$ [Herrera et al 2024] to mimic the actual weakening observed in steady TP-driven dynamic rupture solutions [Viesca and Garagash 2015].

Preliminary results of matching the numerical simulations to the predictions of the LEFM model show that at moderate rupture speeds the fault-wide breakdown work $W_b$ is approximately equal to the LEFM fracture energy governing the rupture front dynamics. At larger speeds, approaching shear-wave speed, the equivalent LEFM fracture energy is a speed-dependent fraction of $W_b$. Our results suggest that the energy dissipation away from the rupture front does shape the front dynamics, i.e. 'tail wags dog', but the effect is modulated by the rupture speed.

# 3D SIMULATION OF SEISMIC NOISE IN A SEDIMENTARY BASIN WITH A BLIND FAULT STRUCTURE: APPLICATION TO THE SENSITIVITY OF SURFACE H/V AND NOISE ARRAY MEASUREMENTS

***David GREGOR*** [1], ***Emmanuel CHALJUB*** [1], ***Marc WATHELET*** [1],
***Fabrice HOLLENDER*** [1,2], ***Vincent PERRON*** [1,2]

[1] ISTerre, Univ Grenoble Alpes, Grenoble, France
[2] CEA, CEA, Cadarache, France

*contact: emmanuel.chaljub@univ-grenoble-alpes.fr*

We have developed a 3D computational tool to synthesize ambient seismic vibration (ASV) wavefields due to surface noise sources. We have applied this tool to a set of receivers located around a blind fault, in a canonical model of the Mygdonian sedimentary basin in Greece. We present the results of several analyses of synthetic noise seismograms (up to 5 Hz) corresponding to many different source-receiver configurations. We further focus on two different analyses: single-station H/V, which are compared to the predictions obtained in the Diffusive Field Approximation, and noise array measurements.

# FAULT SLIP DYNAMICS IN SUBDUCTION ZONES: INSIGHTS INTO FAST FLUID PRESSURE TRANSIENTS

***Avinash GUPTA*** [1], ***Nikolai M. SHAPIRO*** [1], ***Jean P. AMPUERO*** [2], ***Gaspard FARGE*** [3], ***Claude JAUPART*** [4]

[1] Institut de Sciences de la Terre, CNRS, Université Grenoble Alpes, Grenoble, France
[2] Université Côte d'Azur, CNRS, Observatoire de la Côte d'Azur, IRD, Valbonne, France
[3] Department of Earth and Planetary Sciences, University of California Santa Cruz, Santa Cruz, CA, USA
[4] Institut de Physique du Globe de Paris, Université de Paris, Paris, France

*contact: aviggupta0123@gmail.com*

This study delves into the dynamic interaction between fluids and fault slip transients within subduction zones experiencing slow earthquakes. It focuses on the permeable subduction interface saturated with fluids derived from metamorphic dehydration reactions in the descending plate. Drawing from the framework established by Farge et al. (2021), the research employs a model featuring a heterogeneous subduction channel containing low-permeability plugs that act as fault-valves. This system exhibits intermittent fluid transport and rapid pressure fluctuations, which influence fault friction and can lead to transient slip accelerations. Numerical simulations in a 2D in-plane shear geometry are utilized to explore the effects of rapid fluid pressure variations on fault slip behavior. The fault dynamics are governed by rate-and-state friction laws with velocity-strengthening characteristics, while pore fluid pressure varies both temporally and spatially. Initial tests demonstrate that periodic pore pressure oscillations can accelerate fault slip, resembling observed slow slip events. Subsequent analyses delve into more complex pore pressure histories generated by the dynamic permeability model proposed by Farge et al. (2021). The results underscore the critical role of fluid flux and permeability structure in modulating variations in fault slip, particularly in facilitating slow slip events.

# SOIL REINFORCEMENT OF TRANSPORTATION INFRASTRUCTURE: CUSTOMIZED 3D-PRINTED GEOGRID FOR CENTRIFUGE SHAKE TABLE TESTING

***Jordaina HEWITT*** [1], ***Jeffrey NEWGARD*** [2], ***Taylor FOSTER*** [3], ***John S. MCCARTNEY*** [2]

[1] Civil and Environmental Engineering, Howard University, Washington DC, USA

[2] Structural Engineering, University of California, San Diego, La Jolla, USA

[3] Human System Engineering, Arizona State University, Phoenix, USA

*contact: jordaina.hewitt@bison.howard.edu*

Rocking footings in shallow foundations can reliably recenter themselves while dissipating energy during earthquake events. However, the foundations are prone to excessive settlement and residual rotation. This study focuses on using ground improvement strategies during centrifuge modeling to preserve the beneficial traits of rocking footings while counteracting the foundation's settlement and rotation. In civil engineering applications, geogrids are used to reinforce the soil which increases the bearing capacity and strength of the soil. Placing geogrids below the rocking footing has the potential of controlling the kinematics of rocking footings without changing its physical properties. An ideal ground improvement configuration was identified to have minimal settlement and maximum energy dissipation and re-centering. A baseline case was first developed for a rocking footing without ground improvement by subjecting it to shaking at a level that caused it to settle excessively. To represent a stiffer geogrid the design was printed using PLA (polypropylene) and TPU (Thermoplastic polyurethane) for a flexible geogrid. During and after earthquake shaking the rocking footing that was reinforced with the PLA geogrid had the least amount of settlement. By designing 3d printed geogrids for centrifuge testing, you can systematically replicate full size seismic events using relatively small scales and accurately assess the performance of rocking footings and its relation to various types of geogrids. Further implementation of ground improvement strategies on shallow foundations reduces risk of infrastructure failures in the event of severe earthquakes.

# INFERRED SOURCE MODELS FOR ALPINE FAULT EARTHQUAKE SCENARIOS AND INFLUENCE ON SEISMIC HAZARD

***Caroline HOLDEN*** [1], ***John TOWNEND*** [2], ***Calum CHAMBERLAIN*** [2], ***Emily WARREN-SMITH*** [3], ***Carmen JUAREZ-GARFIAS*** [2], ***Olivia PITA-SLLIM*** [2], ***Kasper VAN WIJK*** [4], ***Marine DENOLLE*** [5]

[1] SeismoCity Ltd, SeismoCity Ltd, wellington, New Zealand

[2] School of Geog., Env., and Earth Sciences,
Victoria University of Wellington, Wellington, New Zealand

[3] GNS Science, GNS Science, Lower Hutt , New Zealand

[4] The University of Auckland, The University of Auckland, Auckland, New Zealand

[5] University of Washington, University of Washington, Washington, USA

*contact: caroline.holden@seismocity.co.nz*, *caroline.francoisholden@gmail.com*

As part of the Southern Alps Long Skinny Array (SALSA) project, ∼35+ seismometers have been deployed with 10–12 km spacing along a 450 km-long section of the Alpine Fault. SALSA is focused on determining the ground motions likely to be produced by a future Alpine Fault earthquake. This project is addressing three principal objectives: (1) Determine the Alpine Fault's subsurface geometry, present-day slip rates, and spatial variations in how tectonic stresses are currently accumulating on the fault, (2) Estimate the ground shaking that would be recorded at seismometers throughout central and southern New Zealand by localised slip at different points on the Alpine Fault, focusing on the synthesis of long-period Green's functions representing accurate path effects between sources distributed along the fault and population centres throughout the South Island, and (3) Calculate the ground shaking hazard from geologically informed earthquake rupture scenarios. In this presentation we will address the influence of inferred Alpine Fault source models derived from empirical data as well as current knowledge of the fault geological and geophysical parameters on regional seismic hazard.

# INVERSE PHYSICS-BASED MODELING OF THE 2016 MW 6.1 TOTTORI EARTHQUAKE

***Martin HRONEK*, *František GALLOVIČ***

Department of Geophysics, Faculty of Mathematics and Physics,
Charles University, Prague, Czech Republic

*contact: martin.hronek493@student.cuni.cz*

The 2016 Mw 6.1 Tottori earthquake occurred in the central part of the Tottori Prefecture in western Japan. Published rupture models inferred either from geodetic or seismic data exhibit significant differences. In this study, we perform so-far missing dynamic rupture simulation to improve the understanding of the event. We utilize a finite-difference staggered grid code fd3d_tsn_pt to simulate the dynamic rupture propagation assuming the classic linear slip-weakening (SW) friction law on a planar vertical fault. We thus obtain a spatiotemporal distribution of slip rates and tractions on the fault. Synthetic seismograms are obtained using the representation theorem through the convolution of slip rates with Green's functions precalculated in 1D velocity models.

Firstly, we perform a parametric study considering simple elliptical distributions of prestress and SW friction law parameters using low-frequency seismic data to find an optimal distribution of the dynamic parameters that best fits the observed seismograms. We obtain various models of possible slip evolution on the fault, however, the fit of the seismograms especially at very close distances is not satisfactory.

Secondly, we perform a dynamic source inversion with spatially variable parameters formulated in a Bayesian framework, employing an MCMC approach to sample the posterior distribution of the model parameters. We use low-frequency seismic waveforms and GNSS displacements with various weights to explore their resolution power. We obtain model samples with complex rupture propagation with an improved fit of the recorded waveforms with respect to the simpler elliptical models. We discuss the inferred rupture parameters such as the stress drop, radiated energy, fracture energy and rupture velocity.

# FAULT MATERIAL HETEROGENEITY CONTROLS DEEP INTERPLATE EARTHQUAKES IN KANTO, JAPAN

***Yihe HUANG*** [1], ***Satoshi IDE*** [2], ***Aitaro KATO*** [3], ***Keisuke YOSHIDA*** [4], ***Chengxin JIANG*** [5], ***Peng ZHAI*** [1]

[1] Department of Earth and Environment Sciences, University of Michigan, Ann Arbor, USA
[2] Department of Earth and Planetary Science, University of Tokyo, Tokyo, Japan
[3] Earthquake Research Institute, University of Tokyo, Tokyo, Japan
[4] Graduate School of Science, Tohoku University, Sendai, Japan
[5] Research School of Earth Sciences, Australian National University, Canberra, Australia

*contact: yiheh@umich.edu*

Fault zones usually feature small-scale material heterogeneities that can strongly affect where earthquake ruptures initiate and terminate. However, such observations at scales relevant to earthquake sources are rare in subduction zones where large earthquakes are generated. Here we show that the subducted plate interface that repeatedly rupture seismically in Kanto, Japan also exhibits anomalous material properties. The Kanto region is situated in a special tectonic setting where the Philippine plate is “sandwiched” between the Okhotsk and Pacific plates, generating small to moderate-magnitude earthquakes at 60-70 km. We apply a waveform cross-correlation approach to measure the in-situ Vp/Vs ratios of earthquake patches along the plate interface between the Pacific plate and the Philippine Sea plate, and find highly anisotropic source medium with anomalously low Vp/Vs ratios ($\sim$1.44). We also estimate the stress drop of M$>$3.4 earthquakes using the spectral ratio method, leading to a median stress drop of 4.6 MPa. The low, anisotropic Vp/Vs ratios and typical stress drop values suggest the fault medium is damaged, foliated, and enriched with fluid. Assuming an effective normal stress of 50 Pa as a result of high fluid pressure, our earthquake cycle simulations can reproduce M$\sim$4 earthquakes that alternate between full and partial ruptures every 2-5 years, which are similar to the recurrence intervals of M$\sim$4 Kanto earthquakes along the Pacific slab. Our work demonstrates that such localized structures may cause stress perturbations on faults that in turn favor the frequent occurrence of deep interplate earthquakes in Kanto, Japan.

# APPARENT STRESS OF RIDGECREST EARTHQUAKES 4.0 $\leq$ M$_W$ $\leq$ 5.4: A TIME DOMAIN ANALYSIS

***Chen JI***, ***Ralph J. ARCHULETA***, ***Aaron PEYTON***

Department of Earth Science, University of California, Santa Barbara, Santa Barbara, USA

*contact: ralph.archuleta@ucsb.edu*

We use strong motion records from Southern California Seismic Network (CI) to estimate the apparent stress ($\sigma_a$) of 42 Ridgecrest, California earthquakes in the magnitude range $4.0 \leq M_w \leq 5.4$. The dense CI network allows us to use only those stations within an epicentral distance of 50 km thereby minimizing complex path and attenuation effects. We estimate the seismic radiated energy using the time integral of squared S wave ground motion velocity (Kanamori et al., 1993). We correct for crustal attenuation and site amplification by simultaneously inverting for the attenuation curve $q(r)$ and a station terms ($s_j$). We obtain $q(r) = r^{-1}\exp[(k_1 + k_2 M_w)r], r^2 = \Delta^2 + h^2$ with $k_1 = 0.043$, $k_2 = -0.0026$ where $h$ is the centroid depth and $\Delta$ is epicentral distance. For these earthquakes the centroid depth varies between 3.5 km and 12 km. For epicentral distances $10 \leq \Delta \leq 50$ km, $q(r) \propto r^{-1.6}$. Relative to the hard-rock station CLC (China Lake), other strong motion stations in the studied region amplify the seismic radiated energy by a factor of 5.9 on average with a log10 standard deviation of 0.25. With the data corrected for path attenuation and the station term we invert for the apparent stress. Although $\sigma_a$ has a geometric mean of 0.86 MPa for the 42 earthquakes, $\sigma_a$ increases with depth and magnitude: $\log_{10}(\sigma_a) = 0.104h + 0.240M_w - 1.882$.The apparent stress $\sigma_a$ increases by more than a factor of four when centroid depth increases from $\sim 4$ km to $\sim 10$ km. We find that the strong depth dependence of $\sigma_a$ cannot be accounted by depth-dependent attenuation without adversely affecting the fit to the data.

# FAULT VALVING AND PERMEABILITY EVOLUTION IN SLOW AND FAST FAULT SLIP DYNAMICS

***Danyang JIANG*** [1], ***Antonio P. RINALDI*** [1], ***Luca DAL ZILIO*** [2,3]

[1] Swiss Seismological Service, Swiss Federal Institute of Technology, ETHZ, Zurich, Switzerland
[2] Earth Observatory of Singapore, Nanyang Technological University, Singapore, Singapore
[3] Asian School of the Environment, Nanyang Technological University, Singapore, Singapore

*contact: danyang.jiang@sed.ethz.ch*

Conventional earthquake models often overlook dynamic fluid pressure and poroelastic effects, despite faults potentially acting as either barriers or conduits to fluid flow. To address this, we develop the Hydro-Mechanical Earthquake Cycles (H-MECs) model, integrating solid-fluid interactions, poroelastic stresses, and fluid flow on- and off-fault. Our model employs a 2-D antiplane strike-slip fault framework in a poro-visco-elasto-plastic compressible medium governed by rate- and state-dependent friction and incorporates a permeability evolution law reflecting changes due to fault slip and healing. The model simulates fluid ascent in the seismogenic zone, sourced from metamorphic reactions, and tests various nucleation sizes to study the interplay between fault friction and solid-fluid interactions coupled by poroelasticity. When the nucleation size is relatively large and the healing time is prolonged, we observe an increased dominance of solid-fluid interactions and poroelastic effects within the fault system. This leads to an increase in fault permeability that facilitates the migration of over-pressurized ascending fluids and initiates slow-slip events within the seismogenic zone. Conversely, smaller nucleation sizes enhance the interplay between fault friction and solid-fluid interactions, triggering the upward migration of seismic swarms. These smaller earthquakes are closely followed by pore pressure diffusion of ascending fluids due to fault valving effects, highlighting the critical role of transient fluid effects in slow-slip events and the propagation of seismic swarms. This research advances our understanding of the coupling between strain localization, poromechanics and friction throughout the earthquake cycle.

# RECONCILING BIAS IN MODERATE MAGNITUDE EARTHQUAKE GROUND MOTIONS PREDICTED BY NUMERICAL SIMULATIONS

***Sajan K C*** [1], ***Chukwuebuka C. NWEKE*** [1], ***Jonathan P. STEWART*** [2], ***Robert W. GRAVES*** [3]

[1] Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, USA

[2] Department of Civil and Environmental Engineering, University of California Los Angeles, Los Angeles, USA

[3] Earthquake Hazards Program, United States Geological Survey, Pasadena, USA

*contact: sajankc@usc.edu*

This study employs the Graves-Pitarka broadband ground motion simulation method, integrated within the SCEC Broadband Platform BBP, to conduct finite fault simulations for 51 well-recorded moderate magnitude events in Southern California, ranging from Mw 3.92-5.52. The core objective is to evaluate whether simulated ground motions are biased relative to observations through a direct comparison of effective amplitude spectra (EAS). If bias is found, we also seek to identify sources of misfit in the simulations. We anticipate bias may be present based on systematic underprediction of low-frequency spectral accelerations from prior work (Nweke et al. 2022). We extend that work by considering additional events and using EAS. Bias at frequencies $< 1$ Hz persists in the present results. Further investigation of residuals shows that while site and path-related biases exist, they are minor, as substantial bias remains after accounting for their influence. Therefore, we posit that the remaining bias is likely related to the earthquake source attributes. We hypothesize that the empirical magnitude-rupture area scaling relationship applied in the simulations from Leonard (2010) breaks down for lower magnitude events. This hypothesis appears valid for the 2008 Mw 5.36 Chino Hills event. However, further testing is limited by the unavailability of finite fault models to establish rupture area for events in our dataset. Ongoing research focuses on the effects of fault rupture area - related to stress drop and average slip - on the overall bias. Moreover, we intend to conduct a sensitivity study of other earthquake source attributes, such as average rupture speed, on an event-specific basis to explore potential resolutions for the remaining observed bias.

# UNRAVELING THE PHYSICAL MECHANISM OF LARGE AND LONG-PERIOD, NEAR-FAULT GROUND VELOCITIES IN SURFACE-BREAKING EARTHQUAKES

***Yoshihiro KANEKO*** [1], ***Jesse KEARSE*** [2], ***Yoshito NOZUKA*** [1], ***Hiroyuki GOTO*** [3]

[1] Graduate School of Science, Kyoto University, Kyoto, Japan
[2] School of Geography, Environment and Earth Sciences, Victoria University of Wellington, Wellington, New Zealand
[3] DPRI, Kyoto University, Uji, Japan

*contact: kaneko.yoshihiro.4e@kyoto-u.ac.jp*

Near-fault ground motions in recent, well-recorded surface-breaking earthquakes exhibit large (greater than 1 m/s) and long-period (a few seconds) velocity pulses, posing substantial hazards to tall buildings and large infrastructures. However, the physical mechanism behind their generation remains unclear. In this study, we utilize dynamic rupture simulations to investigate the origin of large and long-period velocity pulses observed during the 2022 Mw7.0 Chihshang (Taiwan) and 2024 Mw7.5 Noto (Japan) earthquakes. Notably, some stations for the Chihshang earthquake are as close as 250 m from the fault trace, providing a rare opportunity to examine the origin of near-fault ground motion in detail. We show that a relatively simple dynamic rupture model with uniform along-strike pre-stress and frictional properties can reasonably reproduce a set of near-fault waveform data and other geophysical datasets. Our results suggest that the dynamic interaction between propagating rupture and the Earth's surface, enhanced by reflected waves from the boundaries of shallow low-velocity layers, leads to large, long-period ground velocities in near-fault regions. This generic mechanism suggests that large, long-period ground motion is a common occurrence in near-fault regions during surface-breaking earthquakes. Our conclusion underscores the significance of dynamic interaction between propagating rupture and Earth's free surface, which must be accounted for to accurately predict near-fault ground motions.

# SEISMIC SOURCE SPECTRAL PROPERTIES OF DYNAMIC RUPTURE WITH A SELF-SIMILAR, SELF-HEALING SLIP PULSE

***Yuto KANO*** [1], ***Yoshihiro KANEKO*** [1], ***Peter M. SHEARER*** [2]

[1] Graduate School of Science, Kyoto University, Kyoto, Japan
[2] IGPP, Scripps Institution of Oceanography , University of California, San Diego, La Jolla, USA

*contact: kaneko.yoshihiro.4e@kyoto-u.ac.jp*

Large earthquakes commonly exhibit pulse-like rupture modes, in which the local slip duration is longer than the source duration. However, stress drops of small earthquakes are often estimated from far-field body-wave spectra using measurements of seismic moment, corner frequency, and a theoretical model of rupture in a crack-like mode. In this study, we develop fundamental models of earthquake rupture with a self-similar, self-healing slip pulse. We examine the resulting spectral properties, scaled energy, and estimated stress drops, and compare them to those derived from self-similar, crack-like rupture models. We find that the source spectra of pulse-like rupture models show classical double corners, consistent with previous studies. In the pulse-like rupture models, the second corner frequency at small take-off angles to the fault normal vector corresponds to the width of the slip pulse, yet in the stacked spectra over the entire focal sphere, it is caused by the rupture directivity and hence is unrelated to the width of the slip pulse. The spherical averages of P- and S-wave corner frequencies increase with the rupture speed and are higher than those of their crack-like rupture counterparts, as expected. The variability of estimated stress drops due to differences in the rupture speed is larger in the pulse-like rupture models than that in the crack-like rupture models. These results suggest that if small earthquakes are indeed mostly pulse-like ruptures, the large variability of estimated stress drops often seen in observational studies may come from variability in source characteristics almost independent of the actual stress drops.

# DYNAMICS OF SLOW AND FAST EARTHQUAKES AND THE EFFECT OF DAMAGE AROUND THE FAULT BY ANALYZING ENERGY VARIATION

***Navid KHEIRDAST*, *Michelle ALMAKARI*, *Harsha S. BHAT*, *Ankit GUPTA***

Laboratoire de Géologie de l'ENS (UMR 8538),
École normale superieure, PSL university, Paris, France

*contact: khairdast@gmail.com*

Stress and displacements in fault zones evolve due to complex mechanical interactions between fractures that span a multitude of length scales in the damage zones surrounding mature faults. In such systems, mechanical energy is stored due to tectonic loading. However, when (micro)fractures are unable to bear the tectonic loads, they host unstable slips, or earthquakes, that dissipate the stored energy in the bulk of rocks across a multiscale rupture magnitude. In this study, we design a fracture-network surrounding a main rough fault, the length and density of fractures follow observationally verified statistical distribution. Frictional strength on each fracture is rate dependent. We run quasi-dynamic seismic cycle simulation for this fault networks. The results show both slow and fast earthquakes on the main fault, as well as tremor-like behavior in the damaged zone, simultaneous with the slow instabilities on the main fault. Given off-faults at different orientations, we study under which conditions ruptures tend to advance slowly. The study of the change in the system's potential energy due to an infinitesimal advancement of slip on the main fault, and computing the share of the main and off-faults in this process, introduces the concept of a generalized force that drives the rupture, wherein off-faults might increase or decrease this generalized force. This force is balanced with the surface resistance against rupture slip, which is dictated by the friction law. We discuss how the rate dependency of friction, translated in terms of instability length increase, balances with the generalized rupture driving force, and how off-faults affect rupture speed by applying a generalized force opposite to the one applied by the rupture on the main fault.

# KINEMATICALLY CONSTRAINED, LINKED AND FULLY COUPLED DYNAMIC RUPTURE AND TSUNAMI MODELING OF THE 2020, $M_W$ 7.0 SAMOS EARTHQUAKE

***Fabian KUTSCHERA*** [1], ***Alice-Agnes GABRIEL*** [1,2], ***Thomas ULRICH*** [2]

[1] Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California San Diego, La Jolla, USA

[2] Department of Earth and Environmental Sciences, Ludwig-Maximilians-Universität München, Munich, Germany

*contact: fkutschera@ucsd.edu*

The tsunamigenic $M_W$ 7.0 Samos earthquake was the deadliest earthquake of 2020 and ruptured a north-dipping normal fault within the eastern Aegean Sea. We aim to unravel the complexity of rupture and tsunami generation by comparing kinematic source models with kinematically informed 3D dynamic rupture models and using different tsunami modeling techniques. We compare two data-driven finite-fault models (Heidarzadeh et al., 2021; Plicka et al., 2022) in 3D kinematic rupture models and select a preferred model based on the comparison against seismic, geodetic, and tsunami observations. Shear stress changes in dip direction of this model inform two spontaneous dynamic rupture models (Tinti et al., 2021): models with uniform and depth-dependent initial normal stress generate comparable peak slip amplitudes. The dynamic rupture model with decreased normal stress near the surface results in extended surface rupture and wider seafloor subsidence within Kuşadası Bay. Kinematic and kinematically informed dynamic rupture simulations show significant differences in (low-frequency, $<$2 Hz) peak horizontal velocities. We use the kinematic and dynamic rupture models as time-dependent sources for one-way linked and fully coupled earthquake-tsunami modeling (Abrahams et al., 2023; Kutschera et al., 2024). In the more efficient shallow-water tsunami simulations, we identify long-term tsunami reverberance lasting locally up to four hours. The tsunami synthetics of the more complex fully coupled earthquake-tsunami simulations (Krenz et al., 2021) contain a higher frequency content than the smoother one-way linked tsunami waveforms. Our analysis may help to design and guide rapid workflows for the joint assessment of physics-based seismic and tsunami hazards.

*Note: Figure is on the next page.*

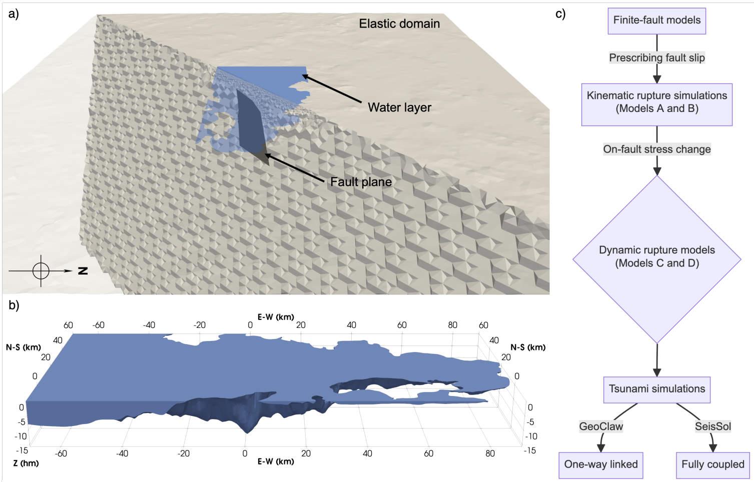


**Figure 1.** a) Transection of the three-dimensional unstructured tetrahedral mesh for the elastic domain (grey) including the water layer (blue) and the north-dipping fault plane (black) of Plicka et al. (2022). The fault plane has a strike/dip/rake of 265°/40°/-110° and intersects the seafloor. The static mesh refinement is visible near the fault plane and the transected domain. b) Dimension of the water layer. Here, we prescribe a rigidity of $\mu = 0$ (Krenz et al., 2021; Kutschera et al., 2024). c) Workflow of this study. We start with two finite-fault models and prescribe their slip distribution in kinematic rupture models. Based on our joint assessment of the kinematic rupture models and their comparison against seismic, geodetic, and tsunami observations, we select a preferred model. We compute and use the on-fault shear stress change in dip direction of this model to inform two spontaneous dynamic rupture models, which enables us to test the mechanical viability of the kinematic model.

# NANOSCALE DYNAMIC FRICTION AND WEAR MECHANISM OF ALPHA-QUARTZ ASPERITIES

***Sheng LI*, *Eiichi FUKUYAMA***

Department of Civil and Earth Resources Engineering, Kyoto University, Kyoto, Japan

*contact: li.sheng.67j@st.kyoto-u.ac.jp*

The frictional wear between fault surfaces commonly involves continuous deformation, fracture, or material removal on rugged projections (asperities), which can significantly influence the fault friction properties and energy dissipation during earthquakes. However, the current understanding of wear mechanism, especially at the microscopic scale, is limited to post-experiment analysis and empirical explanations due to the observation of the opaque wear process during frictional sliding. Here, we focus on the nanoscale wear process of two interlocked $\alpha$-quartz asperities to explicitly reproduce a series of 3-D wear processes by employing molecular dynamics (MD). While the normal force and velocity-dependent dynamic wear damage mechanism was observed, the empirical wear model for volume loss (Archard law) was also compared to discuss the multi-scale applicability. Our findings indicate that the wear attrition mechanism on asperities is less influenced by the loading velocity but governed by the normal force. Under the low normal force, worn atoms are primarily from the bonding and shear traction between interfacial atoms. In contrast, a significant plastic flow by layered shear motion dominates under the high normal force and atoms are more prone to be detached as clusters. Higher normal force corresponds to larger scale clumps of attrition on asperities. Notably, adhesive wear dominates in all results. In addition, the empirical wear model (Archard law) shows some limitations in quantifying the wear volume due to the effect of increasing loading velocity. Instead, the friction work, with considering an instantaneous friction coefficient and a time-varying contact force, could predict the wear volume accurately.

# STUDYING THE VIABILITY OF KINEMATIC RUPTURE MODELS AND SOURCE TIME FUNCTIONS WITH DYNAMIC CONSTRAINTS

***Maria Eugenia LOCCHI*** [1], ***Francesco MOSCONI*** [1], ***Mariano SUPINO*** [2], ***Emanuele CASAROTTI*** [2], ***Elisa TINTI*** [1,2]

[1] Earth Science, La Sapienza University of Rome, Rome, Italy
[2] Istituto Nazionale di Geofisica e Vulcanologia, INGV, Rome, Italy

*contact: mariaeugenia.locchi@uniroma1.it*

Earthquake is one of the greatest natural hazards and a better understanding of the physical processes causing earthquake ruptures is required for appropriate seismic hazard assessment. Kinematic modelling is a standard tool to provide important information on the complexity of the earthquake rupture process and for making inferences on earthquake mechanics. Despite recent advances, kinematic models are characterized by uncertainties and trade-offs among parameters. Prescribing the slip velocity on extended faults is one of the crucial components in the models because it contains key information about the dynamics. However, in kinematic inversions this function is assumed a-priori using different shapes, although functions compatible with rupture dynamics should be preferred. To investigate the effect of the slip velocity function on kinematic inversion models we run a series of forward and inverse models. We generate spontaneous dynamic models and use their ground motion as real events and we invert the data with kinematic models. Kinematic inversions have been conducted assuming both single-time and multi-time windowing and to investigate the uncertainties we adopt four different source time functions. In this way we examine how the slip velocity function influences the slip distribution on the fault plane and if the inferred kinematic parameters are consistent with the dynamic models. We also examine the variability of PGV from synthetic seismograms up to 1 Hz, obtained with forward models assuming the same slip distribution, rise time and rupture velocity, but changing the source time functions. Those results provide a glimpse of the variability that kinematic slip velocity functions might have when used as a constraint to model the earthquake dynamics.

# DYNAMIC RUPTURE SIMULATIONS ON THE ALPINE FAULT, NEW ZEALAND: INVESTIGATING THE ROLE OF FAULT GEOMETRY ON RUPTURE SIZE AND BEHAVIOR OVER MULTIPLE EARTHQUAKE CYCLES

***Julian LOZOS*** [1], ***Emily WARREN-SMITH*** [2], ***John TOWNEND*** [3]

[1] Department of Geological Sciences,
California State University, Northridge, Northridge, California, USA

[2] Seismology Department, GNS Science, Lower Hutt, New Zealand

[3] School of Geography, Environment, and Earth Sciences ,
Victoria University of Wellington, Wellington, New Zealand

*contact: julian.lozos@csun.edu*

The 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 Marlborough Fault System in the northeast consists of two planar sections connected by a major geometrical boundary, which is characterized by a dip change of as much as 40° over an along-strike length of only ∼5 km. Previous studies suggest that changes in dip along a strike-slip fault can affect rupture dynamics. It is therefore possible that this feature controls conditional earthquake segmentation on the Alpine Fault, as documented by the extensive paleoseismic record.

We simulate multiple cycles of dynamic ruptures on the southwestern ∼320 km of the Alpine Fault. We use dynamic rupture simulations for the coseismic period, then account for the interseismic period by incrementing shear stress based on time between events. For each dynamic simulation, we compare the modeled rupture length and surface slip to geologic and paleoseismic studies to ensure that we are producing physically-plausible simulations consistent with observations. We find that the dip change at the segment boundary is not inherently a barrier to rupture within single events, but that stress changes associated with rupture through this boundary in one earthquake can sometimes lead to segmentation in the next one. Our results suggest that rupture hazard on the Alpine Fault may depend both on the slip distribution of and the timing since the previous large earthquake. This also implies that both fault geometry in and of itself and long-term stress patterns resulting from that geometry are important considerations for hazard assessment on other geometrically-complex faults.

# EFFECTIVE STRESS AND FAULT STRENGTH VARIATIONS WITH DEPTH: INSIGHTS FROM SEISMO-THERMO-MECHANICAL SUBDUCTION MODELS AND DYNAMIC RUPTURE MODELS

***Elizabeth (Betsy) MADDEN*** [1], ***Ylona VAN DINTHER*** [2], ***Alice-Agnes GABRIEL*** [3], ***Thomas ULRICH*** [4], ***Iris VAN ZELST*** [5]

[1] Department of Geology, San José State University, San José, USA
[2] Geosciences, Utrecht University, Utrecht, The Netherlands
[3] Institute of Geophysics and Planetary Physics, UC San Diego, San Diego, USA
[4] Geophysics, Ludwig Maximilians University, Munnich, Germany
[5] German Aerospace Center, TU Berlin, Berlin, Germany

*contact: elizabeth.madden@sjsu.edu*

The near-fault stress regime and fault strength before and during fault sliding exert first-order control on mechanics and earthquake rupture dynamics, but remain difficult to constrain, especially in complex subduction zone settings. In addition to inferences from earthquake observations, drill holes and conceptual models, insights from geodynamic-seismic cycle modeling provide an additional avenue by which to constrain these parameters. These seismo-thermo-mechanical models suggest that both the effective stress field near a megathrust and the static and dynamic fault strength vary non-linearly with depth and are materially dependent. We contrast results from two dynamic earthquake rupture models resulting from (A) these heterogeneous initial conditions from geodynamic-seismic cycle models, and (B) simpler, depth-dependent initial conditions that are more commonly used to initiate earthquake rupture models. Although the maximum fault strength is similar in both scenarios, the heterogeneous initial conditions in (A) result in larger fault slip, but lower average dynamic stress drop and lower rupture velocity. In addition, we observe that seismic waves traveling through complex materials around the fault in (A), as opposed to the homogeneous material in (B), influence earthquake rupture style and shallow slip accumulation. These insights underscore the need to better understand initial earthquake conditions from a variety of sources, including integrative modeling, in order to advance understanding of earthquake initial conditions, fault strength, and earthquake behavior.

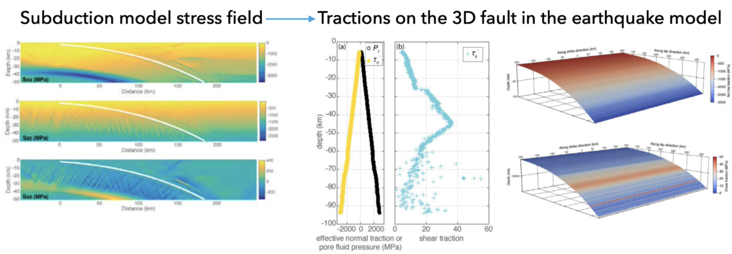


**Figure:** The conditions at the start of a 2-dimensional seismo-thermo-mechanical model slip event (left, middle) are ported to the 3-dimensional dynamic earthquake rupture model as initial conditions (right). The normal tractions increase with depth along the fault, while the shear tractions are below 15 MPa along the upper part of the fault, then increase more rapidly with depth from approximately 30 km depth to a maximum of ~38 MPa at 45 km depth, before decreasing again.

# EFFECTS OF BIMATERIAL INTERFACE ON RUPTURE ALONG STRIKE-SLIP BRANCH FAULTS

***Evan O. MARSCHALL*** [1], ***Roby DOUILLY*** [1], ***Nobuki KAME*** [2]

[1] Earth and Planetary Science Department, Univeristy of California Riverside, Riverside, USA
[2] Earthquake Research Institute , University of Tokyo , Tokyo, Japan

*contact: emars009@ucr.edu*

Crustal faults often separate material with differing elastic properties. Dissimilar media around faults has been shown to cause effects on the rupture process along vertical strike-slip faults. Some previous studies suggest that asymmetry in wave propagation across a bimaterial interface can introduce normal stress changes on the fault near the rupture front that can lead to asymmetric bilateral or unilateral propagation. Furthermore, a bimaterial interface can also lead to differences in strain release across a fault interface for a fixed stress drop. Considering the effects caused by bimaterial interface on rupture propagation and since fault systems can be composed of numerous segments, it is worth understanding whether these effects can impact throughgoing rupture across a geometric complexity. In this work we use dynamic rupture simulations to investigate the effects of a bimaterial interface on rupture propagation along branch faults. We assign a zone of stiffer material to one side of the fault system, such that both the main and secondary fault separate dissimilar media. We vary the material contrast ($\gamma$) from 0-0.20 in the zone of stiffer material such that the p-velocity in the stiffer material is Vp*(1+$\gamma$), where Vp is the p-velocity in the rest of the elastic medium. The results show that when rupture is nucleated on the main fault it is less likely to rupture the secondary segment as the material contrast increases if the main fault and secondary faults have the same sense of slip. If the faults have opposite senses of slip, we find that a larger material contrast promotes rupture propagation on the secondary fault. This could have implications for assessing seismic hazard in regions with complex fault systems which separate dissimilar media.

# DEVELOPMENT OF DYNAMIC SOURCE INVERSION TO UNDERSTAND MECHANISM OF STRONG MOTION GENERATION

***Takeshi MIYAMOTO*** [1], ***Kimiyuki ASANO*** [2], ***Tomotaka IWATA*** [2]

[1] Graduate School of Science, Kyoto University, Kyoto, Japan
[2] Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan

*contact: miyamoto.takeshi.25a@st.kyoto-u.ac.jp*

Source rupture processes for many large earthquakes have been estimated by kinematic source inversion methods. Relationships between the inferred kinematic source models and strong ground motions have been discussed in many papers. Spatial distributions of dynamic source parameters on the fault have been estimated mainly by dynamic rupture simulations and, recently, directly by dynamic source inversion (e.g., Gallovič et al., 2019). This method mainly consists of two parts: generating synthetic waveforms (i.e., convolving slip time functions obtained by the dynamic rupture simulation and Green's functions) and updating values of dynamic source parameters randomly using MCMC method so as to fit the observed waveforms. In this study, a dynamic source inversion is developed following Gallovič et al. (2019) and a validation test assuming a simple dynamic source model is being performed to be applied to the 2016 Kumamoto earthquake. After the validation test with 10,000 iterations, probabilistic distributions of values of dynamic source parameters at all control points were obtained from the last 4,000 source models, which showed higher VR values, and the estimated source model was given as the mean values of these distributions at each point. The estimated values of dynamic parameters didn't show a good agreement with those of assumed model, except in the vicinity of the nucleation point, which resulted in the final slip distribution with larger maximum slip and smaller area, whereas the waveforms were almost the same as those generated by the assumed model. To improve efficiency of dynamic source inversion, appropriate width of step size and physics-based constraint conditions for perturbation of dynamic parameters are being considered.

# THE FINITE-DIFFERENCE MODELLING: WHERE IS IT AND WHAT'S NEXT?

**Peter MOCZO** [1,2], **Jozef KRISTEK** [1,2], **Jaroslav VALOVČAN** [1],
**Martin GÁLIS** [1,2], **Miriam KRISTEKOVÁ** [1,2]

[1] Faculty of Mathematics, Physics and Informatics,
Comenius University in Bratislava, Bratislava, Slovak Republic

[2] Earth Science Institute, Slovak Academy of Sciences, Bratislava, Slovak Republic

*contact: moczo@fmph.uniba.sk*

The finite-difference (FD) method is recently one of three most important and most used numerical methods for modelling seismic wave propagation and earthquake motion. While it is clearly dominant in the seismic exploration, it competes with the spectral-element (SE) and discontinuous Galerkin (DG) methods in the earthquake seismology, being most used for modelling earthquake motion in local small-scale surface sedimentary structures. Very recently, it is to be compared with a new powerful method – the distributional FD method.

The FD method in seismology has been continuously developing for almost 60 years. Surprisingly (or obviously?), the development was neither straightforward nor truly always logical in terms of consistency with mathematics and physics. Likely because the method seems to be very or relatively simple compared to the other methods. Clearly, one of the most important aspects of any numerical method is the implementation of continuous and mainly discontinuous heterogeneities of the medium. Several times in the history of the method, developers of FD methodology and mainly users of FD codes assumed that the problem was satisfactorily or even fully solved by those-times modern FD schemes. Especially the so-called heterogeneous schemes.

In our contribution we demonstrate that it was not always the case. Based on our very recent and surprising findings we explain consequences of implementation of boundary conditions at a material interface, and spatial discretization of a medium and wavefield for heterogeneous FD schemes. We outline what must be still developed in order to find a FD scheme consistent with mathematics and physics.

# MODELING THE 3D DYNAMIC RUPTURE OF MICROEARTHQUAKES INDUCED BY FLUID INJECTION

***Francesco MOSCONI*** [1], ***Elisa TINTI*** [1], ***Emanuele CASAROTTI*** [2], ***Alice-Agnes GABRIEL*** [3], ***Luca DAL ZILIO*** [4], ***Antonio Pio RINALDI*** [5], ***Massimo COCCO*** [2]

[1] Earth Science, Sapienza University of Rome, Rome, Italy

[2] Seismology, Istituto Nazionale Geofisica e Vulcanologia, Rome, Italy

[3] Institute of Geophysics and Planetary Physics,
Scripps Institution of Oceanography, UC San Diego, USA

[4] Earth Science, Earth Observatory of Singapore, NTU, Singapore, Singapore

[5] Department of Earth Sciences, Institute of Geophysics, ETH Zurich , Zurich, Switzerland

*contact: francesco.mosconi@uniroma1.it*

Understanding the dynamics of microearthquakes is a timely challenge to solve current paradoxes in earthquake mechanics and to investigate earthquake ruptures induced by fluid injection. We perform fully 3D dynamic rupture simulations caused by fluid injection on a fault and we generate Mw$\leq$1 seismic events assuming spatially variable stress drops caused by pore pressure changes. Spontaneous arrest of a propagating rupture is possible when we consider a high fault strength parameter S, that is, high ratio between strength excess and dynamic stress drop. With high S values even minor variations in Dc have a substantial effect on the rupture propagation and on the ultimate size of the earthquakes. Modest variations of dynamic stress drop determine the rupture mode, distinguishing self-arresting from run-away ruptures. Several features inferred for accelerating dynamic ruptures differ from those observed during rupture deceleration in a self-arresting earthquake due to the spatial gradient of the effective normal stress. These results integrate those obtained with spatial variations of the initial stress, highlighting the role of the heterogeneities of stress drop and Gc.

# NONLINEAR COSEISMIC OFF-FAULT DAMAGE IN 3D DYNAMIC RUPTURE SIMULATIONS: DELAYED TRIGGERING, HIGH-FREQUENCY RADIATION, AND SEISMIC WAVE SPEED REDUCTION

***Zihua NIU*** [1], ***Alice-Agnes GABRIEL*** [1,2], ***Yehuda BEN-ZION*** [3,4],
***Vladimir LYAKHOVSKY*** [5], ***Heiner IGEL*** [1]

[1] Department of Earth and Environmental Sciences,
Ludwig-Maximilians-Universität München, Munich, Germany

[2] Scripps Institution of Oceanography, UC San Diego, La Jolla, USA

[3] Department of Earth Sciences, University of Southern California, Los Angeles, USA

[4] Statewide California Earthquake Center, University of Southern California, Los Angeles, USA

[5] Geological Survey of Israel, Yesha'yahu Leibowitz 32, Jerusalem, Israel

*contact: zihua.niu@lmu.de*

Off-fault materials can be subject to significant co-seismic damage (moduli reduction) near major faults according to the field and seismic observations (e.g. Sibson, 1977; Mitchell and Faulkner, 2009; Allam et al., 2014). To analyze the effects of non-linear off-fault damage on the dynamic rupture process, as well as the co-seismic interplay of earthquake rupture dynamics in complex fault systems, we implement the Continuum Damage Breakage (CDB) model of Lyakhovsky et al. (2016) in the 3D open-source dynamic rupture and seismic wave propagation solver SeisSol. The localized damage zones (see Fig. 1b) from our numerical simulations originate from a rapid transition from the solid phase to the granular phase of rocks. The damage patterns in the simulation also align with the weak surfaces predicted by the CDB model. Such a phase transition process generates high-frequency seismic energy radiation (see Fig. 1a). We in addition quantify how the energy dissipated due to thermodynamically irreversible off-fault rock damage depends on the parameters of the CDB model.

In strike-slip step-over dynamic rupture simulations, we find that the damage-induced moduli reduction around a rupturing fault can facilitate dynamic triggering ('rupture jumping') of an adjacent fault (see Fig. 1c to 1e). Depending on the accumulation rate of damage, we observe delayed triggering by a variable time interval (from seconds to minutes). These results demonstrate how the mechanical moduli reduction due to a time-dependent damage evolution process in off-fault rocks can contribute to rupture triggering on adjacent faults. Our implementation of the non-linear model in SeisSol also provides the tool to quantify this physical process with 3D regional scale physics-based numerical simulations.

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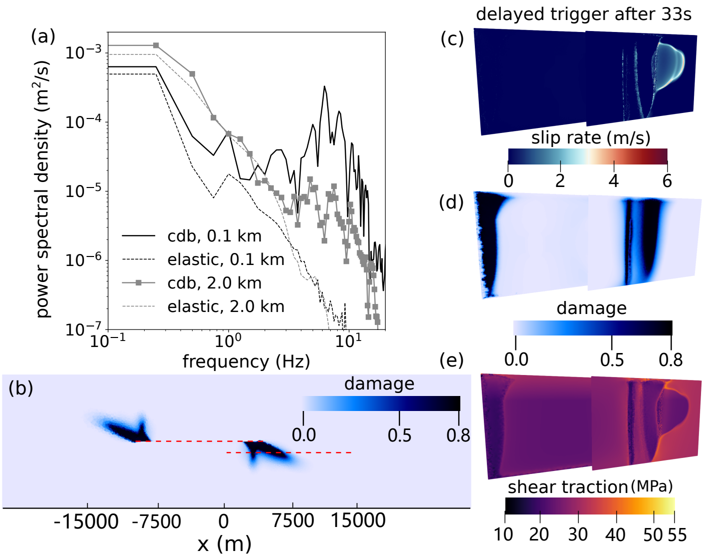


Fig. 1: (a) The power spectral density of velocity time series recorded at 0.1 km and 2.0 km away from the fault plane. (b) The fault localized damage zones (in dark blue) at depth of 7.5 km that follows the weak planes according to the model from Lyakhovsky et al. (2016). The two dashed red lines mark the locations of the two neighboring fault planes, separated by 3 km. We show the slip rate (c), damage (d) and shear traction (e) on the two faults. The nucleation of rupture on the second fault is delayed by 33 s in this example.

# THE ROLE OF OFF-FAULT PERMANENT DEFORMATION ON EARTHQUAKE CYCLES

***Bar ORYAN*, *Alice-Agnes GABRIEL*, *Dave A. MAY***

Scripps Institution of Oceanography, UC San Diego, La Jolla, CA, USA

*contact: boryan@ucsd.edu*

One of the most commonly held assumptions in earthquake hazard assessment is that the off-fault deformation associated with the earthquake cycle is purely elastic. In subduction settings, this suggests that all off-fault strain associated with the slow interseismic loading period is released during large megathrust earthquakes, amounting to effectively zero deformation and surface displacement over numerous cycles. However, recent evidence (Oryan et al., 2024) suggests that interseismic stresses can induce increments of irreversible brittle failure across the overriding plate, creating a spatially variable field of permanent deformation and long-term surface displacement. This indicates that a significant portion of interseismic elastic energy dissipates through yielding and is not available to drive earthquakes.

The impact of this behavior on the coseismic period and earthquake rupture processes remains elusive. To investigate the potential imbalance in co-, post-, and interseismic strain of earthquake cycles, we use Tandem (Uphoff et al., 2022), an open-source discontinuous Galerkin volumetric solver for quasi-dynamic sequences of earthquakes and aseismic slip (SEAS). We simulate SEAS along a 10-degree dipping planar thrust fault with gradually varying off-fault material properties. We incorporate a region with reduced off-fault Lamé parameters to represent a weakened area above the transition in fault-coupling where interseismic stresses and permanent deformation are expected to be most pronounced. Our preliminary findings may hint at a trend towards fewer but larger earthquakes with significant weakening of the wedge, highlighting the importance of off-fault permanent deformation for the long-term behavior of earthquakes.

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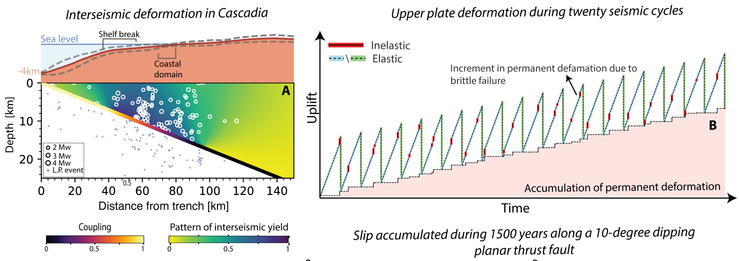
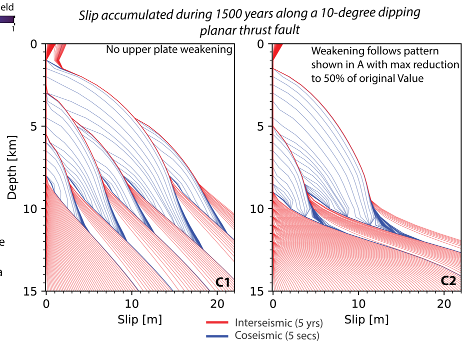



**Temporal and spatial patterns of upper plate brittle failure, illustrated alongside our initial model results.** A displays the modeled pattern of brittle failure in the upper plate of Cascadia, with colors indicating the failure regions and circles marking recorded seismic events. The colors along the megathrust represent the coupling distribution (Oryan et al., 2024). B shows elastic and inelastic deformation at a point in the upper plate over twenty seismic cycles. C shows slip accumulated over 1500 years along a 10-degree dipping planar thrust fault: 1) Reference model without upper plate weakening; 2) Model with Lame parameters weakening following the spatial pattern in Cascadia (A), achieving a maximum reduction to 50% of the original value.

# IMPACT OF STRESS HETEROGENEITY ON RUPTURE NUCLEATION AND SEISMIC CYCLE COMPLEXITY IN A LONG LABORATORY FAULT

***Federica PAGLIALUNGA*** [1,2], ***François PASSELÈGUE*** [1], ***Marie VIOLAY*** [2]

[1] Géoazur, Université de Côte d'Azur, Valbone, France
[2] ENAC , Ecole polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland

*contact: Federica.PAGLIALUNGA@geoazur.unice.fr*

Various aspects of earthquake physics are still not completely understood given its intrinsically complex nature, notably the nucleation process and seismic cycle dynamics. Seismology faces challenges in accessing precise information about the physical processes taking place on the fault plane. Our study demonstrates how laboratory seismology illuminates fault dynamics. Using a large biaxial apparatus (2.5 m fault length), we replicate fault behavior with PMMA samples, imposing heterogeneous loading and specific boundary conditions. Strain gauges at 15 locations measure stress at 40 KHz.

The experiments provide insights into two crucial aspects of laboratory earthquakes: the location of rupture nucleation and the complexity of the seismic cycle. We discover that the initial stress distribution on the fault significantly influences both aspects. Ruptures consistently nucleate in regions where the stress ratio is highest. Remarkably, these values vary across experiments, challenging the prevalent notion that friction coefficients alone dictate instability onset. Additionally, we demonstrate how the heterogeneity of the initial prestress distribution along the fault governs the seismic cycle's complexity. In certain cases, the seismic cycle manifests as system-size events with regular complete ruptures. Conversely, other initial stress distributions generate more complex cycles, marked by multiple contained events preceding the main rupture. The seismic cycle's complexity can be delineated by the number of interseismic events, interevent time, and rupture size.

This study highlights the complexities that emerge when heterogeneous, hence more realistic, stress conditions are applied, providing valuable insights into the physics of natural earthquakes.

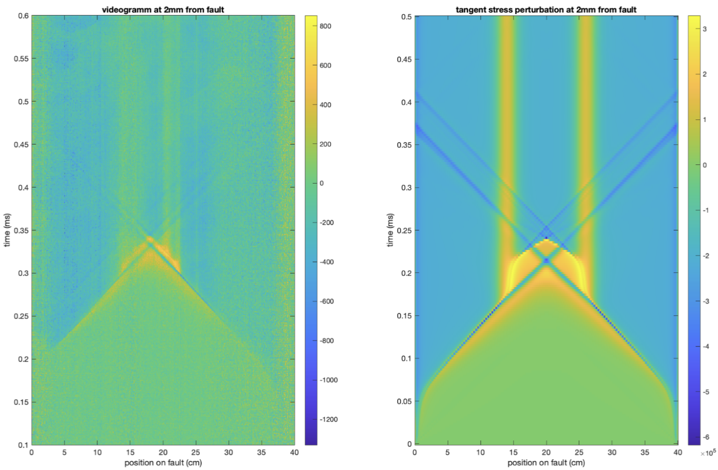
# WHAT HAPPENS WHEN TWO RUPTURES COLLIDE?

***François PASSELÈGUE*** [1], ***Soumaya LATOUR*** [2],
***Federica PAGLIALUNGA*** [1], ***Corentin NOEL*** [1]

[1] CNRS Géoazur, University of Côte d'Azur, Nice, France
[2] IRAP, Université Paul sabatier, Toulouse, France

*contact: francois.passelegue@geoazur.unice.fr*

Here, we present a first and unique experimental observations of the interaction between two rupture fronts that spontaneously nucleate along an experimental fault and ultimately collide during their propagation. While this scenario might initially seem like an experimental anomaly, it may, in fact, be highly relevant for studying the rupture process of complex earthquakes. Indeed, the Mode II geometry presented here can be associated with the rupture of long strike-slip faults, which are known to exhibit intricate behavior. We demonstrate that the dynamic interplay between multiple rupture fronts and the associated radiated waves, as elucidated in our findings, may offer insights into the complex source time function of such earthquakes. Notably, we show, supported by numerical modelling of this phenomenon, that the collision of the rupture fronts generates interface waves that propagate along the sliding interface. Additionally, the rupture fronts interact with the onset and cessation of S-waves radiated by the opposing rupture fronts, which can alter their velocity and also generate interface waves.



# DO PHYSICS-BASED DYNAMIC RUPTURE MODELS CAPTURE GROUND-MOTION VARIABILITY? INSIGHTS FROM THE 2023 TURKEY EARTHQUAKE SEQUENCE

***Rachel PRECA TRAPANI*** [1], ***Mathilde MARCHANDON*** [1], ***Alice-Agnes GABRIEL*** [2], ***Thomas ULRICH*** [1], ***Ming-Hsuan YEN*** [3], ***Fabrice COTTON*** [3]

[1] Department of Earth and Environmental Sciences, Ludwig-Maxmilians-Universität , Munich, Germany

[2] SCRIPPS Institution of Oceanography, UC San Diego , San Diego, USA

[3] GFZ, Helmholtz Centre , Potsdam, Germany

*contact: rachel.precatrapani@gmail.com*

One of the challenges of empirical ground-motion models is the ability to capture the observed ground-motion variability, which may stem from different source, path and site effects. This challenge may be addressed by simulated data from physics-based, non-ergodic earthquake simulations. Dynamic rupture models capture the non-linear interaction of source, path and site effects in a self-consistent way and, once integrated with observations, reproduce a variety of geodetic and seismic data well to first order (e.g., Taufiqurrahman et al., 2022; Jia et al., 2023; Gabriel et al., 2023). However, the variability in ground motions, specifically in long-period pulse orientation, periods (Tp) and amplitudes, may not be fully reproduced. Here we investigate the effects of incorporating both on-fault and structural small-scale heterogeneities within 3D dynamic rupture models of the 2023 Turkey earthquake doublet on the spectral content and the variability of modelled ground motions. We analyse the effects due to fractal on-fault roughness, heterogeneous distribution of fracture energy (Dc) and supershear (Abdelmeguid et al., 2023) compared to sub-shear initiation. Our results suggest that Dc heterogeneity has the most significant influence on Tp variability, while fault roughness appears to mostly affect high-frequency radiation. Supershear rupture initiation minimally increases the variability of Tp and pulse orientation. We plan to explore additional source, path, and site effects, such as including regional VS30 models, to comprehensively capture ground-motion variability and ultimately enhance seismic hazard assessment.

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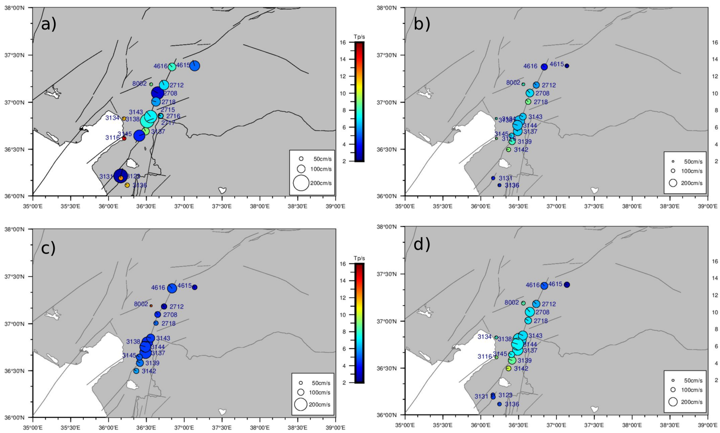

Figure highlighting the different pulse properties for the a) observed data, b) smooth fault reference model, c) rough fault model and d) model with Dc heterogeneities. The size of the circles corresponds to the amplitude, the colour represents the period and the lines within the circles represent the orientation of the pulse extracted at each station.

# MULTI-STAGE DYNAMIC EARTHQUAKE SOURCE INVERSION OF THE 2023 MW 7.8 KAHRAMANMARAS, TURKEY EARTHQUAKE

***Jan PREMUS*, *Jan-Paul AMPUERO***

Observatoire de la Côte d'Azur, Geoazur, Université Côte d'Azur, IRD, CNRS, Nice, France

*contact: janpremus@seznam.cz*

We show results of the dynamic inversion of 2023 Mw 7.8 Kahramanmaraş, Turkey, earthquake. Dynamic source inversion of earthquakes consists of inferring frictional parameters and initial stress on a fault consistent with co-seismic seismological and geodetic data and dynamic earthquake rupture models. In a Bayesian inversion approach, the nonlinear relationship between model parameters and data (e.g. seismograms) requires a computationally demanding Monte Carlo (MC) approach. As the computational cost of the MC method grows exponentially with the number of parameters, dynamic inversion of a large earthquake, with hundreds to thousands parameters, has problems with convergence and sampling. We introduce a novel multi-stage approach to dynamic inversions. We divide the earthquake rupture into two successive temporal (0-21 s, 21-60 s) and spatial stages (140 km central segment, whole 330 km fault). As each stage requires a lower number of independent model parameters, their inversion is faster. Stages are interdependent: earlier stage inversion results are a prior for a later stage inversion. Our main advancement is the use of Generative Adversarial Networks (GAN) to transfer the prior information between inversion stages, inspired by Patel and Oberai (2019). GANs are a class of unsupervised machine learning algorithms originally used for generating images similar to the training set. The trained generator generates synthetic images/samples with low-dimensional noise as an input. We train GANs on samples of dynamic parameters from an earlier stage of the inversion and use the GAN to suggest the dynamic parameters in a later stage. We handle the large rupture by adopting a 2.5D approximation that solves for source properties averaged across the rupture depth.

# FLUID-TRIGGERED SEISMICITY IN A DISCRETE FAULT NETWORK WITHIN A LOW PERMEABILITY FORMATION

***Pierre ROMANET*** [1,2], ***Marco M. SCUDERI*** [1], ***Stéphanie CHAILLAT*** [3], ***Jean-Paul AMPUERO*** [2], ***Frédéric CAPPA*** [2]

[1] Department of Earth Sciences, La Sapienza University of Rome, Rome, Italy
[2] Géoazur, Université Côte d'Azur, Sophia-Antipolis, France
[3] POEMS, ENSTA Paris, Paris, France

*contact: romanet@geoazur.unice.fr*

Hydraulic stimulation in low-permeability formations is crucial for enhancing connectivity of fractures and faults in various industrial projects, such as Enhanced Geothermal Systems (EGSs), gas shale exploitation, and CO2 storage. However, the potential for injection-induced seismicity poses a significant risk to nearby populations.

Discrete Fracture Networks (DFNs) are commonly used to assess hydraulic properties, fluid diffusion and the associated hydromechanical evolution of fractured reservoirs. However, DFNs modeling is typically conducted under a quasi-static approximation, hence lacking a complete description of the interaction between pressurized fluids and the resulting fault slip behaviour, from aseismic creep to earthquake rupture.

Here, we developed a 2-dimensional DFN model to understand fluid-induced earthquakes on multiple interacting and intersecting faults. The model couples hydraulic diffusion together with multiple interacting faults whose slip is governed by Rate-and-State friction law. Elastic interaction between faults is computed using a boundary element method accelerated by H-matrices, and the hydraulic diffusion is modelled with a finite volume method.

With this model, we address the potential for fluid induced slow-slip events and the resulting seismicity on and around the fault system. The long-term goal of this model is to bridge the gap between different scales such as measurements of permeability and frictional stability retrieved from laboratory experiments, in-situ observations of fault slip and opening from fluid injection experiments at decametric scale, and finally, induced seismicity in crustal reservoirs.

# EARTHQUAKES IN SLOVAKIA

**Eva RUTŠEKOVÁ** [1], **Róbert KYSEL** [2,3], **Andrej CIPCIAR** [3],
**Kristián CSICSAY** [3], **Lucia FOJTÍKOVÁ** [3,4], **Jozef KRISTEK** [2,3],
**Martin GÁLIS** [2,3], **Miriam KRISTEKOVÁ** [2,3], **Peter MOCZO** [2,3]

[1] Faculty of Arts,
Comenius University in Bratislava, Bratislava, Slovak Republic

[2] Faculty of Mathematics, Physics and Informatics,
Comenius University in Bratislava, Bratislava, Slovak Republic

[3] Earth Science Institute, Slovak Academy of Sciences, Bratislava, Slovak Republic

[4] Institute of Rock Structure and Mechanics, Czech Academy of Sciences, Prague, Czech Republic

*contact: rutsekova1@uniba.sk*

Territory of Slovakia can be characterized by a low-to-moderate earthquake activity. The earthquake catalogue includes 812 macroseismically observed earthquakes since 1034 and more than 2300 seismometrically localized earthquakes since 1930. Documentation was sporadic before the exceptional earthquakes in 1763 and 1783 near the city of Komárno.

In addition to the Komárno earthquakes, earthquakes in central Slovakia in 1443, near the city of Žilina in 1858 and near Dobrá Voda in 1906 had macroseismic effects on relatively large areas and indicate a potential of future earthquakes in the territory of Slovakia.

In our presentation we focus on results of recent investigations of the historic documentation of the Komárno earthquakes, and historical earthquake activity of the Dobrá Voda source zone (with Smolenice being its part).

# LINKING AMBIENT SEISMIC NOISE HORIZONTAL-TO-VERTICAL SPECTRAL RATIO WITH DAMAGE INDUCED BY SUB-BASIN LOCAL RESONANCES IN STRONG GROUND MOTION

***Francisco J. SÁNCHEZ-SESMA*** [1], ***Richard L. WEAVER*** [2]

[1] Instituto de Ingenieria, Universidad Nacional Autonoma de Mexico, Ciudad de Mexico, Mexico
[2] Department of Physics, University of Illinois , Urbana Champaign, USA

*contact: sesma@unam.mx*

Ambient seismic noise (ASN) is a widely used source of illumination in both seismological and geophysical studies. Among them, the horizontal-to-vertical spectral ratio (HVSR) is a current measurement aimed to assess the dominant soil frequency and, after inversion, the vertical profile of mechanical properties at a given site.We assume that ASN field and comes from equipartioned illumination of random sources and the scattering by heterogeneities leads to energies equilibration. This is a diffuse field.This approach is not completely free of uncertainties about the diffuse character of the wavefield and the non-uniqueness of the inversion. Some strategies are being proposed to mitigate these problems. Besides,the lateral inhomogeneity is often ignored. We attempt to introduce it in the cocktail.

Diffuse fields are intrinsically related with the Green's function of a system. Theory asserts that under the diffuse field assumption (DFA) the average directional energy densities (DED) are proportional to the imaginary parts of the Green's function for coincident source and receiver. Therefore,under the DFA the HVSR, or any energy ratio at a point, should be modeled with the imaginary parts of the Green's function.

Clearly,the potential variations of possible substructures greatly exceed any information present in HVSR. As ever, one must supplement with extra information, possibly non-seismic,and learn to live with some uncertainty. We discuss results and examine the implications for seismic hazard assessment.

# THE LINKED COMPLEXITY OF COSEISMIC AND POSTSEISMIC FAULTING REVEALED BY SEISMO-GEODETIC DYNAMIC INVERSION OF THE 2004 PARKFIELD EARTHQUAKE

***Nico SCHLIWA*** [1], ***Alice-Agnes GABRIEL*** [2,1], ***Jan PREMUS*** [3], ***František GALLOVIČ*** [4]

[1] Department of Earth and Environmental Sciences, Ludwig-Maximilians-Universität München, Munich, Germany

[2] Scripps Institution of Oceanography, UC San Diego, La Jolla, USA

[3] Geoazur, Côte d'Azur University, Nice, France

[4] Department of Geophysics, Charles University, Prague, Czech Republic

*contact: nico.schliwa@lmu.de*

Several regularly recurring moderate-size earthquakes motivated dense instrumentation of the Parkfield section of the San Andreas fault, providing an invaluable near-fault observatory.

We present a seismo-geodetic dynamic inversion of the 2004 Parkfield earthquake, which illuminates the interlinked complexity of faulting across time scales. Using fast-velocity-weakening rate-and-state friction, we jointly model 3D coseismic dynamic rupture and the 90-day evolution of postseismic slip. We utilize a parallel tempering Markov chain Monte Carlo approach to solve this non-linear high-dimensional inverse problem, constraining spatially varying prestress and fault friction parameters by 30 strong motion and 12$\sim$GPS stations.

From visiting $>$2 million models, we discern complex coseismic rupture dynamics that transition from a strongly radiating pulse-like phase to a mildly radiating crack-like phase. Both coseismic phases are separated by a shallow strength barrier that nearly arrests rupture and leads to a gap in the afterslip. Coseismic rupture termination involves distinct arrest mechanisms that imprint on afterslip kinematics. A backward propagating afterslip front may drive delayed aftershock activity above the hypocenter. Analysis of the 10,500 best-fitting models uncovers local correlations between prestress levels and the reference friction coefficient, alongside an anticorrelation between prestress and rate-state parameters $b - a$.

We find that a complex, fault-local interplay of dynamic parameters determines the nucleation, propagation, and arrest of both, co- and postseismic faulting. This study demonstrates the potential of inverse physics-based modeling to reveal novel insights and detailed characterizations of well-recorded earthquakes.

# DETERMINISTIC PHYSICS-BASED EARTHQUAKE SEQUENCE SIMULATORS MATCH EMPIRICAL GROUND MOTION MODELS AND ENABLE EXTRAPOLATION TO DATA POOR REGIMES: APPLICATION TO MULTIFAULT MULTIMECHANISM RUPTURES

***Bruce E. SHAW***

Lamont Doherty Earth Observatory, Columbia University, Palisades, USA

*contact: shaw@ldeo.columbia.edu*

We use the deterministic earthquake simulator RSQSim to generate complex sequences of ruptures on fault systems used for hazard assessment. We show that the source motions combined with a wave-propagation code create surface ground motions that fall within the range of epistemic uncertainties for the NGA-West2 set of empirical models. We show the model is well calibrated where there are good data constraints and has good correspondence in regions with fewer data constraints. We show magnitude, distance, and mechanism dependence all arising naturally from the same underlying friction. The deterministic physics-based approach provides an opportunity for better understanding the physical origins of ground motions. For example, we find that reduced stress drops in shallow layers relative to constant stress drop with depth lead to peak ground velocities in the near field that better match empirical models. The simulators may also provide better extrapolations into regimes that are poorly empirically constrained by data, because physics, rather than data parameterizations, is underlying the extrapolations. Having shown the model is credible, we apply it to a problem where observations are lacking. We examine the case of crustal faults above a shallow subduction interface seen to break coseismically in simulations of the New Zealand fault system. Here, we show that in the model, by breaking up the coseismic crustal and interface rupturing fault motions into two separate subevents, and then recombining the resulting ground motion measures in a square-root-of-sum-of-squares incoherent manner, we reproduce well the ground motion measures from the full event rupture. This provides a new method for extrapolating ground motion models to more complex multifault ruptures.

# SIMULATION OF STRONG GROUND MOTION RECORDED DURING THE 2024 NOTO PENINSULA EARTHQUAKE BASED ON AN EMPIRICAL GREEN'S FUNCTION METHOD

***Hongjun SI***

Engineering Seismology, Seismological Research Institute Inc., Tokyo, Japan

*contact: shj@seismo-r.com*

On 1st January 2024, an earthquake of Mw 7.5 occurred in Noto peninsula, Ishikawa prefecture, Japan. During the earthquake, abundant strong ground motion data have been recorded. In this study, in order to understand the generation of strong ground motion in the seismic source, we try to simulate strong ground motion based on the empirical Green's function method. The source model used in the simulation consists of 3 segments with one or two strong motion generation area in each segment. Two aftershocks are selected as empirical Green's functions, and the source parameters are estimated based on the omega 2 model. All the other parameters are decided for good fitting between the synthetic and observed seismic waves. The results show that the synthetic seismic waves are well consistent with the observations.

# TRIGGERING OF VERY SHALLOW EARTHQUAKES BY SURFACE MASS REMOVAL PROCESSES - A CASE STUDY OF THE 2019 MW4.9 LE TEIL, FRANCE EARTHQUAKE

***Eyüp SOPACI***, ***Jean-Paul AMPUERO***, ***François X. PASSELÈGUE***

Geoazur, Université Côte d'Azur, Observatoire de la Côte d'Azur, IRD, CNRS, Sophia Antipolis/Valbonne, France

*contact: sopaci@geoazur.unice.fr*

Faults are typically aseismic at shallow depths due to their velocity-strengthening (VS) frictional behavior. However, very shallow earthquakes do occur, mostly associated with natural or human-caused mass removal processes. The Mw 4.9 Le Teil earthquake in France on November 11, 2019, is a notable example: its hypocenter was located within the area of favorable stress change induced by a cement quarry, and its slip was limited to 1-2 km depth, resulting in extreme ground motions. It is important to understand how very shallow earthquakes are initiated. Here, we evaluate the mechanical viability of the quarry-triggering hypothesis by conducting rock friction tests and numerical simulations.

The Le Teil earthquake nucleated on the La Rouvière Fault, which cuts through layers of limestones, marly-limestones and marls. Our mechanical tests on rock samples from surface outcrops representative of these layers revealed that the limestones can transition from velocity-weakening (VW) to velocity-strengthening at increasing slip rates, while marls remain velocity-strengthening.

Our multi-cycle earthquake simulations confirmed that a 200 kPa stress change due to 200 years of mass removal by quarrying can trigger a shallow rupture. This readily occurs in models with a shallow VW segment driven by creep on a deeper VS segment, but is less trivial in models with a shallow VS fault segment above a VW segment. In the latter case, we found that, under certain conditions, the shallow VS segment can be driven well below steady-state (inter-seismically locked) by the pinning effect of the deeper locked VW segment. In such scenarios, even if the VS fault cannot generate an earthquake spontaneously, it can be triggered by the surface mass removal without breaking the deeper VW segment.

# ADJOINT-BASED INVERSION FOR STRESS AND FRICTIONAL PARAMETERS IN EARTHQUAKE MODELING

***Vidar STIERNSTRÖM*** [1], ***Martin ALMQUIST*** [2], ***Eric M. DUNHAM*** [1]

[1] Department of Geophysics, Stanford University, Stanford, USA
[2] Department of Information Technology, Uppsala University, Uppsala, Sweden

*contact: cstierns@stanford.edu*

We present an adjoint-based inversion method for stress and frictional parameters in earthquake modeling. The forward problem is linear elastodynamics with nonlinear rate-and-state frictional faults. The misfit functional quantifies the difference between simulated and measured displacements/velocities at receiver locations and may include windowing or filtering operators. We derive the corresponding adjoint problem, which is linear elasticity with linearized rate-and-state friction with time-dependent coefficients derived from the forward solution. The gradient of the misfit is efficiently computed by convolving forward and adjoint variables on the fault. The method thus extends the framework of full-waveform inversion to include rate-and-state frictional faults.

Additionally, we present a dual-consistent discretization of a dynamic rupture problem with a rough fault in antiplane shear, using high-order accurate summation-by-parts finite differences in combination with explicit Runge–Kutta time integration. The dual consistency of the discretization ensures that the discrete adjoint-based gradient is the exact gradient of the discrete misfit functional as well as a consistent approximation of the continuous gradient. Our theoretical results are corroborated by inversions with synthetic data. Figure 1 present results inverting for the direct effect parameter, showing that it is well-constrained within slipped parts of the fault, but unconstrained outside. Similar results hold for initial fault stress. We anticipate that adjoint-based inversion of seismic and/or geodetic data will be a powerful tool for studying earthquake source processes; it can also be used to interpret laboratory friction experiments.

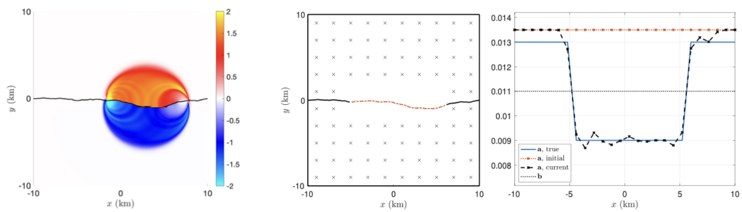


Figure 1: **Left:** Snapshot of high-resolution forward velocity wavefield. **Center**: Receiver locations ($\times$) and unstable part of fault ($--$). **Right**: Direct effect parameter $\mathbf{a}$ after 200 optimization iterations in an inverse crime setting. State evolution parameter $\mathbf{b}$ indicates velocity-weakening ($\mathbf{a} - \mathbf{b} < 0$) and velocity-strengthening ($\mathbf{a} - \mathbf{b} > 0$) regions.

# NEAR-FAULT GROUND MOTION PREDICTION, SITE EFFECTS AND WAVE PROPAGATION AT REGIONAL SCALE FOR A SHALLOW EARTHQUAKE IN SOUTHEAST FRANCE

***Hongyi SU*** [1,2], ***Sébastien HOK*** [1], ***Céline GÉLIS*** [1],
***Mathieu CAUSSE*** [2], ***Cécile CORNOU*** [2]

[1] Bureau d'Evaluation des Risques Sismiques pour la Sûreté des Installations ,
Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Fontenay-aux-Roses, France

[2] Institut des Sciences de la Terre (ISTerre), Université Grenoble Alpes, Grenoble, France

*contact: hongyi.su@irsn.fr*

The 2019 Mw 4.9 Le Teil earthquake was a shallow, moderate event that caused significant damage in its epicentral area and evidenced surface rupture. This event demonstrates that a moderate-magnitude quake can pose a significant threat to infrastructures and its near-fault ground motions (NFGM) need to be properly predicted. However, NFGM records for similar events worldwide are few. To understand their variability and intensity, synthetic physics-based NFGM simulation, including source, propagation, and site effects, is required. An accurate fault rupture model is crucial for NFGM modeling, especially when the fault rupture is shallow and reaches the surface, such as the 2019 Le Teil event. In this study, we employ both kinematic and dynamic approaches to model fault rupture while considering wave propagation and site effects (shallow layer not included yet) by incorporating seismic properties of the medium. We introduce an original method to estimate and map dynamic parameters from inverted kinematic slip models prior to dynamic rupture modeling. Essentially, we derive a 3D distribution of heterogeneous frictional parameters, scaled by slip magnitude and spatially bounded by a static slip distribution, within the slip-weakening friction framework. Furthermore, we investigate the impact of the smoothing level of the inverted slip model on dynamic fault rupture and coupled GM using our approach. Additionally, we apply the strain-constrained condition proposed by Aochi and Tsuda (2023) to configure the initial stress field in a layered model, which hypothesizes that strain gradually increases with depth. Our preliminary results suggest that the variability and intensity of synthetic NFGM depend on the smoothing level of the inverted slip model using our approach.

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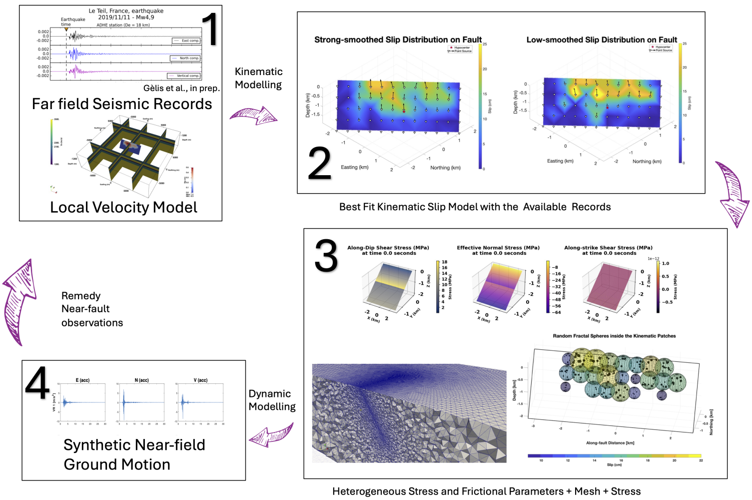
1
Le Teil, France, earthquake
2019/11/11 - Mw4,9
ADHE station (De = 18 km)
Earthquake time
Gèlis et al., in prep.
Far field Seismic Records
Local Velocity Model
Kinematic
Modelling
2
Strong-smoothed Slip Distribution on Fault
Low-smoothed Slip Distribution on Fault
Easting (km)
Northing (km)
Depth (km)
Best Fit Kinematic Slip Model with the Available Records
3
Along-Dip Shear Stress (MPa) at time 0.0 seconds
Effective Normal Stress (MPa) at time 0.0 seconds
Along-strike Shear Stress (MPa) at time 0.0 seconds
Random Fractal Spheres inside the Kinematic Patches
Heterogeneous Stress and Frictional Parameters + Mesh + Stress
Remedy
Near-fault
observations
4
E (acc)
N (acc)
V (acc)
Synthetic Near-field
Ground Motion
Dynamic
Modelling

# ASPERITY LOCATIONS OF THE 2016 KUMAMOTO EARTHQUAKE USING DYNAMIC RUPTURE MODELING WITH A 3D BASIN STRUCTURE

***Jikai SUN*** [1], ***Arben PITARKA*** [2], ***Hiroshi KAWASE*** [1]

[1] Disaster Prevention Research Institute, Kyoto University, Uji, Japan
[2] Seismology Group, Lawrence Livermore National Laboratory, Livermore, USA

*contact: sun.jikai.8n@kyoto-u.ac.jp*, *kawase.hiroshi.6x@kyoto-u.ac.jp*

3D simulations of the Mw 7 2016 Kumamoto earthquake are performed using dynamic rupture modeling with a slip weakening friction law and a 3D velocity model. The assumed 60 km long $\times$ 26 km wide $\times$ 25 km deep 3D velocity structure is constructed. Recorded near-fault three-components ground motions at 26 strong motion stations are used in assessing the quality of the synthetic motions and corresponding rupture models. Based on reported large slip distribution areas, two strategies for searching for the optimal three asperity locations of the mainshock are proposed (Fig. 1). A hybrid goodness-of-fit function is used to evaluate the similarity between the simulated and observed strong ground motions. Parametrical analysis suggests that the average rake angle varies between 20 and 40 degrees. According to an optimal number of successful simulations, 16 of 26 sites were found to have a good similarity between observation and synthetic waveforms. The shallow and deep asperities beneath the Futagawa fault zone with the size of 10 km in length by 6 km and 9 km in depth are located close to the hypocenter (Fig. 2). Large fault slips are mainly located in the shallow Futagawa asperity, as large as 4 m. Large fault slip rates are mostly concentrated in the deeper Futagawa asperity, as high as 6 m/s. The Kostrov-type fault slip-rate functions were found in three asperity areas, whereas the triangle (smoothed rump-function) shape slip-rate function were found in other locations. The forward rupture directivity effects produced a high fault slip-rate toward the direction of rupture propagation and strong seismic motions in Mount Aso and surrounding areas. As a consequence of both rupture directivity and wave path effects the simulated horizontal PGVs in these areas are relatively large.

*Note: Figure is on the next page.*

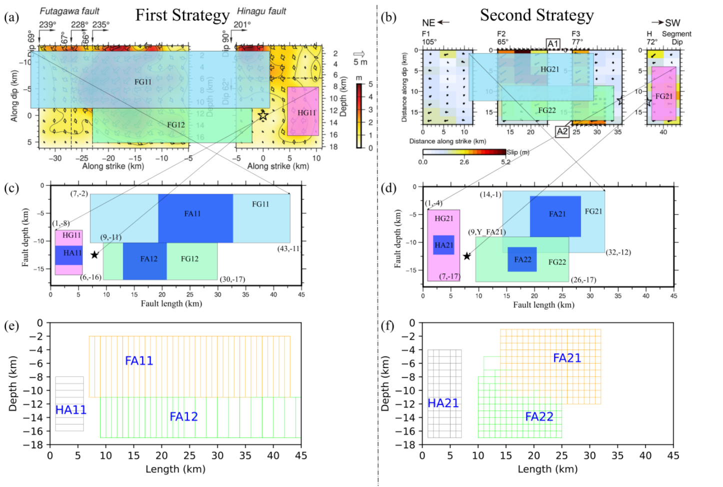


**Fig. 1.** Searching of SMGA locations beneath the Futagawa and Hinagu fault zones. Left and right side of dash dot line are results of first and second strategy, respectively.

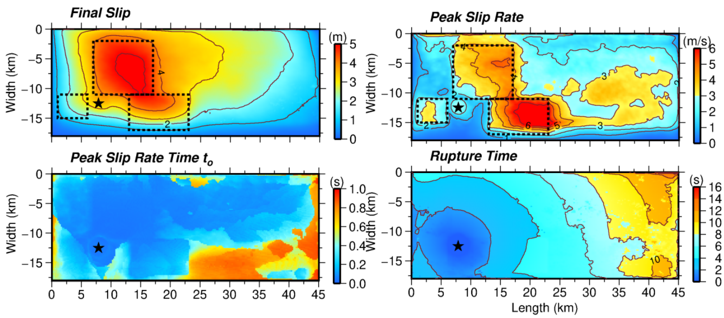


**Fig. 2**. Distributions of final fault slip, peak slip rate time ratio, fault slip rate, rupture time on fault plane of the optimal scenario.

# MICROEARTHQUAKES INDUCED BY FLUID INJECTION: 3D DYNAMIC RUPTURE MODELS AND RADIATED WAVEFORMS

***Elisa TINTI*** [1,2], ***Francesco MOSCONI*** [1], ***Alice-Agnes GABRIEL*** [3], ***Luca DAL ZILIO*** [4], ***Antonio Pio RINALDI*** [5], ***Men-Andrin MEIER*** [6], ***Emanuele CASAROTTI*** [2], ***Mariano SUPINO*** [2], ***Maria MESIMERI*** [6], ***Linus VILLIGER*** [5], ***Massimo COCCO*** [2]

[1] Department of Earth Sciences, Sapienza, Università di Roma, Rome, Italy

[2] Istituto Nazionale di Geofisica e Vulcanologia, INGV, Rome, Italy

[3] Institute of Geophysics and Planetary Physics Scripps Institution of Oceanography, University of California at San Diego, La Jolla (CA), USA

[4] Earth Observatory of Singapore, Nanyang Technological University, Singapore, Singapore

[5] Swiss Seismological Service, ETH Zürich, Zürich, Switzerland

[6] Institute of Geophysics, Earth Sciences, ETH Zürich, Zürich, Switzerland

*contact: elisa.tinti@uniroma1.it*

The ERC-Synergy project FEAR (Fault Activation and Earthquake Ruptures) hosted in the Bedretto Underground Laboratory (Swiss Alps) offers a unique opportunity to investigate fluid-induced micro-events at approximately 1500m depth recorded by a multi-sensor network. Modeling micro-earthquakes necessitates the precise determination of constitutive parameters such as stress, friction, and critical slip at small spatial scales (millimeters to centimeters), which are crucial for understanding rupture propagation over meter-scale distances (1-100 m). We conduct fully 3D dynamic rupture simulations assuming spatially variable stress drops caused by pore pressure changes and we simulate Mw $\leq$ 1 induced earthquakes. Several features inferred for accelerating dynamic ruptures differ from those observed during rupture deceleration in a self-arresting earthquake due to the spatial gradient of the effective normal stress. Analyzing the radiated synthetic waveforms, we examine the differences in the high-frequency content of simulated waveforms between self-arresting and run-away earthquakes and provide an estimation of source parameters obtained through spectral inversion. These estimations are then compared with dynamic forward models and provide critical insights into radiated spectrum, the potential contribution of near-field terms and attenuation enabling us to interpret some recorded events in FEAR experiments. These methods together with the exceptional FEAR monitoring system provide a controlled setting to study the intricate details of earthquake mechanics closely, and offer a chance to push the boundaries of current understanding of earthquake physics.

# INVESTIGATION OF THE INFLUENCE OF FAULT STRENGTH ON FAULT BEHAVIOR FOR THE SHALLOW PART OF THE FAULT BY THE DYNAMIC RUPTURE SIMULATION

***Kenichi TSUDA*** [1], ***Junichi MIYAKOSHI*** [1], ***Naoki IWATA*** [2], ***Akihiro MATSUI*** [2], ***Keita HIGASHI*** [2]

[1] Institute of Technology, Shimizu Corporation, Tokyo, Japan
[2] Numerical solution Deptartment, Chuden Engineering Consultants, Hiroshima, Japan

*contact: kenichi.tsuda@shimz.co.jp*

The dynamic rupture simulation is important approach to understand complex fault behavior on the shallow part of the fault when the surface fault is broken. We constructed the dynamic source model of the 2014 Northern Nagano earthquake that broke the surface fault. This model called the basic model reproduces the features of observations, such as the ground motions at site close to the fault, resultant magnitude, and spatial distribution of surface displacement (Tsuda et al., 2023). We show slip distribution in Figure 1. This basic model referring to the Tanaka et al. (2017) constitutes two asperities (deep and shallow asperity) with rectangle shape and background. We imposed initial parameters for each region.

Based on the basic model, we tried to investigate the fault behavior for the shallow part of the fault by the dynamic rupture simulation. At first, we set the model with deep asperity that broke surface fault by changing depth of the deep asperity whose stress parameters are same as the basic model. We then added the shallow asperity on the shallow part of fault with same location of the basic model. The stress parameters for the shallow asperity are same as the basic model. Even the rupture from the deep asperity broke the surface fault, the shallow asperity was not fully ruptured. Even increasing stress drop on the shallow asperity generated same results. On the other hand, the reduction of fault strength of shallow asperity with same stress drop leads to the fully rupture of the shallow asperity. The stress drop is important parameters for ground motions and thus, the careful attention has been paid so far. Even the fault strength has not been paid much attention like the stress drop, the results of this study show the importance of fault strength as well.

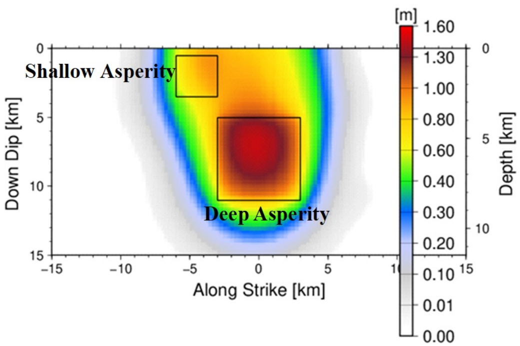


Figure1 Slip distribution of the basic model (Tsuda *et al.*, 2023)

# BROADBAND DYNAMIC SOURCE MODELING CONSTRAINED BY APPARENT SOURCE SPECTRA, WITH APPLICATION TO CENTRAL ITALY

***Lubica VALENTOVÁ K.***, ***František GALLOVIČ***

Department of Geophysics, Faculty of Mathematics and Physics,
Charles University, Prague, Czech Republic

*contact: valent@karel.troja.mff.cuni.cz*

Apparent source spectra characterize station-wise source radiation because they are free of path and site effects. The spectra can be extracted from recordings by, for example, the generalized inverse technique (GIT, Bindi et al., 2009) using a large number of records in areas densely sampled by events and stations such as Central Italy (Pacor et al., 2016). Usually, the Brune (omega-square) model is assumed to translate the apparent source spectra to the source parameters such as corner frequency and, thus, Brune stress drop.

Here, we present an ongoing development on the methodology to use GIT-derived apparent source spectra to constrain dynamic source models. Dynamic models employ friction law to describe the rupture propagation on the fault and are usually constrained only at large scales using low-frequency waveforms. On the other hand, the apparent source spectra can provide information on the high-frequency (up to 25 Hz) source radiation. For the 2016 Mw6.2 Amatrice earthquake, we compare the observed apparent source spectra with predictions from the dynamic model obtained by the low-frequency dynamic source inversion and subsequently enriched by fractal perturbations in dynamic parameters.

Furthermore, we explore the possibility of using the apparent source spectra in dynamic source inversions. However, the resolvability of various source (dynamic or kinematic) parameters solely from the amplitude spectra is enigmatic. We approach the challenge with synthetic Bayesian dynamic source inversion of apparent source spectra and inspect the variability of different source parameters and their trade-offs. The recovered source characteristics in a broad frequency range will give us valuable insight for future scenario modeling.

# INTERPRETATION OF NON-DC COMPONENTS OF MOMENT TENSORS: A REVIEW

***Václav VAVRYČUK***

Institute of Geophysics, The Czech Academy of Sciences, Prague, Czech Republic

*contact: vv@ig.cas.cz*

The moment tensors describe equivalent body forces acting at a seismic point source and are the basic quantity evaluated for earthquakes on all scales. The most common type of the moment tensor is the double-couple (DC) source, which represents the force equivalent of shear faulting on a planar fault. However, accurately determined moment tensors of earthquakes reveal that they frequently deviate from shear faulting and contain significant non-double-couple (non-DC) components. The non-DC components are reported, for cavity collapses in mines, in hydraulic fracturing, in geothermal fields and volcanic areas. The DC as well as non-DC components of the moment tensors provide essential information about details of source processes and tectonic stress conditions of the rock mass.

I review the recent methods for interpreting the DC and non-DC components of the moment tensors and discuss their applications to various types of seismicity. I show that the DC components of moment tensors can be inverted for tectonic stress, fracture orientations and fracture instability. Analysing the DC components of earthquakes, it is possible to monitor spatial and temporal changes of stress and pore pressure, and to map systems of cracks or fractures. The non-DC components can be exploited for characterizing the mode of fracturing and for determining rock properties in the focal zone. Using the model of shear-tensile earthquakes, the non-DC components can be used for distinguishing whether the crack systems are opening or closing and the opening/closing angle between the slip and the fracture plane can be evaluated. Furthermore, the vP/vS ratio of rocks in an isotropic focal zone or the tensor of elastic parameters in an anisotropic focal zone can be determined.

# SIGNIFICANCE OF NON-DC COMPONENTS OF MOMENT TENSORS FOR UNDERSTANDING TECTONIC PROCESSES RELATED TO THE REYKJANES SEISMIC AND VOLCANIC ACTIVITY, ICELAND

***Václav VAVRYČUK*, *Pavla HRUBCOVÁ***

Institute of Geophysics, The Czech Academy of Sciences, Prague, Czech Republic

*contact: vv@ig.cas.cz*

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 seismicity that occurred in the central part of Reykjanes at the place of the Fagradalsfjall volcano prior to and after its eruption on March 19, 2021. We invert well-determined focal mechanisms 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. 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 associated with the transform fault segment displaed predominantly shear strike-slip events. The non-shear fractures were associated with the opening of volcanic fissures trending in the azimuth of 30–35°, perpendicular to the extension. The dip-slips were mainly located close to the volcanic dike. Importantly, 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.

# FAULT DAMAGE ZONES IN CARBONATES: FORMATION, DISTRIBUTION AND ROLE IN THE SEISMIC CYCLE (ITALIAN CENTRAL APENNINES)

***Nolwen VENISSE*** [1], ***Giulio DITORO*** [1], ***Mathilde MARCHANDON*** [2], ***Michele FONDRIEST*** [1], ***Manuele FACCENDA*** [1], ***Alice-Agnès GABRIEL*** [2,3]

[1] Geoscience, Università degli Studi di Padova, Padua, Italy
[2] Geoscience, Ludwig-Maximilians-Universität, Munich, Germany
[3] Geoscience, Scripps Institution of Oceanography, San Diego, CA, USA

*contact: nolwen.venisse@studenti.unipd.it*

Fault zones include one or more fault cores sandwiched by up to hundreds of meter thick damage zones. In carbonates rocks, damage zones are characterized by the presence of in situ shattered rocks (ISRs). Despite their abundance, it remains unclear how damage zones form and how their presence affects the propagation of individual seismic ruptures and associated near field ground motions. In the Italian Central Apennines, seismogenic faults may have damage zones with varying thickness from few meters (e.g., Campo Felice Fault zone) up to 1000m thick (e.g., Monte Marine fault associated with the Abruzzo Mw 6.7, 1703 earthquake). Moreover, along the fault strike, the thickness of the damage zone increases in the presence of geometrical complexities, such as fault step-overs and intersections. By integrating field surveys, data analysis, and numerical modelling, we aim to refine our understanding of the formation of these zones, the factors controlling their spatial distribution (along strike and with depth), and their impact on the seismic cycle. As a first step toward this goal, we present 3D dynamic rupture simulations including off-fault Drucker-Prager plasticity for a 25 km long NW-SE striking extensional fault as representative of the seismic sources in the Central Apennines. Through a suite of Mw 6.0-6.5 dynamic rupture scenarios, we investigate the formation and evolution of damage zones under various geological (lithology, fault geometry, topography), mechanical and loading conditions. This work enable us to clarify on the mechanisms driving ISR formation and distribution and the key factors influencing earthquake rupture propagation. Furthermore, this study will contribute to the assessment of seismic hazard in the Italian central Apennines.

# SCALING RUPTURE CHARACTERISTICS ACROSS EARTHQUAKE SIZES: INSIGHTS FROM 3D DYNAMIC AND KINEMATIC SIMULATIONS

***Jagdish C. VYAS*** [1], ***Martin GALIS*** [2,3], ***Paul Martin MAI*** [1], ***Men-Andrin MEIER*** [4]

[1] Earth Science and Engineering,
King Abdullah University of Science and Technology, Thuwal, Jeddah, Saudi Arabia

[2] Department of Astronomy, Physics of the Earth, and Meteorology,
Comenius University, Bratislava, Slovak Republic

[3] Earth Science Institute, Slovak Academy of Sciences, Bratislava, Slovak Republic

[4] Department of Earth Sciences, ETH Zurich, Zurich, Switzerland

*contact: jagdish.vyas@kaust.edu.sa*

Earthquake rupture dynamics exhibit complexity across various spatial and temporal scales, which significantly differ for different rupture sizes. This complexity influences seismic energy radiation and ground-shaking patterns. In this study, we explore how rupture characteristics scale with earthquake size using 3D dynamic and kinematic rupture simulations. Slip-velocity time-histories from 3D dynamic simulations of events with magnitudes approximately 6.9, incorporating fault roughness are utilized based on previous work by Mai et al., (2017). These simulations serve as the basis for generating down-scaled kinematic rupture models that replicate smaller earthquake sizes (Mw 5.0, 3.0 and 1.0) from which we then compute seismic waveforms.

We propose a three-step algorithm to rescale kinematic rupture properties derived from dynamic simulations to smaller events. First, the spatial discretization (dx) is adjusted based on the ratio of the ruptured fault areas of the target and reference events. Second, the temporal discretization (dt) is scaled while maintaining the ratio of spatial to temporal discretization. This ensures coherence of energy radiation during rescaling from large to small earthquakes. Third, the slip-velocity amplitudes are rescaled based on the ratios of seismic moments and rupture areas of target and reference events. The resulting peak ground accelerations for the rescaled small-magnitude events align with estimates derived from ground-motion prediction equations (Boore and Atkinson, 2008). Our study outlines an efficient method for calculating physics-based ground motions for small earthquakes in induced-seismicity environments.

# EXPLORING THE INFLUENCE OF FAULT-SURFACE TOPOGRAPHY ON EARTHQUAKE RUPTURE DYNAMICS: A STUDY OF RUPTURE PARAMETER CORRELATIONS

***Pramod K. VYAS*** [1], ***Martin GALIS*** [1,2]

[1] Department of Astronomy, Physics of the Earth, and Meteorology, Comenius University, Bratislava, Slovak Republic

[2] Earth Science Institute, Slovak Academy of Sciences, Bratislava, Slovak Republic

*contact: vyas1@uniba.sk*

Geological observations reveal that fault-surface topography exhibits variations at both large (segmentation) and small (roughness) scales. These complexities influence earthquake rupture dynamics, impacting properties such as slip, rupture speed, rise time, and peak slip rate. Understanding the correlations among these rupture parameters is crucial for advancing our understanding of earthquake rupture physics and building synthetic rupture models, which emulate dynamic rupture characteristics within kinematic frameworks. While previous studies have explored these correlations, the influence of fault roughness on them remains unclear. Therefore, our study aims to analyze how small-scale roughness affects rupture parameter correlations. Leveraging a dataset generated by Mai et al. (2017), which includes twenty-one dynamic rupture models with varying roughness realizations, heights of roughness, and hypocenter locations, our analysis seeks to develop a fundamental understanding of how small-scale variations in fault-surface topography impact rupture parameter correlations. This research has the potential to inform the development of realistic synthetic rupture models capable of generating high-frequency seismic waves (approximately up to 6 Hz) consistent with dynamic rupture models.

# RuptureNet2D, A DEEP NEURAL NETWORK-BASED SURROGATE FOR DYNAMIC EARTHQUAKE RUPTURE SIMULATION IN TWO DIMENSIONS

***Ziyi WANG*** [1], ***Zekang GONG*** [1], ***Chao LIANG*** [1], ***Jianze WANG*** [2]

[1] Institute for Disaster Management and Reconstruction, Sichuan University, Chengdu, China
[2] Depart of Civil Engineering, Sichuan University, Chengdu, China

*contact: chao.liang@scu.edu.cn*

Dynamic rupture simulations of earthquakes are crucial for physics-based seismic hazard assessment. However, due to the intricate dynamics of earthquake rupture mechanisms spanning vast spatial and temporal scales, seismic dynamic rupture simulations pose a complex and computationally expensive interface instability problem. Here, we propose an end-to-end deep learning model (RuptureNet2D) as a cost-effective alternative to expensive numerical simulations. This model is trained on dynamic rupture datasets generated by numerical simulations in two dimensions and is capable of simultaneously predicting two key earthquake source parameters: rupture time and final slip. Testing reveals that our model performs exceptionally well on faults with homogeneous and heterogeneous (with one or two asperities) frictional parameters but only requires a fraction (1/1000) of the prediction time compared to numerical simulations. Our work is the first to demonstrate the applicability and efficiency of neural networks as a surrogate model for seismic dynamic rupture simulations, which has a potential of drastically accelerating physics-based earthquake source inversion and advancing our understanding of earthquake physics.

# VISCOELASTIC RUPTURES UNBOUNDED BY CLASSICAL SPEED LIMITS

***Huihui WENG***

State Key Laboratory for Mineral Deposits Research, School of Earth Sciences and Engineering, Nanjing University, Nanjing, China

*contact: weng@nju.edu.cn*

Classical theories using linear elasticity predict that crack propagation is bounded by a limiting speed, beyond which the energy balance becomes unphysical. Recent experiments in viscoelastic materials demonstrated that both tensile and frictional crack propagation can exceed classical speed limits. However, the fundamental physics governing unbounded rupture speeds are still unclear. In this paper, I show via numerical simulations that frictional ruptures in viscoelasticity can propagate at a continuum of terminal speeds that are not bounded by the classical speed limit. All simulated rupture speeds are predicted by the newly developed theory of fracture mechanics incorporating viscoelasticity via the principle of energy balance. In addition to the ratio of the fracture energy to the static energy release rate that can be used to uniquely predict the rupture propagation in linear elasticity, the scales of characteristic lengths in viscoelasticity also govern the energy balance. Beyond the classical speed limit, the energy balance becomes independent of any macroscopic length and is controlled only by the local properties around the rupture tip. These numerical and theoretical findings fundamentally advance our understanding of dynamic rupture propagation.

# COMBINED EFFECTS OF FAST-VELOCITY WEAKENING FRICTION AND STRESS HETEROGENEITY CONTROL MEGATHRUST EARTHQUAKE RE-ACTIVATION, HIGH-FREQUENCY RADIATION, AND ARREST IN 3D DYNAMIC RUPTURE SIMULATIONS OF THE 2011 TOHOKU-OKI EARTHQUAKE

***Jeremy Wing Ching WONG*** [1], ***Alice-Agnes GABRIEL*** [1,2], ***Wenyuan FAN*** [1]

[1] Scripps Institution of Oceanography, University of California San Diego, San Diego, USA
[2] Department of Earth and Environmental Sciences,
Ludwig-Maximilians-Universität Muünchen, Munich, Germany

*contact: jeremywong@ucsd.edu*

Megathrust earthquakes are devastating and often rupture in unexpected ways. For example, the 2011 Mw 9.0 Tohoku-Oki earthquake may have multiple rupture episodes with high-frequency seismic radiation concentrated near the down-dip edge and large, tsunamigenic slips close to the trench, highlighting the importance of resolving rupture complexities due to the faulting conditions.

We use 3D dynamic rupture simulations to examine the roles of fast-velocity weakening rate-and-state friction and multi-scale stress heterogeneity in controlling the observed complexities of the Tohoku earthquake in terms of (i) multiple rupture episodes due to reactivation of the same fault area; (ii) down-dip high-frequency radiation and (iii) spontaneous rupture arrest. Our models account for depth-dependent normal stress, realistic slab geometry (JIVSM), and high-resolution seafloor bathymetry.

Driven by fast-velocity weakening friction alone, we observe complex dynamic interaction of the rupture and healing front that can reactivate the hypocentral area and induce three rupture episodes (Nielsen & Madariaga, 2003; Gabriel et al., 2012). Our models demonstrate that downdip high-frequency slip pulses can be generated without prescribing local stress or frictional asperities. If incorporating additional initial stress heterogeneity, such as from kinematic finite-fault slip models (Wong et al., ESSOAr, 2023), our dynamic models can reproduce spontaneous rupture arrest without requiring frictional barriers. Our results highlight the combined effects of frictional and stress heterogeneity in governing megathrust earthquakes.

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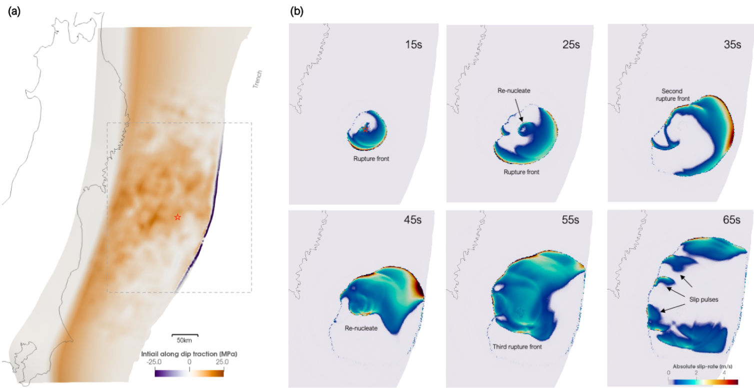



Figure: (a) Initial stress of the dynamic rupture simulation informed by median kinematic slip distribution (Wong et al., 2023). (b) Multiple-rupture front, downdip high-frequency radiation, and rupture arrest of the Tohoku-Oki earthquake simulation. Snapshot of the absolute slip-rate at an interval of 10s. Red star indicates the hypocenter location.

# ENHANCED SEISMIC RUPTURE IMAGING USING OCEAN BOTTOM DAS DATA

***Yuqing XIE*, *Jean-Paul AMPUERO*, *Martijn VAN DEN ENDE*, *Alister TRABATTONI*, *Marie BAILLET*, *Diane RIVET***

GéoAzur, University of Côte d'Azur, Valbonne, France

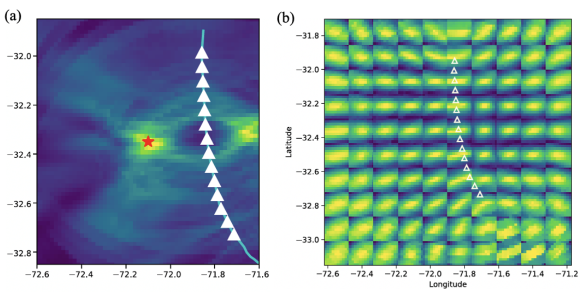
*contact: Yuqing.XIE@geoazur.unice.fr*

Submarine fiber optic cables for Distributed Acoustic Sensing (DAS) provides dense, extensive seismic data near potential major earthquake sources. This study presents an optimized back-projection imaging method for earthquake rupture analysis using DAS data offshore Chile, aiming to significantly enhance the resolution and accuracy of the imaging of large earthquake ruptures.

Our methodology integrates several advancements: (i) the conversion of measured DAS strain into displacement to mitigate wave scattering and to increase spatial waveform coherence, (ii) travel time refinement through shallow sediment adjustments, and (iii), array processing over overlapping cable segments for accurate slowness calculation.

Preliminary tests with a 120-km cable portion revealed a region where the location of seismic sources can be determined with high precision, extending 80 km laterally and down to a depth of 15 km, and less impacted by velocity structure uncertainties. Applied to data from around 50 local earthquakes (magnitudes 1.5 to 3), our method consistently achieved back-projection images with high spatial accuracy, within 1 to 4 km.

Additionally, our approach also effectively images larger earthquakes. Using synthetic waveforms from a magnitude 7 event, simulated based on empirical Green's functions, we demonstrated precise detection and location of sub-sources despite the presence of strong coda waves, after advanced travel time calibration. Further enhancements, including the use of a 3D velocity model, are planned to boost the resolution and accuracy of our method. Those improvements will further support the use of back-projection in accurately imaging medium to large earthquakes and enhancing tsunami early warning systems.




(a) Back-projection imaging result of a Magnitude 1.9 Earthquake. The background color represents the joint spatial probability distribution of the source location. The red star indicates the catalogued epicenter, white triangles represent subarray centers, and the blue curve outlines the cable's geometry. (b) Spatial resolution assessment.

# UNZIP EARTHQUAKE PROPAGATION FROM NEAR-FAULT RUPTURE PHASES OF THE 2023 KAHRAMANMARAŞ, TÜRKIYE MW 7.8 EARTHQUAKE

***Suli YAO***, ***Hongfeng YANG***

Earth and Environmental Sicences Programme,
Chinese University of Hong Kong, Hong Kong, China

*contact: suliyao@cuhk.edu.hk*

Understanding and deciphering wiggles from seismograms has been a long endeavor to understand the internal structure of the Earth and to explore earthquake source properties (e.g., Mohorovičić, 1910; Lehmann, 1936). Here we make the first attempt to decipher the continuous rupture phases as large near-fault velocity pulses along the East Anatolian Fault in the 2023 Mw 7.8 Kahramanmaraş, Türkiye earthquake. Through data analysis and dynamic rupture simulations, we illustrate impacts of fault-normal distance and fault geometry on near-fault velocity pulses. The identified fault-parallel velocity pulses associated with the rupture front suggest a transient supershear along the Amanos segment and rupture deceleration at fault bends. Our study highlights the complexity and superior application of near-fault data in studying earthquake source dynamics.

# SURFACE RUPTURE BEHAVIORS CONTROLLED BY EARTHQUAKE SOURCE DYNAMICS

***Suli YAO***, ***Hongfeng YANG***

Earth and Environmental Sicences Programme,
The Chinese University of Hong Kong, Hong Kong, China

*contact: suliyao@cuhk.edu.hk*

Surface rupture produced by earthquakes pose great threat on near-surface infrastructures. To understand the potential controlling mechanisms, we first collect data for earthquakes with $M_w \geq 6.0$ and $M < 6$ surface-breaching events in seismically active regions. For strike-slip and normal events, almost all earthquakes with magnitudes over 6.7 broke the surface. In contrast, buried and surface-breaching events co-exist with moderate magnitude (6.0-6.7) without systematic difference in hypocentral depth (5-20 km). For reverse events, there is no clear magnitude boundary. We propose that the complex surface rupture behaviors for moderate earthquakes can be attributed to the indeterministic rupture propagation on heterogenous faults, termed the hypocentral dependent effect, as demonstrated by our dynamic rupture models. While those small surface-breaching events are supposed to occur on infrequent shallow isolated velocity-weakening patches with intense stress release. Our study contributes to the understanding of the surface rupture behaviors references for assessing near-surface damage in future earthquakes.

# EXPLORING THE INTERPLAY OF FAULT SLIP, POROELASTICITY, AND PERMEABILITY BARRIERS IN SEISMIC SWARMS

***Jiayi YE*** [1], ***Luca DAL ZILIO*** [2,3], ***Domenico GIARDINI*** [1]

[1] Department of Earth Sciences, ETH Zürich, Zürich, Switzerland
[2] Earth Observatory of Singapore, Nanyang Technological University, Singapore, Singapore
[3] Asian School of the Environment, Nanyang Technological University, Singapore, Singapore

*contact: jiayi.ye@erdw.ethz.ch*

Understanding the dynamic interactions among pore pressure, fluid flow in the fault-zone, and fault mechanics is essential for comprehending earthquake swarm activity. In this study we use the Hydro-Mechanical Earthquake Cycles (H-MECs) model to explore the relationships between frictional slip, poroelasticity, and fluid flow in the occurrence of seismic swarms. We employ a 2-D anti-plane model with a poro-visco-elasto-plastic medium and a fault governed by rate- and state-dependent friction. We model pockets of high pore-fluid pressure, encapsulated by permeability barriers characterized by low permeability and low pore-fluid pressure. Permeability evolution, accommodating changes due to fault slip and healing, provides critical feedback on the dynamics of pore-fluid pressure and fault slip. Our results show that pockets of high pore-fluid pressure coupled with low effective stress generate stable fault creep, while seismicity arises within permeability barriers with relatively lower pore-fluid pressure, which act as seismic asperities. By varying the size of permeability barriers or high pore-fluid pressure pockets, our models display an interplay between aseismic creep, slow-slip transients, foreshocks, and large seismic ruptures. Additionally, back-propagating rupture is observed when the rupture propagates from low permeability barriers into high pore-fluid pressure pockets, due to the transition from pulse-like to crack-like rupture. Notably, seismic ruptures unseal permeability barriers, thus triggering pore fluid pressure diffusion and affecting the seismic moment release. Comparing our findings with observational data reveals the primary role of poroelastic effects and fluid flow in fault stability and the interplay between seismic and aseismic fault slip.

# RATE-AND-STATE SIMULATIONS OF THE DELAYED DYNAMIC TRIGGERING OF THE 2019 MW 7.1 RIDGECREST MAINSHOCK BY NEARBY FORESHOCKS

***Jeena YUN*** [1], ***Yuri FIALKO*** [1], ***Alice-Agnes GABRIEL*** [1,2]

[1] Scripps Institution of Oceanography, University of California, San Diego, La Jolla, USA
[2] Institute of Geophysics, Ludwig-Maximilians-Universität München, Munich, Germany

*contact: j4yun@ucsd.edu*

Earthquake dynamic triggering often exhibits a time delay with respect to the largest stress perturbation. For example, the 2019 Mw 7.1 Ridgecrest, CA, mainshock occurred 16 hours after a nearby Mw 5.4 foreshock that likely caused significant dynamic stress changes at the mainshock hypocenter. Here, we investigate the physical mechanisms that prevent instantaneous triggering due to a large stress perturbation on a fault that is already on the verge of runaway rupture.

We first evaluate spatio-temporal changes in dynamic and static Coulomb stress changes (dCFS) at the Ridgecrest mainshock hypocenter caused by the foreshock using 3D dynamic rupture simulations (SeisSol). We then perform quasi-dynamic seismic cycle simulations on a 2D strike-slip fault governed by rate-and-state friction (Tandem). We incorporate stress and strength heterogeneities to produce complex earthquake sequences on the mainshock fault. Our model exhibits a cascade of foreshocks leading to mainshocks over a range of hypocenter depths. Lastly, our cycle models are perturbed using the stress change history. Most of our perturbed cycle models show a clock advance of several hours, even when the static dCFS is negative. The amplitudes of static and dynamic dCFS positively correlate with the mainshock clock advance. We observe instantaneous triggering only when the peak stress perturbation is elevated to 17.5 MPa. We compare our aging law results to models using different evolution laws. While the slip law yields comparable clock advances to the aging law, the stress-dependent law leads to a systematic decrease in clock advance.

Our results have important implications for a first-order understanding of the controlling factors of near-field triggering and the scarcity of instantaneous triggering.

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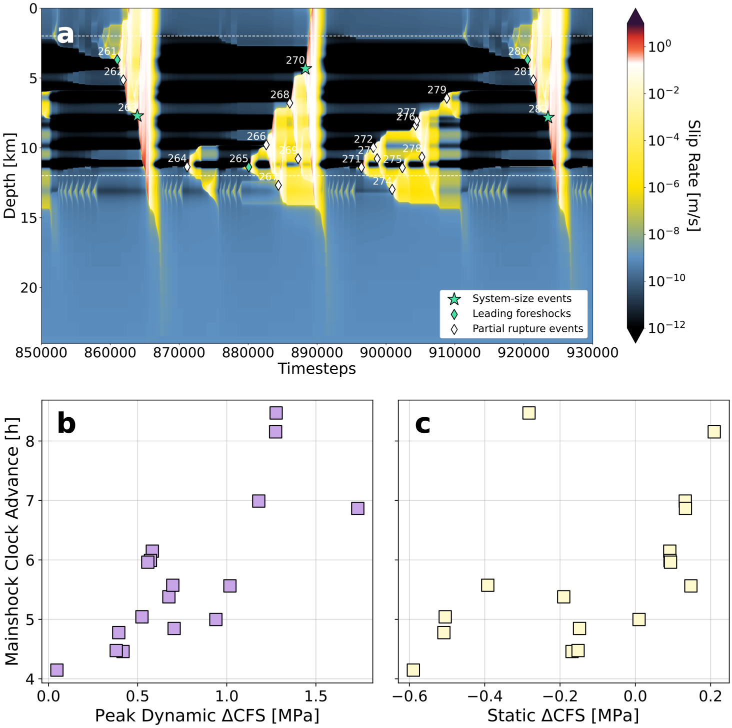

a
Depth [km]
Timesteps
Slip Rate [m/s]
System-size events
Leading foreshocks
Partial rupture events
b
c
Mainshock Clock Advance [h]
Peak Dynamic ΔCFS [MPa]
Static ΔCFS [MPa]

# SIMULATIONS OF EARTHQUAKE CYCLES IN CO-EVOLVING FAULT DAMAGE ZONES CONTROLLED BY DAMAGE RHEOLOGY

***Peng ZHAI*** [1], ***Yihe HUANG*** [1], ***Chao LIANG*** [2]

[1] Department of Earth and Environmental Sciences, University of Michigan, Ann Arbor, USA
[2] Institute for Disaster Management and Reconstruction (IDMR), Sichuan University, Chengdu, China

*contact: pengzhai@umich.edu*

Both short-term coseismic off-fault damage, as evidenced by pulverized rocks, and long-term fault growth during the interseismic period have been suggested to contribute to the fault zone formation. Previous numerical models simulate off-fault plastic yielding either in a single dynamic seismic event or in the context of seismic cycles. However, the co-evolution of fault damage zones and seismic cycles are not yet well understood. Here we simulate the damage evolution of fault damage zones and earthquake cycles together in a 2D anti-plane strike-slip seismic cycle model constrained by the continuum brittle damage framework and rate-state friction law.
Because damage accumulation rate depends on fault slip rate, we consider the coseismic damage accumulation rate to be 6 orders of magnitude larger than the interseismic one. This also generates a coseismic velocity drop of 0.1%-4% as observed by seismic imaging in active fault zones. Damage mainly occurs during the short-term coseismic rupture phase and concentrates at shallow depths as a flower structure, in which an distributed damaged area surrounds a localized, highly damaged fault core. We also find that coseismic damage can be significantly amplified by a pre-existing low-velocity zone (LVZ). As the initial velocity contrasts of fault damage zones increase from 10%-40%, we observe larger coseismic damage and longer recurrence intervals of simulated earthquakes. Moreover, the amount of coseismic damage also depends on the hypocenter depth. Deeper events result in larger coseismic damage distributed in a wider area, which also attenuates more slowly with depth.

# FINITE-DIFFERENCE NUMERICAL SIMULATION OF SEISMIC WAVES PROPAGATION IN MODELS WITH COMPLEX BOUNDARY GEOMETRIES

***Wei ZHANG***, ***Nan ZANG***, ***Luqian JIANG***, ***Wenliang SUN***, ***Xiaofei CHEN***

Department of Earth and Space Sciences,
Southern University of Science and Technology, Shenzhen, China

*contact: zhangwei@sustech.edu.cn*

The Finite-difference method (FDM) is widely used for seismic wave numerical simulation in complex velocity models due to its efficiency and intuitive mathematical principle. A traditional mindset of FDM is that it was only used with Cartesian grids thus was not able to accurately simulate seismic wave propagation in regions with surface topography, which is not true. The true requirement relating to the grids for higher-order FDM is a structural grid, i.e., the points along grid lines can be ordered sequentially, but the grid lines could be curvilinear to conform with the boundary topography. Besides the curvilinear grids, we also need a stable free surface boundary condition implementation with enough accuracy on curvilinear grids and a FD scheme suitable for the velocity-stress equation in a general curvilinear coordinate.

In this work, I will discuss some progresses about key components of the curvilinear grid finite-difference method (CGFDM) for complex geometries, including 1) FD schemes: staggered FD with interpolation, Lebedev FD with explicit filtering, mimetic scheme, collocated-grid central FD with explicit filtering, MacCormack-type scheme with inherent dissipation, and pseudo-spectral operator; 2) Free surface boundary condition implementations: vacuum approach, one-sided FD operator, traction-image approach, and characteristic boundary condition; 3) algorithms for complex geometries: overset grid, multi-block grid, and Adaptive Mesh Refinement (AMR).

# MULTISCALE FAULT ZONE DEFORMATION CONTROLLED BY RUPTURE DYNAMICS DURING THE 2021 MW7.4 MADUO EARTHQUAKE

***Dezheng ZHAO***, ***Huihui WENG***

State Key Laboratory for Mineral Deposits Research, School of Earth Sciences and Engineering, Nanjing University, Nanjing, China

*contact: dezhengzhao@nju.edu.cn*

The existence of fault zones has been widely acknowledged through geological and geophysical observations. However, the physical connection between fault zone deformations and rupture dynamics remains poorly understood. In this study, we use various published datasets spanning spatial resolutions from meters to kilometers to characterize the fault zone deformation of the 2021 Mw7.4 Maduo earthquake, where the immature Jiangcuo fault has accommodated ∼4-5 km in the middle and ∼0.8–1.2 km near the eastern end. Geodetic offset data from optical image correlations, surface cracks, and relocated aftershocks reveal an inverse power decay law with multiscale decay distances at the surface and in depth. To understand the physical control of rupture dynamics on these observations, we construct a series of dynamic rupture simulations assuming an elastoplastic half-space solid. We systematically test various parameters in dynamic rupture models and find that (1) the decay distance of plastic strain at the shallowest depth is consistent with that of observed surface cracks; (2) the decay distance of the shear stress in the upper crust is consistent with that of observed aftershocks. Our results illustrate the critical roles of dynamic ruptures on multiscale fault zone deformation and provide important implications for the dynamics of large earthquakes.

# HIERARCHICAL MATRICES (H-MATRICES) IN EARTHQUAKE CYCLE SIMULATIONS - APPLICATION TO PSHA

***Olaf ZIELKE*, *Paul Martin MAI***

King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

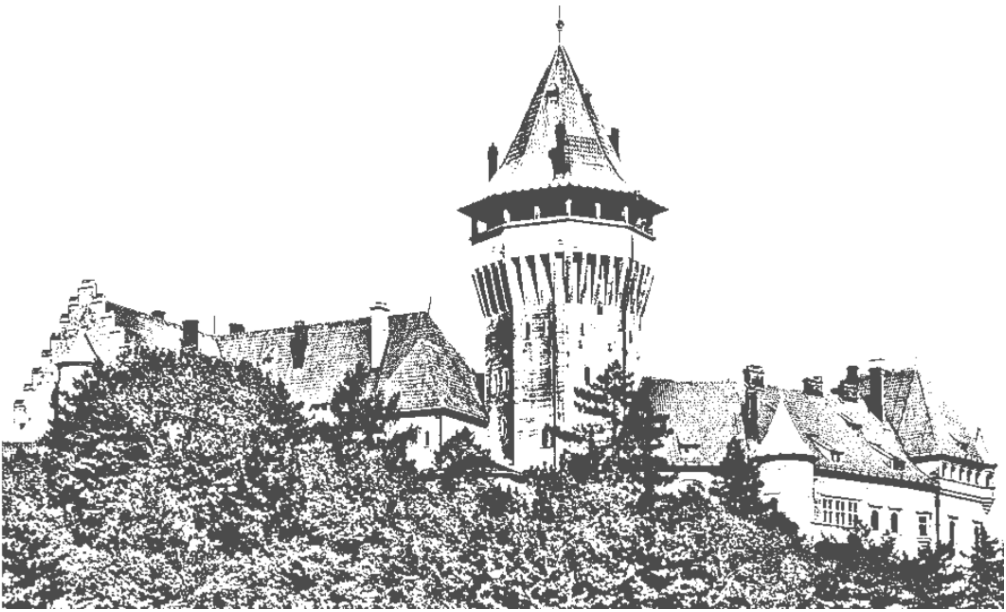
*contact: olaf.zielke@kaust.edu.sa*

Earthquake cycle simulations recreate the seismic cycle (with inter-, co-, and post-seismic phases), providing a virtual "sand box" to investigate how different model parameter influence earthquake rupture (sequences). The potentially complex fault geometries along which earthquakes may occur, are sub-divided into many fault elements where each element may rupture individually or as part of a larger, cascading earthquake. That said, fault element numbers can quickly reach levels that make earthquake cycle simulations prohibitively expensive - even for computationally cheap boundary element codes - especially when aiming to simulate long earthquake catalogs with a wide magnitude range on a large fault system. Increasing the versatility/performance of earthquake cycle simulations therefore requires reducing model complexity from its native $N^2$ scaling.

Since initial publication of our earthquake cycle simulator MCQsim (Zielke and Mai, 2023; BSSA) I incorporated the concept of H-matrices, substantially reducing the program's memory requirements (e.g., size of stiffness matrix $Kh_{ij}$). Additionally, I further optimized when/how $Kh_{ij}$ is accessed, increasing computational efficiency (i.e., not only memory requirements) for small AND large earthquakes.

Here, I provide technical details on how the H-matrix concept was incorporated and how it improved our simulations. I provide scaling tests to quantify the performance increase. Further, I showcase simulation results (i.e., earthquake sequences) for the Gulf of Aqaba and East Anatolian Fault systems, along with the workflow to incorporate them (the earthquake catalogs) into a probabilistic seismic hazard engine (namely OpenQuake).

# *L I S T S*



## LIST OF PARTICIPANTS

as of June 14, 2024

| | |
|---|---|
| **ABRIL** Claudia | LMU Munich, **Germany** |
| **AMPUERO** Jean-Paul | Geoazur, IRD, UniCA, **France** |
| **ANDO** Ryo | University of Tokyo, **Japan** |
| **ARCHULETA** Ralph | University of California Santa Barbara, **USA** |
| **ARIYOSHI** Keisuke | JAMSTEC, **JAPAN** |
| **ARZU** Feyza | Université Côte d'Azur, Laboratorie Geoazur, **France** |
| **BARD** Pierre-Yves | ISTerre, University Grenoble-Alpes, **France** |
| **BERRIOS-RIVERA** Natalia | Stanford University, **USA** |
| **BIRKEL** Brianna | University of Southern California, **USA** |
| **BURGESS** Quentin | Great Basin Center for Geothermal Energy, **USA** |
| **CASTRO-PERDOMO** Nicolas | Indiana University, **USA** |
| **CHALJUB** Emmanuel | ISTerre Grenoble, **France** |
| **CIARDO** Federico | Tufts University, **USA** |
| **DUNHAM** Eric | Stanford University, **USA** |
| **FOJTÍKOVÁ** Lucia | Earth Science Institute, SAS, **Slovakia** |
| **GABRIEL** Alice | Scripps, UCSD / LMU Munich, **USA** / **Germany** |
| **GALIS** Martin | Comenius University in Bratislava, **Slovakia** |
| **GALLOVIČ** František | Charles University, Prague, **Czech Republic** |
| **GAO** Ke | Southern University of Science and Technology, **China** |
| **GARAGASH** Dmitry | Dalhousie Univeristy, **Canada** |
| **GERBER** Jacques | Institute of Mine Seismology, **South Africa** |
| **GUPTA** Avinash | Institut des Sciences de la Terre, **France** |
| **HEWITT** Jordaina | Howard University, **USA** |
| **HOK** Seb | IRSN, **France** |
| **HOLDEN** Caroline | SeismoCity & Victoria University Wellington, **New Zealand** |
| **HRONEK** Martin | Charles University, Prague, **Czech Republic** |
| **HUANG** Yihe | University of Michigan, **USA** |

| | |
|---|---|
| **JIANG** Danyang | Swiss Seismological Service, ETHZ, **Switzerland** |
| **K C** Sajan | University of Southern California, **USA** |
| **KANEKO** Yoshi | Graduate School of Science, Kyoto University, **Japan** |
| **KHEIRDAST** Navid | École Normale Supérieure, **France** |
| **KRISTEK** Jozef | Comenius University in Bratislava, **Slovakia** |
| **KRISTEKOVÁ** Miriam | Earth Science Institute, SAS, **Slovakia** |
| **KUTSCHERA** Fabian | IGPP, SIO, UCSD, **USA** |
| **LI** Sheng | Kyoto University, **Japan** |
| **LIANG** Chao | Sichuan University, **China** |
| **LOCCHI** Maria Eugenia | La Sapienza University of Rome, **Italy** |
| **LOZOS** Julian | California State University, Northridge, **USA** |
| **MADDEN** Betsy | San José State University, **USA** |
| **MAI** Martin | KAUST, **Saudi Arabia** |
| **MARSCHALL** Evan | University of California Riverside , **USA** |
| **MIYAMOTO** Takeshi | Kyoto University, **Japan** |
| **MOCZO** Peter | Comenius University in Bratislava, **Slovakia** |
| **MOSCONI** Francesco | Sapienza University of Rome, **Italy** |
| **NIU** Zihua | LMU Munich, **Germany** |
| **ORYAN** Bar | Scripps UCSD, **USA** |
| **PAGLIALUNGA** Federica | Géoazur, Université de Côte d'Azur, **France** |
| **PASSELEGUE** Francois | Géoazur, CNRS, **France** |
| **PRECA TRAPANI** Rachel | Ludwig-Maximilians-Universität München, **Malta** |
| **PREMUS** Jan | Université Côte d'Azur, Geoazur, **France** |
| **ROMANET** Pierre | La Sapienza, University of Rome/GéoAzur, **France** |
| **RUTŠEKOVÁ** Eva | Comenius University in Bratislava, **Slovakia** |
| **SÁNCHEZ-SESMA** Francisco | UNAM, **México** |
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## Workshop NMEM 2024 is supported by

NSF

We appreciate the financial contribution from the National Science Foundation, Award 2346964, for supporting attendance by US participants in the workshop.

*Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

MicroStep - MIS

ISBN 978-80-8147-140-7