Book of Abstracts

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Seismic swarm migration tracks stress-dependent diffusivity in Enhanced Geothermal Systems

Rahi Abrar * [1], Mateo Acosta *

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[1] Virginia Tech [Blacksburg] – United States

Earthquake swarms are widely interpreted as manifestations of transient fluid transport and pressure diffusion within faults and fractured reservoirs. Their space-time migration patterns have been used to infer hydraulic properties of the medium on which they propagate. In the laboratory, stress dependent diffusivity is pervasive both in intact and fractured granitic rocks. Little evidence of stress dependent diffusivity has been shown in the field. During multi-stage stimulation of the enhanced geothermal system (EGS) at Otaniemi, Finland, analysis of published earthquake catalogs shows that migrating microseismicity systematically exhibits higher apparent diffusivities toward shallower depth and reduced apparent diffusivities toward increasing depth. We leverage seismicity migration as a quantitative signal to constrain depth-dependent diffusivity using a computationally efficient framework. Fluid injection perturbs pore pressure within the surrounding rock mass, modifying the effective stress state and potentially triggering earthquakes along critically stressed preexisting zones of weakness when a critical threshold pressure (CTP) is reached. First, we construct a three-dimensional homogenous reservoir model with a log-normally distributed CTP field. To calibrate the CTP field, we model fluid pressure evolution by solving the diffusion equation with constant injection rate, homogeneous diffusivity, and no-flow Dirichlet boundary conditions. 95th percentile space-time migration envelopes of synthetic seismicity migration fronts are compared to the square-root of time theoretical migration and we choose the best fit for the following simulations. Then, we introduce an exponential depth-dependent diffusivity model defined by reference diffusivity D0 and decay constant A, assuming that depth encodes lithostatic stress. We run forward simulations incorporating the full multi-stage injection history in the Otaniemi EGS to evaluate the performance of (D0, A) parameter pairs at matching observed apparent diffusivities towards shallow and deeper depths compared to the injection depth. The best (D0, A) pair and its probability distribution are inferred using a Markov Chain Monte Carlo (MCMC) approach. By studying seismic swarm spatio-temporal migration in a stress-dependent diffusivity model, our methodology offers a transferable and efficient approach for subsurface characterization, enabling improved assessment of its permeability architecture.

*Speaker

Keywords: seismicity migration, apparent diffusivity, critical, threshold, pressure, Markov Chain Monte Carlo

The 2020 Westmorland, California Earthquake Swarm as Aftershocks of a Slow Slip Event Sustained by Fluid Flow

Mateo Acosta * [1], Krittanon Sirorattanakul , Jean-Philippe Avouac

[1] Virginia Tech [Blacksburg] – United States

Swarms are bursts of earthquakes without an obvious mainshock. Some have been observed to be associated with transient aseismic fault slip, while others are thought to be related to fluids. However, the association is rarely quantitative due to insufficient data quality. We use high-quality GPS/GNSS, InSAR, and relocated seismicity to study a swarm of > 2,000 earthquakes which occurred between 30 September and 6 October 2020, near Westmorland, California. Using 5 min sampled Global Positioning System (GPS) supplemented with InSAR, we document a spontaneous shallow Mw 5.2 slow slip event that preceded the swarm by 2–15 hr. The earthquakes in the early phase were predominantly non-interacting and driven primarily by the slow slip event resulting in a nonlinear expansion. A stress-driven model based on the rate-and-state friction successfully explains the overall spatial and temporal evolution of earthquakes, including the time lag between the onset of the slow slip event and the swarm. Later, a distinct back front and a square root of time expansion of clustered seismicity on en-echelon fault structures suggest that fluids helped sustain the swarm. Static stress triggering analysis using Coulomb stress and statistics of interevent times suggest that 45%–65% of seismicity was driven by the slow slip event, 10%–35% by inter-earthquake interactions, and 10%–30% by fluids. Our model also provides constraints on the friction parameter and the pore pressure and suggests that this swarm behaved like an aftershock sequence but with the mainshock replaced by the slow slip event.

Keywords: Natural Swarms, Salton sea, Aseismic slip, Mechanisms

*Speaker

An overview of the earthquake swarm active for 20 years near the capital of Mongolia

Munkhsaikhan Adiya * [1], Antoine Schlupp * † , Emeelt Project Team - Iag (mongolia) And Eost-Ites (france)

[1] Institute of Astronomy and Geophysics, MAS, Mongolia – Mongolia

In 2005, an earthquake swarm started near the capital of Mongolia and continues up to now with regular crisis of hundreds of events, without mainshock. With the highlight of this swarm we discovered a new active fault with surface rupture in Holocene deposits, named Emeelt fault. This work is the first analysis done on the seismogenic structure of Emeelt fault with a multi-disciplinary approach, including detailed field survey, image and morphotectonic interpretation and geophysical survey such as geomagnetic, seismic survey, seismic profiles and GPR. We focus our presentation on the description of the charcteristics of the swarm and it space and time evolution.
We present an overview of the analysis of this earthquake swarm active now for 20 years. To improve our understanding of this swarm and its space and time evolution, we deployed new stations near the swarm to relocate these earthquakes using the double - difference method after the calculation of a 3D velocity model. The precise relocation shows that the earthquakes are distributed along four parallel segments of few kilometers length and nearly vertical. The events are mainly located at a depth between 5 to 15 km in the upper-mid crust and the activity detected is not deeper than 20 km. The total amount of earthquakes detected since 2005 is 4200 events and half of them have been precisely relocated. Only one structure has been identified at surface but the seismic profile shows several clear deep structures. One pending question is the relation between these swarms and the large active fault of Hustay perpendicular and connected which could produce magnitude of about 7.5 at a distance of only tens kilometer from the capital Ulaanbaatar.

Keywords: earthquake swarm, Emeelt fault, 3D velocity model

*Speaker
†Corresponding author: antoine.schlupp@unistra.fr

Normal stress pulse during injection in soft fracture

Kamal Ahmadov *† [1], Jean Schmittbuhl [1], Thibault Candela [2]

[1] Institut Terre Environnement Strasbourg – université de Strasbourg, Centre National de la Recherche Scientifique : UMR7063, Centre National de la Recherche Scientifique – France
[2] TNO, Geological Survey of the Netherlands, Utrecht, The Netherlands – Netherlands

Fractures play a significant role in fluid transport in a number of georesource applications. Here we study the fluid-driven reopening of a pre-existing fracture when the deformation along the fracture is significant, which has important implications for the initiation and migration of induced seismicity. We compare semi-analytical calculations of the pressure propagation in an elastically deformable fracture during fluid injection with numerical simulations using the Distinct Element Method (DEM) implemented in the 3DEC code (ITASCA).
We show that the normal stiffness of the fracture is a key parameter. Soft fractures produce a sharp pressure front with a significant aperture change, whereas rigid fractures show a smooth and diffusive aperture and pressure distribution. In soft fractures, the sharp aperture/pressure front produces a pulse in normal tensile stress ahead of the propagating front. The amplitude of this stress pulse depends on the parameters of the problem, which we have analyzed through a sensitivity analysis.
The propagation of the normal stress pulse follows a nonlinear diffusion equation in soft fractures, in contrast to the linear diffusion observed in rigid fractures. As a result, propagation is slower in fractures with lower normal stiffness, hence the fluid pressure migrates faster in the rigid fracture case. Despite these differences, the aperture and pressure fronts scale with
\$$\sqrt{\{t\}}$\$*inbothcasesduringconstant−pressureinjection.Incontrast,constant−rateinjectionproducesmigratic*
linearpropagationwithaconstantfrontvelocity.
Theseresultsprovideamechanicalexplanationforthenon−diffusivemigrationpatternsobservedatseveralflui
injectionsitesandhighlightthecriticalroleoffracturedeformabilityandinjectionprotocolincontrollinginduced

Keywords: fluid injection, hydro, mechanical coupling, seismicity migration, numerical simulations, semi, analytical solutions

*Speaker
†Corresponding author: kamal.ahmadov@unistra.fr

Systematic analysis of bursts, swarms, and other earthquake clusters with the nearest-neighbor algorithm

Yehuda Ben-Zion * [1]

[1] University of Southern California [Los Angeles] (USC) – Los Angeles, CA, 90089-0484, USA, United States

I review methodology and results associated with detection and classification of earthquake clusters using the nearest-neighbor (NN) algorithm. The NN approach connects every event in a catalog to its NN in a combined space-time-magnitude domain and provides a robust data-driven technique for systematic clustering analysis of large data sets. The 2-D joint distribution of the NN proximities (normalized space and time separations) of earthquakes exhibits two dominant modes that are observed in local, regional, and global catalogs. One mode corresponds to background events with random proximities and the other mode to clustered events with smaller proximities. This allows for a robust detection of earthquake clusters with a single parameter separating the two modes and a non-parametric approach for declustering catalogs.

The observational results highlight two distinct types of small-to-medium magnitude earthquake clusters, *burst-like sequences* and *swarms*, along with intermediate cluster forms that are a mixture of the two dominant types. Burst-like clusters have few foreshocks, prominent mainshock, a small number of aftershock generations, and approximately spatial isotropy. These sequences are typical in regions with relatively cold temperature and/or low fluid content, they reflect generally brittle failures, and they are well reproduced by branching models like ETAS. Swarm-like clusters have comparable event magnitudes, abundance of foreshocks, many generations of aftershocks, and spatial anisotropy. They are common in regions with relatively high temperature and/or fluid content, are likely associated with mixed brittle-ductile failures, and are not generically reproduced by ETAS. Recent analyses demonstrate the existence of additional refined modes in NN diagrams that can be used to distinguish between induced and tectonic earthquakes, and to identify repeating earthquakes and volcanic seismicity.

*The talk is dedicated to Ilya Zaliapin who led the research on these topics.

Codes for detection and classification of clusters and declustering earthquake catalogs based on the NN algorithm are available at https://github.com/dttrugman/Nearest_Neighbor_Cluster https://github.com/dttrugman/Nearest_Neighbor_Declustering

Keywords: earthquake clusters, nearest, neighbor algorithm, bursts, swarms

*Speaker

Modeling fluid-driven earthquake swarms: Insights from induced seismicity in enhanced geothermal systems

Natalia Berrios-Rivera *† [1], Eric Dunham

[1] Stanford University – United States

Fluid-driven swarm seismicity occurs in various natural and industrial settings, and is often characterized by a migrating seismicity front. Operations for harnessing subsurface energy resources, such as enhanced geothermal systems (EGS), often involve high pressure fluid injection and induced seismicity. Developing a better understanding of the conditions under which seismic or aseismic injection-induced slip occurs provides insight into the physical mechanisms that drive swarm seismicity and how to manage the challenges from induced seismicity. Observations of fluid-induced swarm seismicity expanding with the same diffusive space-time behavior as analytical solutions for fluid-driven aseismic slip have been interpreted as evidence that stress changes from aseismic slip trigger seismic slip. In some cases, aseismic slip is confirmed from crustal deformation measurements or sheared wellbore casing. Our work offers another interpretation of migrating seismicity that may be relevant when there is no independent evidence for aseismic slip.
We develop earthquake sequence models for fluid injection into a velocity-weakening rate-and-state fault with slip-dependent permeability enhancement and fluid transport. In earlier work, we explored these processes through 2D simulations of constant-pressure injection, and an analytical solution for a 2D fluid-driven aseismic shear crack with constant friction and permeability enhancement. These results show that pressure diffusion and elastic stress transfer from seismic slip drive seismicity fronts that expand diffusively outward from the injector, producing the same spatiotemporal expansion predicted by analytical solutions for aseismic slip, even when aseismic slip is not the primary mechanism driving seismicity. Since the expansion of the seismicity front is independent of slip type, velocity-strengthening friction can be used for less expensive simulations, a result we leverage in our 3D work.

We extend our modeling framework to 3D earthquake sequence models of constant-rate fluid injection, and additionally account for wellbore storage and turbulent pressure losses in the well to better represent injection dynamics during reservoir stimulation. In addition, we derive an analytical solution for a fluid-driven aseismic circular shear crack with constant friction and permeability enhancement, and find that it provides a useful estimate of the slip distribution for variable-rate injection cases. We apply this 3D modeling framework to induced seismicity from an EGS project in Cooper Basin, Australia, and use the observed slip front position and the wellhead pressure history to constrain the model. We show that the position of the seismicity front alone does not uniquely constrain the relative amounts of aseismic and seismic

*Speaker

†Corresponding author: nberrios@stanford.edu

slip or the pressure distribution, as multiple combinations of hydromechanical parameters can reproduce the observed migration behavior. However, pressure gauge data can help reduce this nonuniqueness. By combining numerical simulations, observations of seismicity, and wellhead pressure data, it may be possible to constrain the relative amounts of aseismic and seismic slip that occurred at depth.

Keywords: fluid injection, fluid driven seismicity, induced seismicity, aseismic slip, earthquake sequence modeling, permeability enhancement

Beyond Aftershocks: A Mainshock-Triggered Transition to Swarm-Like Seismicity

Marie-Paule Bouin * [1], Claudio Satriano† , Pascal Bernard‡ , Jeffrey Bermido§ , Hesaneh Mohammadi¶

[1] Institut de Physique du Globe de Paris – CNRS – France

On 21 November 2004, an Mw 6.3 intraplate earthquake ruptured the NW–SE striking Roseau Fault south of the Les Saintes archipelago (Guadeloupe), triggering an unusually intense and long-lived seismic sequence. While initiated by a mainshock, the subsequent activity departs markedly from the expected temporal decay of a classical aftershock sequence and instead exhibits characteristics akin to swarm-like seismicity persisting for nearly two decades.
Seismic observations spanning from the immediate post-mainshock period to 2023 show that, rather than decaying or remaining confined to the ruptured fault, seismicity progressively concentrates in a northern sector characterized by dense, volumetric activity not associated with a single fault plane. This behaviour, sustained over nearly two decades, is inconsistent with classical aftershock dynamics and more consistent with a swarm-like regime dominated by transient forcing rather than static stress transfer.

We propose that the 2004 mainshock acted not only as a stress perturbation but also as a trigger for a secondary process, likely involving fluid redistribution and overpressure diffusion within the crustal volume affected by the rupture. In this scenario, the sequence transitions from a rupture-controlled regime to one governed by transient fluid–fault interactions, in which seismicity is sustained by evolving pore-pressure conditions over decadal timescales.
Our results illustrate how a large earthquake can initiate a long-term shift toward a swarm-like dynamical regime dominated by transient processes, challenging the classical separation between aftershock sequences and fluid-driven swarms and emphasizing the need to integrate both frameworks when assessing seismic hazard in the Lesser Antilles.

Keywords: Long, term postseismic activity, Postseismic triggering, Fluid–fault interactions, Pore, pressure diffusion

*Speaker
†Corresponding author: satriano@ipgp.fr
‡Corresponding author: bernard@ipgp.fr
§Corresponding author: bermido@ipgp.fr
¶Corresponding author: hmohammadi@ipgp.fr

Modelling of earthquake swarms suggests magmatic fluids in the upper crust beneath the Eger Rift

Pinar Buyukakpinar *† [1], Torsten Dahm , Sebastian Hainzl , Marius Isken , Matthias Ohrnberger , Jana Doubravová , Siegfried Wendt , Sigward Funke

[1] GFZ Helmholtz Centre for Geosciences – Germany

Earthquake swarms are enigmatic seismic phenomena that occur across diverse tectonic settings, from volcanic to intraplate regions, and are often associated with fluid migration, magmatic activity, or stress redistribution. The Northwest Bohemia/Vogtland region is a globally recognized hotspot and natural laboratory for such activity. This study examines the recent activation of an earthquake swarm in the region after a century of dormancy. By integrating high-resolution seismicity patterns and earthquake source mechanisms with models of fluid migration, we provide a detailed reconstruction of the swarm's temporal and spatial evolution. Our seismicity modeling suggests the activation of a pre-existing fault by natural hydro-fracturing and hydro-shearing under the influence of ascending magmatic fluids, beginning with a high-pressure CO_2-rich fluid intrusion, followed by transitions to low-pressure hydro-shearing on the fault, likely associated with CO_2-magma mixtures. Our results emphasize the pivotal role of fluid overpressure and fault zone weakening in controlling swarm dynamics.

*Speaker
†Corresponding author: pinar@gfz.de

b-value variability in the 2018-2024 Noto Peninsula swarm: catalog completeness independent evidence for systematic spatiotemporal variations

Diego Cardellini *† [1], Blandine Gardonio [2], Mathilde Radiguet [3]

[1] Institut des Sciences de la Terre – Université Savoie Mont Blanc, Centre National de la Recherche Scientifique, Université Grenoble Alpes – France
[2] Institut des Sciences de la Terre – Université Savoie Mont Blanc, Centre National de la Recherche Scientifique – France
[3] Institut des Sciences de la Terre – Centre National de la Recherche Scientifique, Université Grenoble Alpes – France

From 2018 to January 2024, the Noto Peninsula (Japan) experienced an extended swarm of 150,000 earthquakes, concluding with an Mw 7.6 mainshock. The sequence initiated in a compact deep source and then moved to shallower and more extended parts of the fault zone over six years, offering an exceptional opportunity to study the physical mechanisms that control swarm seismicity. Following previous studies in the literature, we utilize two b-value estimators based on catalog completeness, namely b-positive (van der Elst, 2021) and b-Bayesian inversion (Laporte, 2025), in order to independently validate the spatiotemporal pattern of the swarm, without being subject to Mc bias. Spatially, b-positive shows a clear depth dependence in b within the five sub-regions of the fault zone modelled by Hirose et al. (2024), with b increasing from around 0.85 at 5-10 km to around 1.17 at 14-20 km depth. This depth dependence is independently observed in the northern and eastern sub-regions of the fault zone, with the deepest region where activity initiated in 2018 before migrating northeastward and upward to 2021-2023 recording the highest b values. Temporally, from 2018 to 2021, there is clear agreement between b-positive and Bayesian inversion in terms of how b evolves: it starts above 1.3 in 2018, decreases steadily to around 0.80 by late 2020 as the swarm grows laterally, then increases sharply in 2021. The Bayesian method also allows us to identify 10 to 20 statistically significant change points in this time period, with b ranging from around 0.65 to 1.65. After 2021, b varies around 1.0 with increasing variance up to the mainshock, reflecting the complexity and heterogeneity of the fault system in its final years. These results thus validate and quantify, on statistical grounds, the heterogeneity in space and time of the b-values previously suggested for the Noto swarm. The agreement between two independently derived estimates also strengthens confidence in the observed evolution, and underscores the utility of completeness-independent approaches in studying swarm sequences where catalog completeness is known to vary.

*Speaker
†Corresponding author: diego.cardellini@univ-smb.fr

Keywords: b value, earthquake swarm, catalog completeness, Noto peninsula

Stress heterogeneity and seismicity patterns on complex fault systems

Camilla Cattania * [1], Yifan Yin [1]

[1] Massachusetts Institute of Technology – United States

Faults zones consist of one or more fault strands, surrounded by a highly fractured damage zone, and characterized by roughness at all scales. These sources of geometrical complexity contribute to a highly heterogeneous stress field, which plays a first order role on microseismicity and dynamic rupture. Quantifying stress heterogeneity, and relating it to seismicity patterns, remain a challenge.

Here we present recent efforts in this direction, focusing on the interplay between fault roughness, damage, and off-fault stress relaxation. We model seismic cycles on fractal faults surrounded by damage, explicitly represented as an ensemble of small faults with a power-law decay from the main fault. We assume a homogeneous elastic medium and represent far-field loading by a homogeneous stressing rate tensor. First we consider the effect of viscous stress relaxation, approximated by exponential relaxation with a characteristic timescale Tr (Ozawa et al, 2023). We demonstrate that stress heterogeneity is controlled by a competition between elastic interactions and relaxation: while elasticity alone causes unbounded stress perturbations as fault slip accrues, stress relaxation results in a limit cycle with local stress fluctuating around a constant value. Local stress perturbations can be estimated quasi-analytically, and they increase linearly with VTr, where V is the long term fault slip rate. In addition to viscous relaxation, stresses are bounded by small scale off-fault plastic yielding. We estimate this effect by modeling the long term 3-D stress field evolution and identifying regions where a Mohr-Coulomb failure criterion for intact rock is first met. We use these estimates, combined with field measurements of fault roughness and damage distribution, to estimate in-situ stress heterogeneity for several strike-slip faults.

Finally, we consider seismicity patterns for various realizations of fault complexity. Seismicity takes place predominantly in the damage zone, and it consists of background events and clustered sequences. A high degree of stress heterogeneity favors a mixture of seismic and aseismic slip, with feedbacks between them. Subparallel fault strands and near-field faults in the damage zone play an active role during the mainshock nucleation phase: they can host significant preslip as well as cascading foreshock sequences. Aseismic slip often mediates interaction from foreshocks to the mainshock, extending the spatio-temporal range of static stress transfer alone. Several features of simulated seismicity align with observations in natural faults and laboratory experiments, and help elucidate similarities and discrepancies across scales.

*Speaker

Swarms and slow slip in the South Peru subduction zone

Caroline Chalumeau * [1], Hugo Sanchez-Reyes [1], Roa Seif Dine [1], Jannes Münchmeyer [2], Mickaël Langlais [1], Juan Carlos Villegas Lanza [3], Alex Gonzales [4], Edmundo Norabuena [3], Hernando Tavera [3], Anne Socquet [1]

[1] ISTerre, Université Grenoble Alpes, Université Savoie Mont-Blanc, CNRS, IRD, Université Gustave Eiffel – Université Grenoble Alpes – France
[2] German Research Centre for Geosciences - Helmholtz-Centre Potsdam – Germany
[3] Instituto Geofísico del Perú – Peru
[4] Institut de Recherche pour le Développement – Peru

The South Peru subduction zone is a complex, highly active region, where the flat slab associated with the Nazca Ridge subduction in the North transitions to a much steeper subduction in the South. This transition not only causes the slab to contort, but affects seismicity patterns in the region. Here we use data from 26 seismic stations active from March 2022 to December 2024 as part of the DEEPTrigger project, along with 16 permanent Peruvian stations and 15 permanent Chilean stations, to create a 3-year seismicity catalogue of South Peru. Using PhaseNet for phase picking and PyOcto for phase association, we obtain a total of 166 825 events. These earthquakes are located with NonLinLoc-SSST using a new 3-D P and S-wave velocity model of the region obtained from full-waveform inversion (Kan et al., in review.), then relocated using double difference methods with cross-correlation times to obtain precise locations. We thus obtain the first dense and precisely-located earthquake catalog of the region. This catalog shows the presence of many seismic swarms where the Nazca Ridge enters subduction, while they are absent from the rest of the margin. These seismic swarms contain numerous repeating earthquakes which, in combination with GPS records of nearby stations, hint at the likely presence of slow slip. We also find that the occurrence of the Mw 7.2 Acari earthquake at the southern edge of the Nazca Ridge triggers a seismic swarm _˜150 km to the north, providing an example of far-field interactions between large megathrust earthquakes, small-magnitude seismic swarms and aseismic slip.

Keywords: Subduction, Repeating earthquakes, South America, Ridge subduction

*Speaker

Permeability and dilatancy control seismicity migration and slip behaviour during injection on a rate-and-state fault

Martin Colledge * [1], Pierre Dublanchet [2], Frédéric Cappa [1], Louis De Barros [1]

[1] Geoazur – Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, IRD, Géoazur – France
[2] Centre de Géosciences – MINES ParisTech, PSL Research University – France

Seismic swarms display complex migration patterns, including outward propagation linked to fluid diffusion processes, rapid burst-like migrations, and aseismic slip backfronts. To investigate the mechanisms underlying these behaviours, we perform quasi-dynamic 1D simulations of a permeable velocity-weakening planar fault subjected to a localized fluid injection. The model incorporates porosity-dependent permeability, elastic pore dilatancy, and velocity-induced plastic dilatancy. Results show that variations in permeability and plastic dilatancy exert a strong control on the fault's mechanical response. For low to moderate plastic dilatancy, the fault produces earthquake sequences with seismic-cycle-like ruptures spanning the low-effective-normal-stress fluid-pressurized region, with aftershocks nucleating near the stressed terminations of previous events. In all simulations, a seismic front emerges ahead of the fluid pressure fronts, driven by stress perturbations induced by fluid pressure diffusion. In contrast, for high plastic dilatancy combined with strong permeability variations, slow-slip fronts propagate along the fault at velocities consistent with those observed for fluid-induced seismicity migration. In this regime, rapid burst-like swarm migrations can arise from fluid-induced aseismic fronts, which propagate through a highly dilatant medium and activate seismogenic asperities along their path. These results highlight the critical role of the hydromechanical response of faults in controlling swarm dynamics, and provide a framework linking fluid diffusion, dilatancy, and the emergence of fast migrating seismic bursts commonly present in natural seismic swarms, but rarely seen in anthropogenic fluid-induced sequences.

Keywords: Numerical modeling, Rate and State, Injection, Swarms, Dilatancy, Seismicity Migration

*Speaker

Pause in migration and seismic rates reveals a long-term preparatory phase of large earthquakes during seismic swarms

Nicolas Cosso Hoedt * [1], Louis De Barros [1], Quentin Bletery [1]

[1] Géoazur, UCA, CNRS, IRD, Sophia Antipolis, France – Université Côte d'Azur, CNRS, IRD, Observatoire de la Côte d'Azur, Géoazur – France

Seismic swarms are sometimes observed prior to major earthquakes (Aquila 2009, Noto 2024...) and could retrospectively be seen as "precursory events". Similarly, large mainshocks may also occur during swarm sequences, in either natural or injection-induced sequences. Here, we aim to explore if changes in swarm dynamics may reveal earthquake preparatory processes. We focus on three swarm sequences with different geological, mechanical and structural settings (Basel, Cahuilla and Corinth). For each case, we examine the temporal evolution of the seismicity rate, spatial migration, and b-value with a specific focus on what happen right before the largest magnitude events.

Our results reveal a consistent long-term pattern before large events: the seismicity rate systematically decreases and spatial migration halts prior to the main event, while b-values show no significant nor systematic variations. A comparison with injection parameters from the Basel sequence indicates that these trends are not correlated with fluid-injection processes. We observe a short-term foreshock sequence associated with an increase in the seismicity rate preceding six out of the nine events we studied.

According to our observations, we propose a conceptual model in which swarm growth is arrested by a large asperity. During this locked period, seismic activity decreases and spatial migration stops while the stress on the asperity is loading. Then, in most of the studied cases, a foreshock sequence occurred shortly before the rupture of a large asperity. Our results open potential new ways to anticipate the occurrence of large events, by the observation of a long-term changes in seismicity, in addition to foreshock sequences.

Keywords: seismic swarms, precursory processes, spatial migration, b value

*Speaker

Rake-changing repeaters : stress gauges for measuring aseismic processes

Lucile Costes *† [1], David Marsan [1], Blandine Gardonio [1]

[1] Université Savoie Mont Blanc – ISTerre lab., University Savoie Mont-Blanc - CNRS, Le Bourget-Du-Lac, France – France

Repetitive rupture of the same asperity has been documented in various tectonic settings through the observation of highly correlated waveforms from co-located earthquakes (mature faults, subduction interface, swarms). These events, known as repeaters, are of particular interest because they provide key constraints on small-scale fault processes and can be used to investigate slip rates on faults, aseismic deformation, earthquake nucleation... In fewer cases, highly similar earthquakes exhibiting polarity inversions at all recording stations have been identified. These so-called anti-repeaters are thought to rupture the same asperity with an inverted focal mechanism and are associated with specific driving processes. To our knowledge, no intermediate case involving rupture of the same asperity with a change in slip direction (rake) has been reported, despite the fact that such a scenario is theoretically plausible.
In this study, we search for such events within the aftershock sequence of the M7.1 Miyagi-Oki earthquake (26 May 2003), in the northeastern Japan subduction zone. This intermediate-depth intraslab sequence (70 km depth) exhibits a high seismicity rate and is well recorded by a dense seismic network. Using data from the 17 closest three-component broadband stations, we compute waveform coherence, cross-correlation and anti-correlation (flipped traces) for both P and S waves of close event pairs. We identify 40 pairs of highly similar earthquakes displaying polarity inversions at several (but not all) stations. After performing relative hypocenter relocation using correlation-derived time delays, we retain ten co-located pairs with high-quality waveform similarity and polarity inversion. By comparing measured amplitude ratios with synthetic radiation pattern ratios, we invert the rake change for each event pair.

At this stage, the physical mechanism responsible for this newly identified class of similar earthquakes, that we name 'rake-changing repeaters', is uncertain. A change in rake between successive ruptures of the same asperity likely reflects a highly localised modification of the stress field. It could be driven by transient pore-fluid pressure variations or stress perturbations induced with nearby moderate slip.
The identification of rake-changing repeaters opens new perspectives for investigating the complexity of local faulting processes at depth, and complements existing insights from repeaters and anti-repeaters. In particular, because of their sensitivity to localised stress changes and the precise constraints they provide on rupture location, rake-changing repeaters could help track pore-fluid pressure variations, for example within seismic swarms.

*Speaker
†Corresponding author: lucile.costes@univ-smb.fr

Keywords: Repeaters, Rake change, Intermediate depth seismicity, Japan, Stress gauge

Structure and seismicity of Monchique: A seismic nest in SW Iberia

Susana Custodio *† [1], Ferdinando Napolitano [2], Goncalo Emidio [1], Nuno Dias [1,3], Simone Cesca [4], Osorio Cavacundo [3,1], Marta Neres [5], Rosario Carvalho [1], Stephanie Dumont [1]

[1] Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa – Portugal
[2] Geophysics and Seismology Laboratory, Dept. of Physics, University of Salerno – Italy
[3] Instituto Superior de Engenharia de Lisboa, Instituto Politécnico de Lisboa – Portugal
[4] GFZ German Research Center for Geosciences, Potsdam – Germany
[5] IPMA, Instituto Português do Mar e da Atmosfera, Lisboa – Portugal

The Monchique Massif is a prominent topographic high in SW Iberia, standing out from the surrounding plane of southern Portugal. It is located to the north of the Eurasia-Africa plate boundary, which locally accommodates slow oblique convergence (_˜5 mm/yr). At the surface Monchique shows alkaline magmas that intruded during the Late Cretaceous, following the break-up of Pangea. Monchique is a well-known region of hydrothermal activity, with several natural springs and an active natural water bottling industry and spa services. Monchique also hosts the seismic cluster in mainland Portugal with the highest seismic rate. However, most earthquakes in Monchique are of low magnitude (lower than M4) and no active seismic faults are mapped.

In this work, we present the results of the analysis of seismic data recorded by a 2-year temporary seismic array (8 BB, 14 SP). We apply a fully automated workflow to obtain a high-resolution earthquake catalogue, based on Lassie, PhaseNet and NLL-SSST-coherence. We analyse focal mechanisms, using first motion polarities and a joint inversion of polarities and waveforms. We image the structure of the seismic nest using Vp, Vs, absorption and scattering tomography. Finally, we carry out hydrological analyses in the natural springs. The results surprisingly reveal the existence of two two independent systems of fluid circulation: a shallow system (above 8 km depth), consisting of the magmatic intrusion as modeled by magnetic data, where rainwater percolates at shallow levels and acquires an alkaline signature, characterized by high seismic scattering and low Vp; and a deeper system (8-15 km), below the intrusion, where earthquakes are located, characterized by high b-value and a high absorption anomaly. Although fluids seem to exist in the two systems, they appear disconnected. In this presentation we discuss the characteristics of the structure and seismicity of the Monchique nest, and its relationship with crustal fluids.

*Speaker
†Corresponding author: sicustodio@fc.ul.pt

Keywords: Seismic nest, Monchique, hydrothermalism, Earth structure

New insights on earthquake swarms dynamics from an enhanced earthquake catalog of the Gulf of Corinth, Greece

Philippe Danre *† [1], Olivier Lengliné [2], Louis De Barros [3]

[1] German Research Centre for Geosciences - Helmholtz-Centre Potsdam – Germany
[2] Institut Terre Environnement Strasbourg – Ecole Nationale du Génie de l'Eau et de l'Environnement de Strasbourg, université de Strasbourg, Institut National des Sciences de l'Univers, Centre National de la Recherche Scientifique – France
[3] Géoazur – Institut National des Sciences de l'Univers, Observatoire de la Cote d'Azur, Université Côte d'Azur, Centre National de la Recherche Scientifique, Institut de Recherche pour le Développement – France

The processes that control earthquake swarms dynamics are still unresolved, despite several mechanisms proposed in the literature. To be able to discriminate between the role of pore pressure perturbation, aseismic slip, stress transfer or poroelasticity, among others, precise and repeated observations are required. Using the long and dense continuous seismic monitoring in the Western Gulf of Corinth, Greece, we computed a 12 years long seismicity catalog to get more insight into the dynamics of swarms that occur in the region. We use an AI-based phase picker, template matching and relocation, to obtain a rich seismic catalog with more than 400.000 relocated hypocenters. The first observation is the complexity of the earthquake sequences, that behave either like swarms, (foreshock-)mainshock-aftershock or show complex and intermediate behaviors. Catalog also highlights complex spatio-temporal behavior of earthquake swarms, which show a seismic front with a slow migration, but also fast migration episodes within the swarms. Both migration velocities seem however consistent with fluid processes. Finally, it sheds new lights on the seismogenic structures, and their control on seismicity, by showing that seismicity clusters at the intersection between steeply dipping planes (normal faults) and well-defined horizontal planes. The multiple observations help better understanding the dynamics of seismicity within the Gulf, while comparison with swarms occurring in other regions lead to more general results about earthquake swarm dynamics.

Keywords: seismology, earthquake swarm, detection

*Speaker
†Corresponding author: danre@gfz.de

Triggering of swarms and complex mainshock–aftershocks sequences by fluid processes in the Ubaye Region (Western Alps)

Louis De Barros *† [1], Marion Baques [1], Clara Duverger [2], Maxime Godano [1], Hervé Jomard [3]

[1] Géoazur – Institut National des Sciences de l'Univers, Observatoire de la Cote d'Azur, Université Côte d'Azur, Centre National de la Recherche Scientifique, Institut de Recherche pour le Développement – France
[2] Lithium de France – Lithium de France – France
[3] Bureau d'évaluation des risques sismiques pour la sûreté des installations (ASNR/PSE-ENV/SCAN/BERSSIN) – Autorité de Sûreté Nucléaire et de Radioprotection – France

The Ubaye Region (French Western Alps) is one of the most seismically active regions in France. It is characterized by alternating mainshock-aftershock sequences and swarms. Notably, a long seismic swarm occurred in 2003-2004, which appears to have been driven by fluid diffusion. During the 2012–2015 crisis, three mainshocks with Ml $>$ 4 occurred, in a complex sequence that can be globally seen as a swarm. The seismic activity following the largest earthquake (Ml = 5.2, 7 April 2014) show both aftershocks triggered by stress transfer and seismic swarms involving fluid processes. The diversity of seismic behaviour in this area highlights the presence of complex processes at play, which are likely involving fluid pressure. To refine the role of fluid processes, we invert the stress-state from focal mechanisms in order to reconstruct the fluid pressure that induces the earthquakes. Most of the events, including the largest mainshocks, appear to be triggered by fluid overpressure of between 15 and 40 MPa (17 to 40 per cent of the hydrostatic pressure). While fluid overpressure decreases over time in the aftershock sequences, it varies randomly at high levels during swarm sequences. We also examine variations in the b-value over time during those sequences. Swarms show a consistent temporal increase in b-value, whereas the temporal b-value pattern for the mainshock-aftershock-like sequences shows a drop right after the mainshock, followed by an increase above the background level. We interpret this pattern as a trade-off between stress transfer from the mainshock and the release of pressurized fluid. Therefore, based on these different observations, we propose that: (1) the fluids trapped in the fault plane tends toward lithostatic pressure, triggering the mainshock rupture and (2) part of the aftershocks are induced by the diffusing fluid pressure within small swarms. Conversely, swarms require external fluid pressure feedings, likely from deep sources. Therefore, in this area, fluid pressure appears to be a common triggering process of earthquakes, in either mainshock-aftershocks or swarm sequences, although the processes involved may differ depending on the type of seismic sequence.

*Speaker
†Corresponding author: louis.debarros@geoazur.unice.fr

Keywords: Ubaye (Alps), fluid pressure, b, value, complex seismic sequences

Growth of seismic moment with volume and distance for natural swarms and fluid-induced sequences

Louis De Barros *† [1], David Marsan [2], Philippe Danre [3]

[1] Géoazur – Institut National des Sciences de l'Univers, Observatoire de la Cote d'Azur, Université Côte d'Azur, Centre National de la Recherche Scientifique, Institut de Recherche pour le Développement – France

[2] Marsan David (ISTerre) – ISTerre USMB – Campus scientifique, 73376 Le Bourget du Lac cedex, France

[3] Institut Terre Environnement Strasbourg – Ecole Nationale du Génie de l'Eau et de l'Environnement de Strasbourg, université de Strasbourg, Institut National des Sciences de l'Univers, Centre National de la Recherche Scientifique – France

The relationship between seismic moment and injected volume is now commonly used to predict the seismic moment released during seismic sequences induced by human activity. However, such relationships are still the subject of debate and cannot be applied to natural swarms, for which the volume of fluid is unknown. We here aimed at extrapolating to the natural swarms the gained knowledge on the dependency of the seismic swarms on the injected volume.
By examining global compilations of induced sequences, we demonstrate that the injected volume is directly proportional to the number of events, rather than the magnitude of earthquakes. This suggests that fluid controls the nucleation of earthquakes, either through direct pressure or fluid-induced aseismic slip. Meanwhile, the size of the earthquake rupture is likely to be controlled by fault and stress properties. As seismic moment is a crucial parameter for risk assessment, relations between the number of events and seismic moment should be considered. However, the commonly used relations (Wyss, 1973) exhibit unphysical anomalies. Starting from the Gutenberg–Richter relationships, we derive and validate new relationships that theoretically allow us to relate fluid volume to released seismic moment.
Recent studies (e.g. Danré et al., 2024) also propose a relationship between the distance from the injection site and the injected volume based on rupture mechanics theory. We confirm this relationship using our global datasets of fluid-induced sequences. Given these relationships between volume, distance, and moment, we explore the dependency between seismic moment and distance. While volume controls seismic moment, migration distance is directly related to seismic moment and depends on stress state and, likely, fault properties. Applying the calibrated empirical relation to the beginning of natural swarms proves to be an efficient way of anticipating future released moment. This could provide a new approach to forecasting seismic swarm evolution, whether natural or anthropogenic.

*Speaker
†Corresponding author: louis.debarros@geoazur.unice.fr

Keywords: induced seismicity, natural swarms, seismic moment, b, value

Creep as Possible Driver of Persistent Shallow Seismicity within a Fault-Zone Intersection in Northern Switzerland

Tobias Diehl *† , Toni Kraft [1], Martin Schoenball [2], Angela Landgraf [2], Sandro Truttmann [3], Michael Schnellmann [2], Stefan Wiemer [1]

[1] Swiss Seismological Service [ETH Zurich] – Switzerland
[2] Nationale Genossenschaft für die Lagerung radioaktiver Abfälle – Switzerland
[3] Institute of Geological Sciences (University of Bern) – Switzerland

Seismicity below the town of Eglisau in northern Switzerland is peculiar for several reasons. First, instrumental seismicity indicates unusually shallow hypocenters within the topmost 2 km of the crust, in the vicinity of a Permo-Carboniferous (PC) trough. Second, although the area is located in a low strain region, microseismicity is locally persistent over at least two decades of instrumental recordings and several felt earthquakes are documented in this region since 1661 AD with estimated Mw up to 3.9. The strongest instrumentally recorded earthquake was an Ml 3.2 strike-slip event in 1999. We performed a seismotectonic analysis to understand the occurrence of the Eglisau Seismicity Cluster (ESC), combining data of local monitoring stations operational since 2004 with template-matching detection, hierarchical cluster analysis, hypocenter relocation, and waveform modeling. The shallow focal depths result in complex waveforms that hamper the analysis and the downstream hypocenter location of these microearthquakes. To overcome this problem, a multi-method relocation procedure was developed to derive accurate and precise inter- and intra-cluster hypocenters to constrain the spatio-temporal characteristics of this seismicity. Results suggest that seismicity mostly locates within PC units on the NNW shoulder of the trough. Seismicity has persisted for over 21 years, forming several subclusters that indicate activity across multiple segments of two intersecting fault zones, imaged by 3D seismics, with critically stressed asperities. Focal mechanisms and slip tendencies suggest that the NW-SE striking Eglisau fault is favorably oriented for reactivation in the present-day stress field. Deviating orientations in the 1999 mechanism suggest local stress rotations in the intersection zone. Statistical analysis including occurrence patterns and interevent times points to a persistent internal loading driving the ESC. In line with the nearly uniform slip rates, we suggest fault creep as a possible mechanism loading small-scale asperities in the intersection zone. This study provides insights into fault-zone complexities and possible models explaining long-lasting seismic activity in low-strain regions by fault-creep processes.

*Speaker
†Corresponding author: tobias.diehl@sed.ethz.ch

Controls on the Maximum Magnitude of Fluid-Induced Earthquakes in Rate-and-State Asperity models

Pierre Dublanchet * [1], Martin Colledge [2], Louis De Barros [3], Frédéric Cappa [3]

[1] Mines Paris - PSL (École nationale supérieure des mines de Paris) – Université Paris sciences et lettres – France
[2] Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, IRD, Géoazur – Université Côte d'Azur, CNRS, IRD, Observatoire de la Côte d'Azur, Géoazur – France
[3] Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, IRD, Géoazur – Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, IRD – France

Earthquake swarms are commonly interpreted as the result of deep fluid overpressure re-equilibration or transient aseismic slip on tectonic faults, which bring critically stressed seismogenic asperities to failure. Quantifying the amount of fluid and aseismic slip involved, however, remains challenging. Studies of induced swarms in geoenergy reservoirs, together with recent hydromechanical experiments, have nevertheless provided new observations that have led to semi-empirical relationships between injected energy and radiated seismic energy. In particular, the dependence of the maximum earthquake magnitude on the total injected fluid volume, first highlighted by (McGarr, 1976; 2014), has received considerable attention. This relationship has opened new perspectives for seismic hazard mitigation and for estimating the fluid volumes involved during natural earthquake swarms. However, these empirical laws still fail to explain the full range of observations and point to the highly nonlinear hydromechanical response of faults to transient stress perturbations. Deeper insight can be gained through physics-based earthquake cycle models that incorporate poroelastic coupling and rate-and-state friction, allowing both aseismic slip and the spontaneous nucleation of earthquake ruptures along pre-existing faults.

Here we report a series of numerical injection experiments performed with such a model. Earthquakes spontaneously nucleate on a set of hierarchical velocity-weakening asperities embedded within a two-dimensional creeping planar fault, as a result of both direct pore-pressure increases and enhanced aseismic slip induced by injection. Whithin this framework, we explore a range of fault scenarios by varying the fault size, asperity distribution, and the initial stress state on the asperities. We also investigate different hydraulic injection protocols, ranging from controlled injection rate to controlled pore-pressure at injection site.

Our results show that the total moment released by the fault in response to fluid injection, including both seismic and aseismic contributions, evolves between two asymptotic regimes. At early times, the response is governed by slow slip on velocity-strengthening regions of the fault, where the direct frictional response balances the rate of pore-pressure increase. At later times,

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the total moment approaches a global steady-state response controlled by the pore-pressure increase and an effective stiffness of the fault. These asymptotic regimes depart from previous theoretical predictions, which do not account for the coupled seismic and aseismic response, spontaneous earthquake nucleation, or the possibility of multiple fault reactivations.

For a range of model parameters, we obtain maximum seismic moments and injected fluid volumes consistent with observations from both reservoirs and laboratory experiments. In general, the maximum seismic moment is controlled by the size and initial stress state of the largest asperity on the fault, in a manner consistent with fracture mechanics theory as described by (Galis et al., 2017). However, the fluid volume required to initiate rupture of this main event can vary by up to two orders of magnitude, depending on the injection scenario and on the stress distribution within both velocity-weakening and velocity-strengthening regions of the fault. This variability may explain the observed scatter in maximum magnitude–fluid volume scaling relations. Our results also suggest that fluid injection primarily governs the nucleation process but plays a secondary role in controlling the final rupture extent, which is largely determined by the pre-existing stress state along the fault. Consistently, comparison with dry simulations performed on similar faults shows that the magnitude–frequency distribution is only marginally affected by fluid injection for pore-pressure increases remain moderate relative to the ambient normal stress.

Overall, these numerical results provide a new framework for interpreting magnitude scaling relationships in both natural and induced seismicity.

Keywords: magnitude, injected volume, pore pressure, rate, and, state friction, nucleation

Seismic Moment Release Patterns and Stress Triggering in a Swarm-Dominated Fault System

Tomas Fischer * [1], Josef Vlček , Ali Masihi , Eva Káldy

[1] Charles University, Faculty of Science (CUNI) – Albertov 6, Prague, Czech Republic

For the last 35 years more than 10 earthquake swarms exceeding ML 3 occurred in the main focal zone of West-Bohemia/Vogtland, Central Europe. Each swarm activated a distinct part a complex, N-S oriented steeply dipping fault system with left-laterally slipping focal mechanisms in depths ranging from 5 to 13 km. While most clusters gradually filled the fault zone indicating a successive rupture growth, some of them overlapped and repeated activations occur.
We analyze the relocated seismic catalog of more than 30 000 events to better understand the regime of seismic moment release and interactions between different segments of the fault zone.

The clusters were first classified in terms of their swarm or mainshock-aftershock character using the timing of the mainshock, skewness of moment release and its autocorrelation along the fault plane. The fault segments hosting mainshock-aftershock sequences show strongly uneven seismic moment density compared to those hosting the swarms.

Seismic moment density and effective stress drop was evaluated along the focal zone to identify repeated activations of fault segments and gaps prone to failure.
Possible stress triggering of individual swarms was examined using spatial correlation between seismicity and Coulomb failure stress change due to the considered point sources of various source mechanisms.

Keywords: swarms, mainshock, aftershock, West Bohemia, coulomb, stress triggering, effective stress drop

*Speaker

How stress-dependent permeability and porosity decipher the development of a swarm sequence: Insights from numerical modeling of seismic swarms in northwestern Bohemia (Czech Republic)

Clara Fockenberg *† [1], Sandro Truttmann [2], Thomas Heinze [1]

[1] Ruhr University Bochum, 44801 Bochum – Germany
[2] Spektrum Geophysik AG, 4600 Olten – Switzerland

The city of Nový Kostel represents a prominent study site for investigating swarm seismicity, a phenomenon first described by Credner in 1900. Since 1997, several recurring swarm sequences have been monitored in the Nový Kostel region through a dense seismic network, with this study focusing on the sequences that occurred in 2008, 2011, 2014, 2017, and 2018. In general, these swarm events migrate from south to north, while also exhibiting seismic gap-filling behavior. For instance, the 2014 swarm occurred between the 2008 and 2011 sequences, whereas the 2018 event filled the gap between the 2011 and 2017 swarms. The results of our study aims to provide valuable insights into the relevance of fault geometry and heterogeneous hydraulic parameters for swarm propagation elsewhere and shape the next generation of three-dimensional physics-based swarm models.
Often fluid diffusion processes, which lead to pore pressure perturbations are associated with triggering swarm sequences. The Nový Kostel focal zone is characterized by mofettes and mineral springs that display isotopic signatures that indicate a mantle origin of the fluids. Observations of CO2 emission rates at the surface, i.e. mofettes, vary during swarm activity, further strengthening the hypothesis of fluid-driven swarm activity. These fluid diffusion processes are often modeled in the 2D or even 1D-domain. Considering that the orientation of the fault planes within the stress field are often the decisive factor if a fault (-patch) gets triggered by pore pressure perturbations, we implement a 3D-Model of the Nový Kostel fault zone that is coupled to the stress field. Since the swarm sequences in Nový Kostel occur at depths of 6 to 12 km and show no surface traces, knowledge on the fault geometry is sparse. Therefore, we use an updated version of the hypocenter-based 3D fault imaging method presented in Truttmann et al., 20231, 3D meshes of active faults were obtained from the seismic catalog. The resulting 3D geometry was then incorporated into COMSOL Multiphysics® for the simulation of the pore pressure evolution with dynamic permeability and porosity depending on pore pressure and the local stress field. With its three-dimensional design, this model is the first to reproduce the stress conditions in the Nový Kostel focal zone along the complex fault geometry, which is derived from the available seismic data, and to investigate its impact on the fluid pressure propagation. The physics-based simulations allow to assess the relevance of permeability/porosity variations

*Speaker
†Corresponding author: clara.fockenberg@rub.de

along the fault and the complex fault geometry in general on the pore pressure evolution. Future work will extend this model towards multi-component flow of uprising supercritical carbon dioxide and deep groundwater to investigate the dependence of pore pressure evolution on flow parametrization.

Reference: 1Truttmann, S., Diehl, T., & Herwegh, M. (2023). Hypocenter-based 3D imaging of active faults: Method and applications in the Southwestern Swiss Alps. Journal of Geophysical Research: Solid Earth, 128, e2023JB026352. https://doi.org/10.1029/2023JB026352

Keywords: Swarm seismicity, numerial modeling (FEM), 3D fault imaging, dynamic peremeability/porosity, pore pressure evolution

UNDERSTANDING EARTHQUAKE SWARMS FROM QUASI-STATIC DAMAGE PROCESS AND STRESS DIFFUSION

Jean-Luc Got * [1,2]

[1] Institut des sciences de la Terre (ISTerre) – CNRS : UMR5275, Université de Savoie – BP 53 38041 Grenoble cedex 9, France
[2] ISTerre – Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, IFSTTAR, ISTerre, 38000 Grenoble, France – France

An earthquake swarm is characterized by the occurrence of numerous earthquakes within a limited volume, without a strong mainshock. Seismic activity often increases and then decreases, a pattern that can be modeled using Omori laws (direct and inverse). The process is progressive, without dynamic instability.
A progressive failure is a damage process. Kachanov's (1958, 1986) original model of damage was based on studies of the tensile rupture of metal rods. It allows the progress of the failure process to be characterized by using a simple damage parameter D, defined as the ratio of the damaged (ruptured) area to the area to be ruptured. Kachanov also defined continuity as ψ = 1–D.

Considering that the solid is in equilibrium under the effect of the applied force F = σS (where σ is the stress applied over S) and the solid's reaction σS, it can easily be shown that $\sigma = \sigma/\psi$. σ is Kachanov's effective stress, actually applied to the remaining, undamaged surface. This stress increases as the undamaged surface area decreases, if the material's strength is sufficient; it thus describes the progressive transfer of stress to the undamaged surface.

The solid is not really in equilibrium since it deforms slowly; this is therefore a quasi-static deformation. We must therefore introduce time during this stress transfer to account for its dynamics, using for example Charles's law (1958): tf/tf0 = (σ/ σ)-α , where tf and tf0 are the times to failure for applied stresses σ and σ.

Considering that the time to failure can be estimated as the average time between two failures, and that the stress inducing earthquakes is the effective Kachanov stress applied to undamaged surfaces, Charles's law can be written as n(t)/n = (1/ψ)α; n(t), n0 : earthquake rates at σ and σ.

Since continuity depends on the already damaged surface - that is, on the number of earthquakes that have already occurred, N(t) - this relationship allows us to derive an earthquake production law that takes the form of a differential equation in N(t). We will see that the solution to this equation yields the inverse Omori law, or the inverse Omori-Utsu law, depending

*Speaker

on crack interaction intensity.

This simple reasoning allows us to identify some of the conditions that must be met for this law to hold true. The first condition is that the process must be quasi-static. For this condition to be met, the action (applied stress) must remain close to the reaction (rock strength) throughout the process. This is particularly true when the deformation process is post-peak: in this case, the applied stress must decrease with strain, just as the rock strength does. This condition is possible in a displacement- or rate-controlled triaxial compression test. It is also possible when the applied stress is due to fluid pressure applied within rock fractures: in this case, as the fracture volume increases after each failure, the pressure decreases if the time constant controlling the fluid transfer is not very small. This more generally occurs when the rate at which the applied stress decreases with strain is at least as rapid as the rate at which the rock's post-peak strength decreases. In the opposite case, dynamic instability and a stronger shock may occur. We will discuss this reasoning, using examples taken from the seismicity of basaltic volcanoes, from local hydromechanical systems and from rock mechanics experiments.

Keywords: Earthquake swarms, damage process, stress diffusion, fluid, structure interaction, hydraulic fracturing

Identifying seismic swarms around Utah FORGE – a comprehensive overview from 2016 - 2026

Elisabeth Glück *† [1], Katherine Whidden [1], Marius Isken [2], Kristine Pankow [1]

[1] University of Utah Seismograph Station – United States
[2] German Research Centre for Geosciences - Helmholtz-Centre Potsdam – Germany

The Utah FORGE (Frontier Observatory for Research in Geothermal Energy) is a field-scale laboratory with the goal to enhance our knowledge on how to utilize hot, dry rock for geothermal energy production, which may act as one of the base-load capable components contributing towards the clean energy transition. To transport heat from the underground to the surface, fluids circulate though the reservoir. Considering the low permeability of granite at the targeted depth of _˜3km, it is necessary to create fluid pathways through hydraulic stimulation. This process may involve the opening of new fractures or re-activation of existing ones, potentially inducing seismicity. In addition to the anthropogenic events, there is also a record of natural seismic swarms mostly west of the Utah FORGE associated with the Mineral Mountains.
To better understand where and when stimulation induces seismicity and what role natural seismicity plays in this geological setting, it is essential to have a comprehensive overview of the seismic activity and potential structures in the larger area. Utah FORGE provides a seismic dataset that includes recordings from a permanent network first emplaced in 2016 and continuously expanded since, multiple temporary nodal arrays, and downhole geophone chains. Using this extensive database, we utilize machine learning models to create a continuous enhanced event catalogue ($>$ 50.000 events) for the Milford valley. To clean the catalogue from false detections and to identify different swarms, natural and induced, we roughly cluster the events according to their location. In a second step we investigate the similarity of the event waveforms within those clusters, allowing a further division into sub-clusters that point towards different seismic sources. Our analysis identifies swarms coincident with EGS activities and swarms previously identified as well as new swarm source zones. Comparing the temporal and spatial evolution between swarms both associated and un-associated with anthropogenic activity provides insights into the role of fluids in swarm zones.

Keywords: geothermal, swarms, fluids

*Speaker
†Corresponding author: elisabeth.gluck@utah.edu

Strain Deformation-Driven Cascades Explains Volcanic Earthquake Swarms

Cataldo Godano * [1], Vincenzo Convertito [2], Anna Tramelli [2], Umberto Tammaro [2], Valentina Bruno [3], Giuseppe Petrillo [4]

[1] Depertment of mathematics and physics-Università della Campania – Italy
[2] INGV-Osservatorio Vesuviano – Italy
[3] INGV-Osservatorio Etneo – Italy
[4] Earth Observatory of Singapore – Nanyang Technological University, Singapore

Volcanic earthquake swarms are among the most enigmatic precursors of eruptions, often reflecting the interplay between deformation, fluid migration, and fault activation. Yet, a unifying quantitative law linking deformation to swarm productivity has remained elusive.
Here we show that, across six active volcanic systems worldwide, the cumulative number of earthquakes grows as a double-exponential function of ground deformation, revealing a universal deformation-driven scaling. This relationship naturally emerges from an epidemic-type model in which the triggering efficiency is modulated by deformation and limited by saturation effects. The model reproduces the observed behaviour across volcanic environments ranging from fluid-driven calderas to rift-related volcanoes.
The fitted parameters constrain the relative roles of elastic loading and plastic dissipation, suggesting that swarm evolution results from the competition between strain accumulation and relaxation in a disordered, velocity-strengthening medium. These findings identify a universal physical mechanism underlying swarm generation and provide a predictive framework for linking ground deformation to seismic hazard at active volcanoes.

Keywords: Number of earthquake and ground deformation, Epidemic model, Disordered medium, Plastic deformation

*Speaker

Optimized 4D DBSCAN Declustering for Seismic Catalog Analysis: Application to Southern California QTM Catalogue

Eloise Granier * [1], Agnès Helmstetter† [2], Maxime Godano‡ [3], Christian Sue§ [4]

[1] Institut des Sciences de la Terre (ISTerre) – Institut de Recherche pour le Développement, Institut National des Sciences de l'Univers, Université Savoie Mont Blanc, Centre National de la Recherche Scientifique, Université Gustave Eiffel, observatoire des sciences de l'univers de Grenoble, Université Grenoble Alpes – France

[2] Institut des Sciences de la Terre – Centre National de la Recherche Scientifique, Université Grenoble Alpes – France

[3] Géoazur – Institut National des Sciences de l'Univers, Observatoire de la Cote d'Azur, Université Côte d'Azur, Centre National de la Recherche Scientifique, Institut de Recherche pour le Développement – France

[4] Institut des Sciences de la Terre – Institut de Recherche pour le Développement, Institut National des Sciences de l'Univers, Université Savoie Mont Blanc, Centre National de la Recherche Scientifique, Université Gustave Eiffel, observatoire des sciences de l'univers de Grenoble, Université Grenoble Alpes – France

Distinguishing background seismicity from clustered sequences (aftershocks and swarms) is essential for seismic hazard assessment and for understanding earthquake triggering mechanisms. Traditional declustering methods often rely on predefined temporal and spatial windows or model-dependent approaches (e.g. ETAS), which may not capture the full complexity of seismic clustering, particularly in heterogeneous catalogs.
We present a novel approach using 4D DBSCAN (Density-Based Spatial Clustering of Applications with Noise) extended to spatio-temporal dimensions (longitude, latitude, depth, time) to decluster the QTM (Quake Template Matching) catalog for Southern California. Unlike previous DBSCAN applications limited to spatial dimensions, our method incorporates temporal evolution by converting time to equivalent spatial distance through a weighting parameter, enabling simultaneous clustering in space and time.

The main challenge lies in optimizing three critical parameters: spatial radius ϵ, minimum cluster size, and temporal weight. To objectively identify optimal parameters, we impose two selection criterion based on two complementary objectives: maximizing the number of background events while ensuring their temporal randomness. The optimal parameter set is selected by maximizing background events among combinations that have a probability $p > 0.05$ of obeying a Poisson Process, using a KS test for 3 different hypothesis : uniform distribution of times, exponential distribution of inter-event times, and Poisson distribution of number of events per

*Speaker

†Corresponding author: agnes.helmstetter@univ-grenoble-alpes.fr

‡Corresponding author: godano@geoazur.unice.fr

§Corresponding author: christian.sue@univ-grenoble-alpes.fr

time interval 15 days.

Preliminary results demonstrate that this method effectively separates background seismicity from sequences, with typical optimal parameters yielding 60-70% background events. This approach successfully identifies both compact aftershock sequences and spatially extensive earthquake swarms. Compared to standard temporal window methods, our approach better captures sequences with complex spatio-temporal evolution, such as migrating swarms.

This methodology provides an objective, data-driven framework for catalog declustering applicable to any seismic region, with direct implications for improved seismic hazard models and better understanding of earthquake triggering processes. Future work will extend this approach to longer time periods and compare results with traditional declustering methods (Reasenberg, nearest-neigbhours) to assess performance across different tectonic settings.

Keywords: Seismic declustering, Background seismicity, Earthquake clustering, DBSCAN algorithm, Spatio, temporal clustering, Southern California.

From Seismic Sequences to Swarms and Aftershocks: Properties of Western Alps Seismicity

Eloise Granier * [1], Agnès Helmstetter† [2], Maxime Godano‡ [3], Christian Sue§ [4]

[1] Institut des Sciences de la Terre (ISTerre) – Institut de Recherche pour le Développement, Institut National des Sciences de l'Univers, Université Savoie Mont Blanc, Centre National de la Recherche Scientifique, Université Gustave Eiffel, observatoire des sciences de l'univers de Grenoble, Université Grenoble Alpes – France

[2] Institut des Sciences de la Terre – Centre National de la Recherche Scientifique, Université Grenoble Alpes – France

[3] Géoazur – Institut National des Sciences de l'Univers, Observatoire de la Cote d'Azur, Université Côte d'Azur, Centre National de la Recherche Scientifique, Institut de Recherche pour le Développement – France

[4] Institut des Sciences de la Terre – Institut de Recherche pour le Développement, Institut National des Sciences de l'Univers, Université Savoie Mont Blanc, Centre National de la Recherche Scientifique, Université Gustave Eiffel, observatoire des sciences de l'univers de Grenoble, Université Grenoble Alpes – France

Seismicity in the Western Alps is distributed as isolated events, aftershock sequences following mainshocks, and earthquake swarms without an identifiable main event.
While aftershocks are well-documented as triggered events following mainshock-induced stress redistribution, swarms exhibit distinct behavior characterized by continuous activity without a clear mainshock, progressive hypocenter migration, and prolonged duration ranging from days to years.

The triggering mechanisms of swarms remain debated, with proposed explanations including deep fluid transfer, slow slip episodes, or a combination of both processes.

This study analyzes significant seismic sequences (> 20 events) in the Western Alps from an alpine catalogue declustered using the DBSCAN algorithm adapted 4D (latitude, longitude, depth, and time). Through collective expert evaluation based on temporal evolution, magnitude distribution, and spatial characteristics, we classified sequences into swarms (70%) and aftershock sequences (30%).

Using statistical analysis of more than 30 parameters combined with bootstrap resampling, we identified significant discriminators between these two types of sequences. Our results reveal fundamental differences: aftershock sequences show higher mainshock magnitudes (median 2.7

*Speaker

†Corresponding author: agnes.helmstetter@univ-grenoble-alpes.fr

‡Corresponding author: godano@geoazur.unice.fr

§Corresponding author: christian.sue@univ-grenoble-alpes.fr

vs 2.2), clearer Bath's law signatures (ΔM=0.75 vs 0.57), and faster temporal decay following Omori's law (p≈1 vs p≈0.5). Swarms exhibit larger spatial extent (1.6 vs 1.3 km), higher cluster-to-rupture ratios (12 vs 6) (ratio between the spatial extent of the cluster to the expected rupture length for the mainshock magnitude, after Wells & Coppersmith 1994), longer durations (816 vs 468 hours), and higher pre-to-post mainshock event ratios (1.1 vs 0.4).

The Gutenberg-Richter transition magnitude Mt (completeness threshold of the catalog) is lower for swarms (2.5 vs 3.7), consistent with fluid-driven triggering models.

Focal mechanism analysis shows predominance of normal faulting in swarms with respect to aftershocks (34.6% vs 24.7%), correlating with extensional domains along the Briançonnais and Piedmont arcs.

Together, these results establish a robust statistical and physical framework for distinguishing swarms from aftershock sequences in the Western Alps.

Keywords: Western Alps, Earthquake, swarms, Aftershock sequences, Seismic clustering, DBSCAN clustering.

A deformation-driven earthquake interaction model for seismicity at Campi Flegrei

Sebastian Hainzl *† [1], Torsten Dahm *

[1], Anna Tramelli *

[2]

[1] German Research Centre for Geosciences - Helmholtz-Centre Potsdam – Germany
[2] INGV-Osservatorio Vesuviano – Italy

Since 2005, the Campi Flegrei nested caldera volcano, located about 10 km west of Naples, Italy, has experienced accelerating uplift accompanied by increased seismicity, raising concerns in this densely populated area. This ongoing uplift is part of a millennium-long history of inflation-deflation cycles, in which seismicity correlates with uplift phases, albeit nonlinearly. Here, we show that the combination of stress shadowing and loading with frictional fault behavior reproduces the observed long-term seismicity trend. However, in the short term, earthquake clustering occurs, which we demonstrate is at least partly related to earthquake interactions and can be effectively modeled by overlapping aftershock sequences. Merging the long- and short-term approaches yields a combined model that effectively replicates the observed seismicity patterns. A pseudo-prospective test shows that the model can also provide probabilistic short-term forecasts of earthquake rates and maximum magnitudes on weekly to monthly time horizons.

Keywords: seismicity model, earthquake swarms

*Speaker
†Corresponding author: hainzl@gfz.de

High-resolution seismicity and fluid-driven swarm dynamics in the Kleifarvatn–Krýsuvík hydrothermal system (Reykjanes Peninsula, Iceland)

Sonia Heuninck * [1,2], Laurent Geoffroy [1,2], Julie Perrot [1,2], Thibaut Barreyre [1,2], Egill Arni Gudnason [3]

[1] Institut Universitaire Européen de la Mer – CNRS : UMR6538, Université de Bretagne Occidentale (UBO) – France
[2] Geo-Ocean – Université de Brest, Centre National de la Recherche Scientifique – France
[3] Iceland GeoSurvey – Iceland

The onshore segment of the Mid-Atlantic Ridge in southwest Iceland forms the actively extending Reykjanes Peninsula, a region characterized by intense seismicity, active volcanism, and high-temperature geothermal systems. In the Krýsuvík geothermal area, deformation is partly accommodated by a network of N–S oriented strike-slip faults associated with peninsula-scale "bookshelf faulting". The interaction between tectonic deformation, magmatic processes, and hydrothermal circulation creates a dynamic crustal environment in which permeability and fluid pathways may evolve in response to transient phenomena such as earthquakes or magmatic intrusions.
This study focuses on the relation between crustal fluid flow and deformation along the Kleifarvatn–Krýsuvík volcano-tectonic segment. Kleifarvatn is an endorheic lake located within the Krýsuvík geothermal area whose hydrological and hydrothermal activity are highly sensitive to variations in crustal permeability. The southern part of the lake hosts at least two major hydrothermal vent areas that proved to be located over episodic seismic swarms at depth. To investigate the relationship between microseismicity, tectonic deformation and fluid circulation, a dense temporary seismic network composed of 12 land stations and two ocean-bottom seismometers (OBS) was deployed around and within the lake.

Seismic data recorded between spring 2025 and winter 2026 were processed using an automated workflow designed to detect and locate low-magnitude earthquakes within swarm-like seismic sequences. Phase arrivals were first identified using the deep-learning phase picker PhaseNet, then probabilistically associated into earthquake events using the GaMMA algorithm. The resulting catalogue was subsequently refined through iterative velocity-model optimization and earthquake relocation using VELEST. This processing strategy yields a high-resolution microseismic catalogue for the Kleifarvatn–Krýsuvík area. During the July 2025 seismic crisis, we detected more than a thousand earthquakes, increasing the number of events compared with routine regional catalogues. This catalogue was mixed with that of stations within our network hold by other groups working in the area in the framework of a collaborative work.

*Speaker

This new catalogue provides an unprecedented view of microseismic activity in the Kleifarvatn–Krýsuvík hydrothermal system and offers a unique opportunity to investigate the mechanisms controlling swarm dynamics. In particular, it enables us to investigate whether seismic swarm activity is primarily governed by fluid-pressure diffusion, fracture reactivation within the fault network, or transient tectonic stress perturbations associated with the evolving kinematics and current volcanism of the Reykjanes Peninsula.

Keywords: microseismicity, hydrothermal fluid, Rekjanes peninsula, Earthquake catalogue

Correlation between in-Situ Vp/Vs and b-value Reveals Temporal and Fine-Scale Spatial Variability in Fault-Controlled Seismic Swarms

Stephen Hicks *† [1], Chao Li [1,2], Ana Ferreira

[1] University College, London – United Kingdom
[2] Nanjing University – China

During seismic swarms, temporally varying b-values of the Gutenberg–Richter frequency–magnitude relation are widely used as an indicator of changing stress state and/or fluid conditions in the crust. However, there is typically little direct evidence linking *b*-values to changes in pore pressures and permeabilities. Vp/Vs ratios provide insight into pore-fluid pressure and crack properties; however, traditional tomographic approaches lack the resolution to image Vp/Vs directly at the seismogenic source and are poorly suited to resolving temporal changes. In this study, we use a novel differential travel-time method to measure in-situ (i.e., at-source) Vp/Vs variations without requiring a formal tomographic inversion. We apply this in-situ Vp/Vs approach to a seismic swarm triggered by a magmatic dike intruding a crustal fault zone beneath the island of São Jorge in the Azores archipelago. We utilise a high-precision earthquake catalogue comprising _˜18,000 events, relocated with relative depth uncertainties typically < 40 m, recorded by _˜80 seismic stations including ocean-bottom seismometers. We compute time-dependent changes in Vp/Vs for individual clusters and find strong spatial variability, ranging from _˜1.7 to _˜2.0 over distances of just a few hundred metres.

For many clusters, we observe a strong positive correlation between b-value (computed with the robust b-positive method) and Vp/Vs, with both increasing at the onset of the seismic swarm. In some clusters, seismicity ceases when Vp/Vs reaches very high values (_˜2.1), suggesting feedback between permeability evolution and brittle failure.
Integrating in-situ Vp/Vs imaging with b-value analysis, therefore, provides a powerful framework for identifying zones of elevated fracture density and fluid accumulation in the crust. These findings have implications for the mechanisms driving seismic swarms and for understanding permeability variations in fault damage zones.

*Speaker
†Corresponding author: stephen.hicks@ucl.ac.uk

Tectonic, volcanic and anthropogenic swarm activity at Hengill volcano, Iceland

Vala Hjorleifsdottir * [1]

[1] Reykjavík University – Iceland

The volcano Hengill lies at a plate-boundary triple junction approximately 30 km from Reykjavík, Iceland. Two large geothermal power plants operate on its flank, together providing nearly 20% of Iceland's electricity and about 40% of the hot water used for district heating in the capital area. Intense geothermal operations involve more than 100 production wells and about 15 deep injection wells that together receive more than 1000 l/s of geothermal fluid, including wells that are also used for CO2 mineralization.
The combined effects of tectonic, volcanic and anthropogenic stresses results in intense seismicity that is highly clustered in space, and in some regions in time. In the late 1990s a deep volcanic intrusion caused very high seismicity rates in the volcano. While geothermal operations in the 90s did not induce substantial seismicity, the commission of a new injection field in 2011 resulted in intense seismicity with two events reaching M 4.4, causing public concern.

The seismicity in the area is monitored by the Iceland Meteorological Office, the national monitoring agency, and by Iceland Geosurvey on behalf of the geothermal operatorON Power. In addition, several research initiatives - including DEEPEN, Carbfix2, S4CE, COSEISMIQ, and SUCCEED - have deployed temporary seismic networks in the area to investigate both natural and induced seismicity.

In this presentation, I summarize key observations from more than three decades of seismic monitoring at Hengill and discuss how tectonic, volcanic, and anthropogenic processes interact to generate distinct types of earthquake swarms in this complex system.

Keywords: induced seismicity, geothermal, Hengill, volcano, Iceland

*Speaker

Understanding the nature of fluid migration in the Noto earthquake swarm region through in-situ Vp/Vs ratio analysis

Yihe Huang * [1], Keisuke Yoshida [2], Aitaro Kato [3], Satoshi Ide [4]

[1] Université du Michigan = University of Michigan [Ann Arbor] – United States
[2] Tohoku University – Japan
[3] Earthquake Research Institute, University of Tokyo – Japan
[4] Department of Earth and Planetary Science, The University of Tokyo – Japan

The interaction between fluids and fault rocks can lead to fault instability and swarms of earthquakes, resulting in elevated seismic hazards. The 2024 Mw 7.5 Noto mainshock exemplifies how earthquake swarms can evolve into a damaging large earthquake. The Noto earthquake swarms are thought to be driven by a deep fluid source associated with a nearby magma system; however, the nature of fluid migration in the fault network and their contribution to the development of swarms remain unclear.
Here, we analyze clusters of earthquake swarms through their spatiotemporal evolution and associated in-situ Vp/Vs ratios. We apply the HDBSCAN algorithm to cluster earthquakes both spatially and temporally and then estimate the in-situ Vp/Vs ratio of each earthquake cluster using a waveform cross-correlation based approach. We find that the spatial distribution of in-situ Vp/Vs ratios is highly heterogeneous but is primarily controlled by the locations of earthquake clusters. Within each earthquake cluster, the Vp/Vs ratios show a weak temporal dependence, mostly with a change of less than 0.1 after the 2023 Mw 6.2 Noto earthquake.
Our results suggest that, instead of fluid migration along faults from a single fluid source, the Noto fault system is likely saturated with fluids before the 2023 Mw 6.2 Noto earthquake. Fault rock deformation associated with earthquakes and aseismic slip has driven multiple episodes of fluid migration along faults, which redistributed stresses in the fault system and eventually contributed to the nucleation of the 2024 Mw 7.5 Noto mainshock.

Keywords: Noto earthquake, fluid migration, rock deformation, Vp/Vs ratio analysis

*Speaker

Mining volcanic swarm data for improved eruption forecasting, with application to the 2025 Santorini seismic crisis

Pesicek Jeremy * [1], Stephanie Prejean [1]

[1] United States Geological Survey – United States

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Volcanic swarm analysis is a critical task for volcano observatories yet inferring the physical processes driving a swarm near a volcano can be difficult. Observatories need strategies to rapidly assess the likelihood that a new swarm may lead to eruption. Typically, the significance of a new swarm is assessed in comparison to prior similar swarms at that volcano. This approach, although often qualitative, has been successful at many volcanoes. Unfortunately, at volcanoes with low background seismicity rates, short monitoring histories, or with rare swarm occurrence, such comparisons become limited. However, the increasing quality and availability of volcanic earthquake catalogs makes rapid quantitative comparisons to other analogous volcanoes more feasible. Despite variations in monitoring networks and crustal conditions, certain swarm attributes can be meaningfully compared across regions if they are computed in consistent ways. For example, the b-value and moment skew of swarms can be directly compared around the world. In addition, sometimes the feature of interest within a new swarm can be used to directly define the search for analogous seismicity within global earthquake catalogs, bypassing the need for swarms to be predefined. For example, hypocenter migration can be detected at volcanoes using catalogs of earthquakes rather than catalogs of swarms.

We apply both approaches to gain insight into swarm behavior at volcanoes. First, we built

*Speaker

a growing database of > 200 volcanic swarms for all U.S. volcanoes, including > 50 that are associated with eruptions. For each swarm, we compute a variety of attributes that allow us to consistently track swarm evolution, compare between swarms, and assess the likelihood of eruption based on past analogous swarms. For searches beyond our U.S. swarm database, we search publicly available earthquake catalogs for features of interest and define matching swarms where the feature is present. Comparative analyses of swarm attributes derived from these methods, when coupled with eruption timing data, have already proven useful in several forecasting scenarios. We highlight several examples of these analyses, the most recent of which pertains to the extraordinary seismic crisis at Santorini in early 2025.

To expand on these efforts, we are building an open access database to house user-defined swarms at volcanoes and to facilitate analog searches. Any attribute can be consistently computed for defined swarms, allowing quick winnowing and analysis of desired sub-populations of swarms. As with existing earthquake catalogs, the swarm catalog could serve as reference database for direct analysis, or as a starting place for more detailed analyses derived from the raw seismic data. We illustrate the uses and benefits of such a database and solicit community feedback and engagement in its development.

Keywords: santorini, forecasting

Stress state around Copiapó SSE 2023 inferred from focal mechanisms of accompanying seismic swarms

Tatiana Kartseva * [1], Jannes Münchmeyer [2], Blandine Gardonio [1], Agnès Helmstetter [1], David Marsan [1], Anne Socquet [1], Diego Molina [1]

[1] Institut des Sciences de la Terre – Institut de Recherche pour le Développement, Institut National des Sciences de l'Univers, Université Savoie Mont Blanc, Centre National de la Recherche Scientifique, Université Gustave Eiffel, observatoire des sciences de l'univers de Grenoble, Université Grenoble Alpes – France

[2] German Research Centre for Geosciences - Helmholtz-Centre Potsdam – Germany

The 2023 shallow slow slip event (SSE) offshore Copiapó, Chile, was accompanied by intense swarm-like seismicity localized near the subducted Copiapó ridge. Previous observations showed migrating earthquake clusters along the plate interface, interpreted as driven by fluid overpressure and transient fault weakening. However, the associated stress evolution remains unresolved. In this study, we use a newly compiled catalog of earthquake focal mechanisms, including both interface and intraslab events, to investigate temporal stress variations across the SSE cycle. Using stress inversion, we investigate temporal variations in stress orientation and stress ratio as proxies for possible fluid pressure changes. Previous studies suggest that stress ratio variations track fluid pressure accumulation and release during slow slip cycles. This study aims to provide preliminary insights into the relationship between fluids, stress variations, and swarm activity in this subduction zone.

Keywords: Slow slip event, subducting ridge, stress tensor inversion, focal mechanisms, seismic swarm

*Speaker

From swarms to tremors: depth-dependent controls on aseismic slip along the Central Range Fault, Taiwan

Chen Kate *† [1], Wei Peng [1]

[1] National Taiwan Normal University – Taiwan

Tectonic tremors, earthquake swarms, and repeating earthquakes (REs) represent distinct manifestations of aseismic slip, often influenced by stress state, lithology, and fluid conditions. In Taiwan's active collision-subduction transition zone, these phenomena co-occur along the Central Range Fault (CRF), offering a rare opportunity to examine their depth-dependent behavior and fluid sensitivity. Using continuous seismic data from 2012 to 2022, we detected five tremor clusters spanning a 200 km distance along the orogenic belt. All clusters lie above the Moho and exhibit thrust-dominant mechanisms. Amplitude–duration analysis shows exponential scaling of tremor signals, consistent with localized fluid driven processes rather than cascading rupture. In the northern Longitudinal Valley of eastern Taiwan, swarms (

Keywords: Tectonic tremors, earthquake swarms, and repeating earthquakes, aseismic slip, Central Range, Taiwan

*Speaker

†Corresponding author: katepili@gmail.com

Climate-change-induced seismicity: The recent onset of seasonal microseismicity at the Grandes Jorasses, Mont Blanc Massif, France/Italy

Toni Kraft * [1], Verena Simon [1], Toledo Tania [1], Helmstetter Agnes [2], Jean-Christoph Marechal [3], Tobias Diehl [1]

[1] Swiss Seismological Service [ETH Zurich] – Switzerland
[2] ISTerre, CNRS, Université Grenoble Alpes – ISTerre, CNRS, Université Grenoble Alpes, CR1 Univ. Gustave Eiffel, 38058 Grenoble – France
[3] Bureau de Recherches Géologiques et Minières – Direction Eau Environnement Processus et Analyses – France

Modelling studies indicate that the geosphere can dynamically respond to climate change, increasing geological and geomorphological hazards. One such hazard is climate-driven seismicity due to hydrological changes, though observational evidence supporting this phenomenon remains scarce. We present the first dataset linking climate-change-induced snow/glacier melt to increased seismic hazard. Using a template-matching-enhanced catalogue (2006–2025), we analyse the ongoing Grandes Jorasses Earthquake Sequence (GJES, Mont Blanc Massif, France/Italy; ML≤3.1), which exhibits a sudden onset of strong annual periodicity in fall 2015. Our relocations identify seismicity along a major fault zone outcropping in the Mont Blanc Tunnel, where runoff and isotope data suggest that inflow is dominated by young surface meltwater. Modelling meltwater infiltration with a 1D-hydraulic diffusion constrained by the S2M meteorological snowpack model confirms that most of the GJES seismicity can be meltwater-induced. Additionally, our statistical analysis reveals a migratory seismicity component, hosting the largest events. While initially triggered by seasonal meltwater, this component expands primarily via a tectonic mechanism affected by aseismic slip. We attribute the onset of increased and periodic seismicity in 2015 to intensified climate-change-driven heat waves affecting the Mont Blanc Massif's high-altitude cryosphere. Retreating permafrost and glaciers alter meltwater-infiltration pathways, inducing pore-pressure changes that trigger seismicity in new source areas. During peak meltwater-driven seismicity, the seismic hazard levels can rise by two orders of magnitude compared to pre-2015 levels. Our findings suggest that climate change can significantly elevate the local seismic hazard in alpine regions. This phenomenon may affect other glaciated areas globally, highlighting the need for improved seismic risk assessment for impacted alpine communities.

In this presentation, we introduce the latest template-matching-enhanced catalogue (2007–present) of the GJES and present our approach to forecasting seismic activity based on meteorological indicators.

*Speaker

Keywords: Climate, driven seismicity, Snow and glacier melt, Hydrological triggering, Alpine seismic hazard, Seismicity Forcasting

Automated Identification and Classification of Swarm-like Seismicity in West Bohemia (1991–2026)

Eva Káldy * [1], Tomáš Fischer [1], Ali Masihi [1], Josef Vlček [1]

[1] Institute of Hydrogeology, Engineering Geology and Applied Geophysics; Faculty of Science, Charles University – Czech Republic

The West Bohemia/Vogtland region is one of the most active intracontinental earthquake swarm areas in Europe and provides a unique long-term dataset for studying swarm dynamics. However, the seismic catalog spanning 1991–2026 is heterogeneous in the magnitude of completeness, including changes occurring even within individual swarm episodes. This poses challenges for systematic identification and classification of earthquake clusters.
We apply the density-based clustering algorithm HDBSCAN (Campello et al., 2013, 2015) to automatically identify seismic clusters in a four-dimensional space–time framework. To distinguish between swarm-like and mainshock–aftershock behavior, we adopt the approach of Zhang & Shearer (2016), which uses the normalized timing of the largest event (*tm*) and the skewness of moment release (*μ3*). Particular attention is given to adapting this method to an inconsistent catalog by accounting for variable magnitude of completeness and evaluating how this variability influences cluster statistics and classification.

We investigate how the choice of threshold values for *tm* and *μ3* affects the separation between swarm and mainshock–aftershock sequences and explore strategies for validating these limits. The automated classification is compared with detailed studies of individual sequences, such as the 2018 activity analyzed by Bachura et al. (2021), allowing us to assess the performance of automated methods relative to more manual swarm analysis.
Finally, we examine whether large clusters identified by HDBSCAN consist of multiple sub-clusters with distinct temporal evolution. Two clustering parameterizations-optimized for detecting large clusters and smaller sub-clusters-are to evaluate how hierarchical swarm structure influences sequence classification and how it resonates with the interpretation of the underlying physical processes.

Keywords: Swarm vs. mainshock–aftershock classification, West Bohemia / Vogtland seismicity, Long, term seismic catalog analysis, HDBSCAN, Space–time clustering of earthquakes

*Speaker

Repeating earthquakes reveal fluid-driven aseismic slip during a fault stimulation experiment at BedrettoLab

Aurora Lambiase * [1], Men-Andrin Meier [1], Elena Spagnuolo [2], Mehdi Nikkhoo [3], Marsan David [4], Antonio Pio Rinaldi [1], Valentin Gischig [1], Massimo Cocco [2], Domenico Giardini [5], Stefan Wiemer [1]

[1] Swiss Seismological Service [ETH Zurich] – Switzerland
[2] Istituto Nazionale di Geofisica e Vulcanologia - Sezione di Roma – Italy
[3] German Research Centre for Geosciences - Helmholtz-Centre Potsdam – Germany
[4] Université Savoie Mont Blanc – Université Savoie Mont Blanc, Université Grenoble Alpes, CNRS, IRD, IFFSTAR, ISTERRE, Chambéry – France
[5] Institute of Geophysics [ETH Zürich] – Switzerland

Swarm seismicity is commonly interpreted as the manifestation of fluid intrusions, aseismic slip, or a combination of both (i.e., fluid-triggered aseismic slip). However, distinguishing which process dominates in natural settings remains challenging, largely because in-situ observations are typically limited to earthquake source parameters, with little or no direct measurements of near-fault deformation.
Here, we present results from the 'FEAR1' experiment conducted at the Bedretto Underground Laboratory for Geosciences and Geoenergies (Switzerland), where we used fluid injections to activate a natural fault and fracture network in crystalline rock under in-situ stress conditions at _˜1 km depth. This experimental setting is particularly well suited to investigate induced seismicity and the role of aseismic processes in fault activation, thanks to dense near- and on-fault strain, pressure, and seismic monitoring.

During several injections performed in FEAR1, we observed the activation of a steeply dipping, highly permeable fracture zone, which intersects a densely instrumented borehole. Hydraulic stimulations triggered seismicity ($-4.9 < \text{Mw} < -2.3$) that organized along a plane whose orientation is consistent with geological observations in boreholes cores, logs and on the laboratory tunnel wall. Simultaneously, high-resolution Fiber Bragg Grating strain measurements revealed progressive, irreversible tensile deformation localized near the fracture intersection with the monitoring borehole, reaching nearly 1000 $\mu\epsilon$ over the course of the experiment.

Static elastic modeling demonstrates that the cumulative strain produced by the recorded earthquakes accounts for less than 1% of the observed deformation, indicating that fault slip was dominantly aseismic. The spatial and temporal evolution of seismicity shows systematic up-dip migration toward the strain concentration zone and the emergence of families of repeating earthquakes. The recurrence rate and cumulative slip of these repeaters correlate with the measured strain rate and strain, suggesting a scenario where seismic asperities are embedded within a

*Speaker

creeping fault segment sustained by pore pressure stress perturbations.

Inversions of irreversible strain for simplified slip sources indicate a predominantly strike-slip mechanism consistent with the estimated local stress field. However, trade-offs between source location, source dimension and slip direction highlight the limits of 1D strain observations. Our results provide direct experimental evidence for fluid-driven aseismic slip on a natural fault and demonstrate how microseismicity and repeaters can serve as indirect proxies for underlying slow deformation.

Origin of swarm-like seismicity at Hengill volcano, SW Iceland.

Franck Latallerie *† [1], Vala Hjörleifsdóttir [1], Marius Isken [2], Ettore Biondi [3], Peidong Shi [4], Anne Obermann [5]

[1] Reykjavik University – Iceland
[2] GFZ-Potsdam – Germany
[3] Stanford University – United States
[4] Cardiff University – United Kingdom
[5] ETH Zurich – Switzerland

There are several active volcanic systems in SW Iceland, of which four are used for power production, together producing about 20% of Iceland's electricity and providing 80% of the population with district heating.
The volcano Hengill, to the east of Reykjavík, has two major geothermal stations (Nesjavellir & Hellisheii). Seismicity in the area appears to be highly clustered, with activity in the form of earthquakes swarms. Intermittent seismic activity has been observed to the west at Mosfellsheii, but the origin for this seismicity is unclear. In this project, we aim to clarify the possible role of geothermal fluids, and thus to inform on the potential of the area for geothermal energy production.
We use data from the recent two large seismic deployments; DEEPEN and COSEISMIQ. We implement the double-difference method on P- & S-wave travel times from local earthquakes to estimate Vp/Vs ratios local to clusters of earthquakes. These ratios are heavily perturbed by the presence of fluids and estimating them can thus shed new light on the origin of the clusters of seismicity at Hengill, and more particularly, on the seismic swarms at Mosfellsheii.

Keywords: Geothermal energy, Vp/Vs ratios, Iceland, Hengill volcano, Double, differences, Body, waves, Local earthquakes

*Speaker
†Corresponding author: Franckl@ru.is

Longlasting and slowly migrating midcrustal earthquake swarms across the Rhenish Massif, Germany

Patrick Laumann * [1,2], Gesa Petersen [1], Marius Isken [1], Hao Zhang [1], Torsten Dahm [1,2]

[1] German Research Centre for Geosciences - Helmholtz-Centre Potsdam – Germany
[2] University of Potsdam = Universität Potsdam – Germany

Seismicity in the inter-rift zone between the Upper Rhine Graben and the Lower Rhine Embayment has historically been dominated by activity along the Ochtendung Seismic Zone near the Laacher See Volcano in the East Eifel. In recent years, however, seismicity occurred further south, beginning with a seismic swarm in 2018 in the Taunus region near Bad Schwalbach, followed by another swarm initiating in 2024 near Mörsdorf in the Hunsrück region. Both swarms are ongoing since then.
We analyzed the spatio-temporal migration patterns and source mechanisms of both midcrustal swarms. Both show a systematic migration with a propagation rate of approximately 3 to 7 m per day, consistent with a pore pressure diffusion processes observed for human-induced seismicity. . Migration is unilateral in SE direction and slightly upward over 6 km length. Moment tensor solutions reveal a consistent NW–SE striking fault orientation for both sequences, in agreement with the dominant Variscan basement fault structures , reactivated regional Rhenish structural trends, and the present-day stress field.
The combination of slow, continuous migration over distances of 6 km and long duration distinguishes these sequences from typical short-lived tectonic swarms and instead suggests a sustained pressure source and diffusion-controlled processes, for instance maintained by transient influx of crustal or mantle fluid from below. By comparing migration behavior, focal mechanisms, and seismicity rates, we document systematic similarities and differences between the sequences and discuss their implications for persistent intraplate swarm activity.

Keywords: Eifel, Rhenish Massif, slow migration

*Speaker

Injection-induced seismicity fronts and stress distribution on rough faults

Hsiao-Fan Lin *† [1,2], Thibault Candela [2], Jean Paul Ampuero [1]

[1] Géoazur – Institut National des Sciences de l'Univers, Observatoire de la Cote d'Azur, Université Côte d'Azur, Centre National de la Recherche Scientifique, Institut de Recherche pour le Développement – France
[2] TNO, Geological Survey of the Netherlands, Utrecht, The Netherlands – Netherlands

The increasing occurrence of injection-induced earthquakes has raised public concern and highlighted the importance of understanding subsurface processes to assess induced seismic hazards and risks. A feature of natural faults that has not received sufficient attention in induced seismicity modeling is their geometric roughness. We develop a simple physics-based model to investigate how fault roughness can control induced seismicity during fluid injection.
The first approach to modeling along-fault stresses prior to injection is to project the background stress tensor onto the rough fault. In this case, our models and theoretical analysis show that the apparent diffusivity of seismicity fronts can deviate significantly from the hydraulic diffusivity. Faults with realistic roughness generally display slow seismicity migration, producing apparent diffusivities far below the hydraulic values. Thus, seismicity fronts often lag behind the pressure front, especially at low background stresses and small roughness amplitudes. Only in the rare case of very rough faults stressed very close to failure, apparent diffusivity can exceed the hydraulic diffusivity, leading to seismicity fronts that outpace pressure fronts.

The second approach to modeling along-fault stresses prior to injection is to simulate stress evolution after multiple tectonic rupture cycles. This ongoing work explores the resulting stress heterogeneity after multiple tectonic rupture cycles and examines whether seismicity migration follows the same trend as in the first approach, i.e., whether seismicity migration is generally slower than the pressure front on rough faults.

Apart from seismicity migration, the magnitude-frequency statistics are also analyzed. Along this single rough fault the frequency-magnitude distribution is bimodal. These results demonstrate how fault roughness and stress conditions control the induced seismicity through their influence on the criticality of the fault and stress transfer, and link long-term fault loading processes with short-term seismicity migration patterns in fluid injection scenarios.

Keywords: Induced seismicity, Fault roughness, Seismicity migration, Stress distribution

*Speaker
†Corresponding author: hsiao-fan.lin@geoazur.unice.fr

Exploring seismicity at Lucky Strike Hydrothermal Vent field with self-supervised contrastive learning on decadal ocean bottom seismometers network (2009–2019)

Timothé Lin *† [1], Thibaut Barreyre‡ [1], Clément Hibert§ [2,3]

[1] Geo-Ocean, UMR6538 – Université de Brest, Centre National de la Recherche Scientifique, IFREMER – France

[2] Institut Terre Environnement Strasbourg – Ecole Nationale du Génie de l'Eau et de l'Environnement de Strasbourg, université de Strasbourg, Institut National des Sciences de l'Univers, Centre National de la Recherche Scientifique – France

[3] Ecole et Observatoire des Sciences de la Terre – université de Strasbourg, Institut National des Sciences de l'Univers, Centre National de la Recherche Scientifique – France

Seafloor hydrothermal circulation at mid-ocean ridges (MORs) plays a key role in mediating heat and chemical exchanges between the lithosphere and the ocean and sustaining unique ecosystems in extreme environments. The EMSO-Azores observatory has enabled long-term monitoring of these systems at the Lucky Strike Hydrothermal Vent field on the Mid-Atlantic Ridge since 2007. A network of five Ocean Bottom Seismometers (OBSs) is complemented by autonomous sensors, including temperature probes, turbidimeters, and pressure sensors. This setup provides a unique, multidisciplinary dataset for investigating the interplay between hydrothermal fluid flow and natural forces, including tidal loading, crustal permeability changes, and volcano-tectonic processes.

Traditional detection and localisation methods (STA/LTA, NLLoc, HypoDD) are limited in their ability to capture temporal variations in seismicity types and rare events (Wayne et al., 2013; Bohidar et al., 2023). To address this limitation, we applied a novel workflow combining self-supervised contrastive learning (SSL-BYOL) with k-means and hierarchical agglomerative clustering (Rimpot et al., 2024, 2025). This approach enables the classification of large volumes of trimmed seismic data without prior knowledge of seismic source types. Using one year of vertical-component data from a single station with 3-minute windows, _~200,000 images were grouped into _~500 clusters. We identified Volcano-Tectonic (VT), Hydrothermal Acoustic (HA), Tremor-like clusters and noise sources such as airguns, whale vocalisations, and other anthropogenic or biological signals. This classification enabled the construction of an image-based seismic catalogue covering 2009–2019 and allowed us to investigate temporal relationships between seismicity and hydrothermal temperature variations.

*Speaker

†Corresponding author: timothe.lin@univ-brest.fr

‡Corresponding author: thibaut.barreyre@univ-brest.fr

§Corresponding author: hibert@unistra.fr

We explored this new catalogue during periods of elevated activity in 2015–2016 (Bohidar et al., 2023). These episodes coincided with a transient decoupling between tidal forcing and vent temperature fluctuations, suggesting that sub-seafloor hydrothermal systems at slow-spreading ridges may also respond to crustal deformation, similar to intermediate- and fast-spreading ridges. Our results demonstrate the potential of machine learning techniques for analysing long-term seafloor observatory data and contribute to a better understanding of the coupling between seismicity and hydrothermal circulation.

Keywords: hydrothermal circulation, mid ocean ridges, ocean bottom seismometers, deep sea, self supervised learning, SSL BYOL, tidal forcing, permeability, EMSO, Azores, Lucky Strike Hydrothermal Vent field

Evidence of slow slip before earthquake swarms on oceanic transform faults

Xiaoge Liu *† [1], Luigi Passarelli [2], Barreto Alejandra [1], Ófeigsson Benedikt [3], Jónsson Sigurjón‡ [1]

[1] King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia – Saudi Arabia
[2] INGV - Istituto Nazionale di Geofisica e Vulcanologia, sezione di Bologna Viale Berti Pichat 6/2, Bologna, Italy – Italy
[3] The Icelandic Meteorological Office, Reykjavík, Iceland – Iceland

Oceanic transform faults (OTFs) accommodate significant global plate motion, yet their low earthquake moment release indicates that silent, aseismic slip must govern the tectonic evolution. However, given the absence of direct evidence, the physical mechanisms driving these slow transients and their link to recurrent earthquake swarms remain elusive. Here, we use land-based continuous GNSS data from the Húsavík-Flatey Fault (HFF) in North Iceland to provide the first geodetic evidence of slow slip events (SSEs) on OTFs. By utilizing a signal-stacking strategy based on the peak time of density of clustered earthquake swarms, we captured the subtle aseismic transients from the residual GNSS time series with large stochastic noise. The results show a weeks-long preparatory phase of ultra-slow SSEs, with an average moment magnitude of Mw 5.34, systematically precedes the seismic swarms in the western portion of HFF. The spatial complementarity between these SSEs and swarm hypocenters, confirm that aseismic slip is the primary mechanical driver for the productive swarm-like activity along the western weakly coupled portion of HFF. Conversely, the eastern segment of HFF is strongly coupled with minor earthquake clusters occurrence, that indicates a fundamental along-strike heterogeneity in fault behavior. This contrast is further evidenced by the spatial heterogeneity of b-values estimated from declustered background events, exhibiting distinct temporal behaviors from quasi-periodic, stress-driven cycling in the west to an aperiodic (long period), locked regime in the east. b-values map reveals a probabilistic hotspot that hindcasts the nucleation site of the energetic 2020 M5.7 swarm. These findings underscore the importance of capturing aseismic transients in providing a mechanistic explanation for how rheological complexity dictates slow and fast slip release across OTFs.

*Speaker
†Corresponding author: xiaogeliucsu@gmail.com
‡Corresponding author: sigurjon.jonsson@kaust.edu.sa

Earthquake swarms in subduction zones

David Marsan *† [1], Jannes Münchmeyer [2], Anne Socquet [2]

[1] Université Savoie Mont Blanc – Laboratoire ISTerre - UMR CNRS 5275 – France
[2] ISTerre – UGA – France

This presentation aims at giving an outlook at previous studies on earthquake swarms in subduction zones, as well as presenting a new study on a large catalog over 2 years in Chile, during which period no major megathrust earthquake occurred. In the latter, a method already developed in previous works (e.g., Reverso et al., EPSL, 2015) for detecting swarms is modified to accommodate very large datasets as produced now by advanced (ML) methods.

*Speaker
†Corresponding author: david.marsan@univ-smb.fr

Characterizing the seismic response to fluid injection: a stepwise background rate model

Julie Maury *† [1], Hideo Aochi [1], Arthur Cuvier [1]

[1] BRGM-French Geological Survey – BRGM-French geological survey, 3 avenue Claude Guillemin, BP 36009, 45060 Orléans, France – France

Understanding the relationship between the evolution of induced seismicity and fluid injection parameters remains a complex challenge, with no unique solution. To isolate seismicity not driven by earthquake-to-earthquake interactions, we apply the Epidemic-Type Aftershock Sequence (ETAS) model (e.g., Ogata, 1988). In this framework, the background seismicity rate is modeled as a sum of hyperbolic tangent functions, allowing for step-like variations in response to changes in injection conditions.

We apply this approach to the stimulation dataset from Soultz-sous-Forêts. Our analysis reveals that increases in the injection rate are followed by a rapid rise in the background seismicity rate, which subsequently decays to a lower level over the course of several hours. When the earthquake-to-earthquake triggering component is removed from the model, the majority of the observed seismicity rate is still captured, suggesting that earthquake interactions play a limited role-except in the vicinity of the largest events.

We compare the forecasting performance of this adapted ETAS model with that of gradient-boosting machine learning methods (Cuvier et al., 2025). While the full analysis is still ongoing, preliminary results indicate that both approaches capture key trends in seismicity dynamics.

*Speaker

†Corresponding author: j.maury@brgm.fr

Intermittent earthquake activity signifies complex magmatic-tectonic interactions during the 2025 Santorini-Amorgos seismic sequence

Georgios Michas * [1,2], Vassilis Karastathis [2], Evangelos Mouzakiotis [2], Fevronia Gkika [2], Eleni Daskalaki [2], Konstantinos Chousianitis [2]

[1] National and Kapodistrian University of Athens – Greece
[2] National Observatory of Athens – Greece

The 2025 seismic crisis in the Santorini-Amorgos volcanic-tectonic zone added a novel episode of unrest in an area where Plinian and sub-Plinian volcanic eruptions, as well as large tsunamigenic earthquakes have occurred in the past. The seismic sequence started to evolve as an earthquake swarm at the end of January 2025 in the offshore area east of Santorini, in the proximity of the submarine Kolumbo volcano, precisely succeeding the six-months inflation period in the intra-caldera region. At the same time, inflation signals from GNSS at Santorini alternated to rapid surface deformation with subsidence motion towards the offshore area to the east. In the next days seismic activity escalated abruptly registering numerous earthquakes with magnitudes reaching or exceeding 5.0 and exhibiting some remarkable migration patterns with several onward and backward propagation episodes. Using a robust high-resolution earthquake catalogue assisted by machine-learning techniques, consisting of 18,157 events for the most intense period of seismic activity, i.e. 26 January to 28 February 2025, the finer details of seismicty are examined. Seismicty evolved in three main propagation phases with greater moment release along the main fronts over a period of 11 days, characterized by a step-like propagation pattern and various secondary seismicity fronts trailed by aseismic zones. The main propagation front during the first phase is consistent with a lateral dike propagation model that also delineates the NE end that seismicity reached during the third phase, while migration velocities and durations of the various secondary fronts are comparable to the ones reported in a global dataset of various dike-induced seismic sequences that was compiled. In addition, b-value spatial variations depict distinct high-low zones likely induced by high differential stresses combined with increased pore-pressures at shallower depths. Overall, the analysis and results, jointly interpreted with deflation signals resolved by GNSS and other seismic observations as volumetric components in full moment-tensor solutions, indicate a magmatic dike intrusion facilitated by the regional tectonic fabric as the main driver of the remarkable earthquake activity recorded during February 2025 in the Santorini-Amorgos volcanic-tectonic zone.

Acknowledgements
We would like to thank all the personnel of the Institute of Geodynamics, National Observatory of Athens and especially the seismic analysis team and the technical staff for their tireless efforts in monitoring and responding to the Santorini - Amorgos seismic crisis. The research project

*Speaker

is implemented in the framework of H.F.R.I call ”4th Call for H.F.R.I.’s Research Projects to Support Postdoctoral Researchers” (H.F.R.I. Project Number: 28909).

Keywords: Santorini Amorgos seismic sequence, seismicity migration, dike induced seismicity

Spatiotemporal analysis of intermittent induced seismicity at the Rittershoffen geothermal site, France

Riccardo Minetto * [1], Olivier Lengliné , Jean Schmittbuhl

[1] Institut Terre Environnement Strasbourg – université de Strasbourg, Institut National des Sciences de l'Univers, Centre National de la Recherche Scientifique – France

Since 2016, the Rittershoffen geothermal site has successfully produced heat through the large-scale circulation of fluid in a faulted reservoir at a depth of around 2500 m. Despite an approximately constant injection rate, fluid reinjection has typically been accompanied by low-magnitude (ML $<$ 1.5) seismicity occurring in the form of bursts. In 2024, the first felt events exceeding ML 2.0 were recorded, alongside the most productive seismic bursts to date. On December 4, 2025, an ML 2.5 earthquake led to the suspension of injection operations, but eight days later the largest event of the sequence occurred (ML 2.8). In this study, we combine machine-learning detection, template matching, and double-difference relocation to build a high-resolution seismic catalog from January 2023 to March 2026, using recordings from the local Dense Semi-permanent Seismic Network (DSSN), comprising 35 Raspberry Shake stations. The resulting catalog (_˜4,000 events) is used to characterize and compare the b-value, spatiotemporal migration patterns, and fault geometry associated with the major seismicity bursts, with particular emphasis on the December 2025 crisis. Finally, we investigate how the sudden suspension of the multi-year fluid injection influenced the seismic response in the following months.

*Speaker

Identifying and Incorporating Transient Triggers into Seismicity Forecasts

Leila Mizrahi * [1]

[1] Swiss Seismological Service, ETH Zurich – Switzerland

Earthquake swarms are often characterized as sequences of earthquakes that lack a clear mainshock. Alternatively, they are characterized by the mechanics of their origination: In contrast to the typical mainshock-aftershock sequences that are driven by plate tectonics, earthquake swarms have been proposed to originate from aseismic transients such as fluid pressurization, aseismic slip events, and magmatic stress perturbations in volcanic regions. Both these characterizations of swarms describe them as "non-mainshock-aftershock-like". This poses a challenge for earthquake forecasting, which mainly relies on the known statistical properties of aftershock triggering, best known within the framework of the ETAS model. I propose a method to account for known external earthquake triggers in ETAS parameter estimation as well as during short-term forecasting. This can be useful to identify the most likely among several triggers, as I demonstrate using synthetic tests. In the context of induced seismicity, the method was applied to a case study of the Hengill geothermal field (Ritz et al., 2024). By incorporating injected and produced volumes, the model demonstrated improved performance in pseudo-prospective forecasting tests. Although forecasting swarm activity remains inherently limited by our ability to observe and forecast external forcing, this approach offers a mathematical framework to invert for such drivers and, once identified, directly integrate them into seismicity forecasts.

*Speaker

Seasonal modulation of seismicity in an intraplate setting, the case of southeastern Australia

Farzaneh Mohammadi * [1], Romain Jolivet [2,3], Eric Beaucé [4]

[1] Laboratoire de Géologie, Département de Géosciences – Ecole Normale Supérieure, PSL Université, CNRS UMR 8538, 24 Rue Lhomond, 75005, Paris, France – France
[2] Laboratoire de Géologie, Département de Géosciences – Ecole Normale Supérieure, PSL Université, CNRS UMR 8538, 24 Rue Lhomond, 75005, Paris, France – France
[3] Institut Universitaire de France – 1 rue Descartes, 75006 Paris, France – France
[4] Lamont-Doherty Earth Observatory, Columbia University, NY, United States – United States

While most earthquakes occur at plate boundaries, significant seismic events also occur within stable continental regions (SCRs), despite their low strain rates. These intraplate earthquakes, including rare but damaging events, raise fundamental questions about how elastic strain cumulates, is stored, and released in slowly deforming crust. We develop a high-resolution seismicity catalog for southeastern Australia, a tectonically stable intraplate region, spanning 2005-2025. The catalog was constructed using the BPMF workflow which integrates backprojection-based detection, deep learning phase picking, nonlinear probabilistic relocation, and matched filtering. Relative to the Geoscience Australia catalog, our approach increases the number of detected events by approximately a factor of six and achieves a magnitude of completeness of $M_c
≈ 2.1$, *enablingrobuststatisticalanalysesovertwodecades.Thisenhancedresolutionenablestheexplorationofse*
seismicityenvironment.Usingthiscatalog, weidentifyastatisticallysignificantseasonalmodulationofseismic
−springandreachingaminimumduringsummer−−fall.Theseasonalsignalpersistsafterdeclusteringandisob

*Speaker

Destabilizing a velocity-strengthening fault with fluid-injection

Francesco Mosconi *† [1], Pierre Dublanchet [2], Elisa Tinti [1], Massimo Cocco [3]

[1] Dipartimento di Scienze della Terra, La Sapienza Università di Roma, Rome, Italy – Italy
[2] Centre de Géosciences, Mines Paris PSL University – Geosciences Department, MINES ParisTech, PSL University, Fontainebleau, France – France
[3] Istituto Nazionale di Geofisica e Vulcanologia - Sezione di Roma – Italy

Most studies on subsurface fluid injection, including applications related to the energy transition such as CO storage and geothermal exploitation, aim at maximizing injected volumes while minimizing induced seismicity. The occurrence of fluid-induced earthquakes during geo-energy exploitation, has motivated efforts to better understand the physical processes controlling the nucleation and dynamic propagation of induced ruptures. Direct observations of earthquake sources at very short distances remain extremely rare, because only a few on-fault observatories worldwide allow natural faults to be instrumented and reactivated under controlled conditions. The **FEAR** project follows this approach and aims at reactivating a natural target fault through controlled fluid injection in the Bedretto Tunnel (Swiss Alps, Switzerland), located at _˜1000 m depth, to generate a M_˜1 earthquake to be recorded by a dense multi-disciplinary monitoring network for investigating the rupture processes at very close distance.
Experimental characterization of the frictional properties of the FEAR target fault for the stimulation indicates a velocity-strengthening behavior, so the stable response to fluid injection is expected. However, even for velocity-strengthening rocks, as described by rate-and-state formulation, a dynamic instability can occur under specific conditions. One requirement is that the initial shear stress on the fault (t0) exceeds the steady-state shear stress tss = s'n (m* + (a-b) ln(V/V*)), with s'n the effective normal stress, m* the reference friction, a the direct effect, b the evolution effect and V* the refence velocity. This is a necessary but not sufficient condition. A second requirement is that the dimension of the region where t0 > tss must exceed the characteristic lengthscale Lb = Gdc /s'nb, where G is the shear modulus, dc the critical slip distance.

We systematically explore, with quasi-dynamic earthquake cycle simulations, different initial fault conditions and injection scenarios to maximize the likelihood of generating an M=1 earthquake on the velocity-strengthening FEAR target fault. Specifically, we test the effects of injection system geometry using one or two boreholes and investigate different injection protocols, including variations in injection rate and multi-phase stimulation sequences with and without prior on-fault pore-pressure preconditioning, in order to best reproduce the experimental settings at Bedretto Lab. Our results show that if the fault is initially above steady state (t0 > tss), stimulation through a single borehole can trigger acceleration with radiative slip velocities. In contrast, if the fault is initially below steady state (t0 < tss), the expected response is

*Speaker
†Corresponding author: francesco.mosconi@uniroma1.it

predominantly aseismic slip. In this case, however, unstable slip can still be promoted through preconditioning of the on-fault pore pressure prior to the main injection phase. Increasing pore pressure reduces the effective normal stress and proportionally lowers tss, thereby shifting the initial state of the fault from $t0 < tss$ to $t0 > tss$, which enables the rupture acceleration.

Furthermore, the use of two boreholes for fluid injection provides better control over the pore-pressure distribution along the fault. This configuration can ensure that a sufficiently large portion of the fault reaches elevated pore-pressure levels (for a sufficiently long injection duration). As a result, the region satisfying $t0 > tss$ can grow large enough to meet the second requirement for instability, $L > Lb$.
Overall, our results show that systematic exploration of both injection parameters and initial on-fault conditions is essential to constrain the possible responses of a natural target fault. Such an approach helps identify the range of scenarios that may lead or not, to the nucleation of the M=1 earthquake.

Keywords: Induced seismicity, rupture nucleation, velocity strengthening

Mount Cameroon 2010 seismic swarm characteristics and volcanological (geodynamic or tectonic) implications

Delair Dieudonne Ndibi Etoundi *† [1], Eddy Ferdinand Mbossi , Sofiane Taki-Eddine Rahmani , Bekoa Ateba

[1] Institute of Geological and Mining Research – Cameroon

Seismic swarms are commonly observed in active volcanic regions and often reflect complex interactions between tectonic stresses, magmatic intrusions, and hydrothermal processes. In 2010, a remarkable seismic swarm occurred beneath Mount Cameroon, one of the most active volcanoes along the Cameroon Volcanic Line (CVL). Understanding the characteristics of this swarm is essential for improving our knowledge of volcanic processes and seismic hazard in the region. In this study, we investigate the temporal evolution and statistical properties of the 2010 seismic swarm using a non-stationary Epidemic-Type Aftershock Sequence (ETAS) model. This approach allows us to quantify time-dependent variations in seismicity rates and to distinguish background seismicity from earthquake triggering processes. The earthquake catalog analyzed in this study consists of events recorded by the local seismic monitoring network operating around Mount Cameroon. Our results reveal significant temporal fluctuations in the background seismicity rate, suggesting transient processes affecting the seismic activity beneath the volcano. The analysis also indicates clustering behavior consistent with earthquake interaction and possible stress transfer mechanisms. These observations may reflect magma migration or fluid movement within the volcanic edifice or in the underlying crust. The results provide new insights into the dynamics of swarm-type seismicity at Mount Cameroon and highlight the usefulness of non-stationary ETAS modeling for investigating volcanic seismicity. This study contributes to a better understanding of the mechanisms controlling seismic swarms along the Cameroon Volcanic Line and may help improve monitoring strategies for volcanic hazards in the region.

Keywords: Seismic swarm, Mount Cameroon, magma intrusion, volcano, tectonic earthquakes, ETAS model.

*Speaker

†Corresponding author: del_ndibson@yahoo.fr

Landslides as Natural Laboratories for Fluid-Driven Seismic Swarm Processes: Insights from the Åknes Rock Slope, Western Norway

Peter Niemz * [1], Nadège Langet [1], Volker Oye [1]

[1] NORSAR – Norway

While most studies of seismic swarms concern earthquake activity in volcanic-tectonic settings, subduction zones, or induced seismicity, this contribution focuses on landslides, where fluids and transient deformation may also govern swarm-like microseismicity. The triggering of landslides or increased internal deformation is often attributed to the increased availability of fluids within the system. However, the relation between bursts of microseismicity and the deformation itself is still under debate. We elaborate on potential fluid-based triggering processes based on near-surface seismic observations from the Åknes rock slope located above Sunnylvsfjord in western Norway. While near-surface deformation in landslides may differ from processes at depth in typical earthquake swarm activity, the better accessibility provides unmatched opportunities to study such naturally fluid-forced deformation and the accompanying swarm-like microseismic activity. The steep Åknes rock slope is slowly moving toward the fjord at a rate of a few centimeters per year. Due to the tsunami-genic potential of a collapse into the fjord, the site is monitored by a multitude of geophysical instruments, including an 8-level geophone string installed in a borehole on the slope. We present four years of microseismic observations from the Åknes rock slope and discuss the interplay between the observed swarm-like activity, transient deformation and fluid availability, highlighting the potential of landslides as natural laboratories for fluid-driven seismic swarm processes.

Keywords: swarms, landslide, microseismicity, Norway

*Speaker

Detecting Earthquake Swarm and Analyzing their B+ trends in the Salton Trough Region of Southern California

Astrid Olsson *† [1], Yihe Huang [1], Xiaowei Chen [2]

[1] University of Michigan [Ann Arbor] – United States
[2] Texas AM University [College Station] – United States

The Salton Trough region of Southern California is known for having short, frequent earthquake swarms. Defining swarms in this region is challenging because they are often brief and do not exhibit many of the patterns typically associated with longer-duration swarms. Additionally, the high overall level of seismicity further complicates distinguishing short swarms from background activity. However, because the area is highly populated, frequent earthquakes pose a significant hazard to the local population. Therefore, we apply two methods to detect earthquake swarms and examine whether the swarms are associated with changes in earthquake statistics. We analyze the temporal and spatial variations in b-values that quantify the magnitude-frequency distribution. The b-value variations have been shown to serve as an indicator of changes in earthquake behavior and thus may reveal periods when swarm-like activity is more likely to emerge.

To ensure the robustness of earthquake swarm detections, we first apply the nearest neighbor method (Zaliapin & Ben-Zion, 2020) and the clustering method from Chen and Shearer (2011) to identify swarms in the Salton Trough region. By comparing the results from two different methods, we create a more complete swarm catalogue, spanning 1981 to 2023. With the revised catalogue, we observe an average offset between swarm identification methods of 1.36 km and a mean temporal median offset of 0.28 days between the median locations, indicating a strong correlation between swarm identification methods. The swarms we find last, on average, about 10 days, some as short as less than a day, and the longest swarm being 19 days. Swarm events are spatially concentrated, with most events within a few kilometers. We also observe alternating periods of higher (1981 - 1986, 1996 - 2012, 2016 - 2024) and lower (1986 - 1996, 2012 - 2016) swarm activity.

In order to examine spatial and temporal changes in b-values associated with detected swarms, we use the b+ method (van der Elst, 2021), which is based on the distribution of magnitude differences and is more robust to the incompleteness of the earthquake catalog. We find that b+ spatial trends largely coincide with large-magnitude events; however, we do not identify a consistent relationship between the temporal variations of b+ and the occurrence of swarms for the whole region, suggesting that b+ is not a reliable predictor of swarm activity at the regional scale. These findings indicate that regional b+ variations primarily reflect large-scale stress interactions rather than swarm-driven processes, underscoring the complexity of forecasting short swarm activity in the Salton Trough and the need for improved methods to characterize short-duration seismic clustering in regions with high background seismicity.

*Speaker
†Corresponding author: astrido@umich.edu

Keywords: Salton Trough, B Value, Nearest, neighbor Clustering, Earthquake Swarm

Variation in Swarm Response from Multiple Hydraulic Operations at Utah FORGE

Kristine Pankow * [1], Katherine Whidden [1], Grant Spraker [1], Van Fleet Nicholas [1], Elisabeth Glück† [1], Peter Niemz [2], Gesa Petersen‡ [3]

[1] University of Utah – United States
[2] Norwegian Seismic Array – Norway
[3] German Research Centre for Geosciences - Helmholtz-Centre Potsdam – Germany

The Utah Frontier Observatory for Research in Geothermal Energy (FORGE) is a field scale laboratory to develop the technologies to de-risk Enhanced Geothermal Systems (EGS). This laboratory also provides a unique setting for studying seismic swarms. A key assumption in many swarm studies involves the influence of fluids. During operations at Utah FORGE, fluids are actively injected and volumes and pressures are measured. There are two modes of operations associated with EGS: 1) stimulation, when fluid is injected at high pressures to fracture the rock and 2) circulation, when fluid is injected at lower pressures to pull heat out of the rock. In this study, we look at operational activities from the 2022 stimulation, 2023 circulation, 2024 stimulation, 2024 circulation, and will show early results from the upcoming 2026 multi-month circulation. We perform a statistical analysis (e.g. b- and a-values, moment rate, skewness) comparing features between stimulation and circulation. Additionally, we will look at how the seismicity migrates with time and whether the same fractures are activated during stimulation and circulation. Results from this analysis are compared to similar analyses for natural swarms located both close to the Utah FORGE site (the 2021 Milford swarm and swarms from the Mineral Mountains) and further away in Yellowstone National Park.

Keywords: induced swarms, geothermal, comparison to natural swarms

*Speaker
†Corresponding author: elisaebeth.gluck@utah.edu
‡Corresponding author: gesap@gfz-potsdam.de

Spatiotemporal Analysis of Seismicity During the 2010–2025 Unrest at Campi Flegrei Caldera

Luigi Passarelli * [1]

[1] INGV - Istituto Nazionale di Geofisica e Vulcanologia, sezione di Bologna – Italy

Campi Flegrei is one of the world's highest-risk volcanic systems and since 2010 is currently undergoing a prolonged period of unrest. The unrest phase began around 2010 with a slow and progressive uplift of the caldera floor detected through GNSS data, with respect to two decades long subsidence of the caldera floor started after the 1982-1984 unrest phase. The slow deformation has been accompanied by an intensification of fumarolic emissions. Along with deformation, seismicity gradually increased, with a steady rise in earthquake occurrence likely reflecting the crustal rock response to uplift induced increase in strain rate. From 2019 and 2020 it has been registered an increase in the deformation rate and a consequent marked acceleration of the earthquake productivity with a gradual increase in the magnitude of earthquakes. This evolution raised significant concerns about the structural integrity of the caldera.

In this study, we examine the seismic evolution of the caldera from 2022 to 2025 using a high- resolution, machine-learning-enhanced catalog. The dataset includes approximately 50,000 precisely relocated events, offering unprecedented insight into subsurface fracturing processes. Through the application of spatial clustering algorithms, we identify four distinct seismic clusters that closely align with the main structural features of the caldera system. To better resolve temporal dynamics, we also isolate short-lived bursts of activity that interrupt the long- term increasing trend of seismicity rate. We analyzed the seismic productivity of each cluster across different sectors of the caldera and correlated these results with observed ground deformation. Our findings indicate that the background seismicity rate is primarily controlled by caldera-scale uplift and its temporal fluctuations in velocity. In contrast, individual seismic bursts appear to be linked to localized fluid transients. The properties of these transients vary considerably depending on the sector in which they occur, pointing to a complex interplay between caldera deformation, fluid circulation, and intense hydrothermal activity.

*Speaker

Propagation of aseismic slip front during fluid injection experiments

Francois Passelegue * [1]

[1] Géoazur – Institut National des Sciences de l'Univers, Observatoire de la Cote d'Azur, Université Côte d'Azur, Centre National de la Recherche Scientifique, Institut de Recherche pour le Développement – France

Fluid-induced seismicity results from complex interactions between fluid injection, fault friction, and the ambient stress field. While seismic swarms often display spatiotemporal migration, it remains unclear whether this reflects fluid pressure diffusion or stress transfer from aseismic slip. Fracture mechanics models suggest that aseismic slip may either lag behind or outpace the fluid pressure front, depending on injection conditions and the fault's initial stress state. However, direct experimental validation of these predictions has been lacking. Here, we report laboratory experiments on granite samples under upper crustal stress conditions, where we simultaneously tracked the propagation of fluid pressure and aseismic slip during fluid injection. We show that aseismic slip lags the pressure front at low injection rates and low initial stress, but rapidly outpaces it under high-rate injection or near-failure initial stress conditions. The transition is governed by a dimensionless loading parameter that integrates injection rate, fault strength, and initial shear stress. Our results provide direct support for fracture mechanics models of fluid-induced aseismic slip and suggest that in critically stressed crustal faults, rupture propagation may commonly outpace fluid diffusion. These findings help reconcile contrasting observations of seismicity migration and improve our understanding of induced seismic hazards.

Keywords: Friction, fluid, induced rupture, laboratory experiments

*Speaker

Aseismic slip and seismic swarms leading up to the 2024 M7.3 Hualien earthquake

Wei Peng * [1], Kate Huihsuan Chen [1], Roland Bürgmann [2], Ya-Ju Hsu [3], Yanhong Chen [4]

[1] Dept. of Earth Sciences, National Taiwan Normal University – Taiwan
[2] Department of Earth and Planetary Science, University of California – Berkeley, United States
[3] Institute of Earth Sciences - Academia Sinica – Taiwan
[4] Institute of Earth Sciences - Academia Sinica – Taiwan

Understanding the role of aseismic slip in earthquake cycles is essential for assessing seismic hazards and short-term forecasting. Eastern Taiwan's double-vergence suture zone, where the Philippine Sea Plate subducts beneath the Eurasian Plate, experiences frequent M $\geq$ 6 earthquakes and widespread aseismic slip, making it an ideal natural setting to study earthquake triggering processes. Here we demonstrate how aseismic deformation contributed to the April 3, 2024 Mw7.3 Hualien earthquake by analyzing a 24-year catalog of repeating earthquake sequences (RESs) and earthquake swarms. We find that six out of nine swarms in the epicentral area, northern Longitudinal Valley, were accompanied by increasing aseismic slip rates, as revealed by RESs on the west-dipping Central Range Fault (CRF). A notable aseismic slip episode in 2021, indicated by GNSS signals, the accelerated RES-derived slip rate, and a four-month-long swarm sequence with high diffusivity (_˜5.2 m^2/s), suggests joint contributions from over-pressured fluids and deep fault creep. Following this episode, a sequence of M6+ events occurred in 2022, and both seismicity and aseismic slip gradually increased again starting in 2023. Coulomb stress modeling indicates that cumulative aseismic and seismic slips since 2021 generated up to _˜30 kPa positive stress on the eventual rupture, promoting fault weakening and shallower seismicity. This study provides compelling evidence for aseismic-slip-induced stress triggering of a major earthquake and highlight the importance of integrating aseismic processes into earthquake hazard models for collisional fault systems.

*Speaker

The character of small, low-magnitude earthquake swarms at the VEI 6 caldera of the Laacher See volcano, Germany

Gesa Petersen * [1], Patrick Laumann [1,2], Torsten Dahm [1,2], Marius Isken [1], Zhiguo Deng [1], Heiko Woith [1], Christian Voigt [1], Martin Zimmer [1], Martin Hensch [3], Martin Zeckra [4], Bernd Schmidt [5], Hao Zhang [1]

[1] GFZ Helmholtz Centre for Geosciences – Germany
[2] University of Potsdam – Germany
[3] Landeserdbebendienst Baden-Württemberg, Landesamt für Geologie, Rohstoffe und Bergbau – Germany
[4] University of Cologne – Germany
[5] Landesamt für Geologie und Bergbau Rheinland-Pfalz – Germany

On October-09/10, 2025, a short-lived 6-hour-long microseismic swarm (Mw_max=1.4) occurred at the vicinity of the caldera rim at Laacher See Volcano in the East Eifel Volcanic Field (EEVF), Germany. The EEVF is a dormant, distributed volcanic field comprising hundreds of Quaternary volcanoes. The last eruption at the Laacher See Volcano _˜13,000 years ago was highly explosive (VEI 6) producing more than 6 km3 dense-rock equivalent (DRE) and a steep caldera. The multisensor monitoring of the Laacher See region has recently been enhanced by the GFZ's Central European Volcanic Province Observatory (CVO), which integrates multi-sensor data streams including seismic data, GNSS, a superconducting gravimeter, and 12 fluid-monitoring sites to detect subtle signals of volcanic and tectonic activity.

The October 2025 swarm is the first seismic activity measured at the Laacher See caldera, and therefore caused public and scientific interest. Further, the comprehensive unique multisensor dataset allows the first time for quantitative correlations of observations. Our preliminary seismic analysis, moment tensor inversions and cross-correlation-based clustering indicate that earthquakes were highly self-similar activating faults with oblique normal to strike-slip rupture mechanisms in agreement with the regional stress field. The hypocenters indicate a depth between 8 and 6 km. So far, we could not detect transients on GNSS, fluid or gravity data correlating with the seismic sequence. The October 2025 swarm illustrated the feasibility of a fast, multidisciplinary assessment of unrest periods in the EEVF. Motivated by the 2025 unrest at the Laacher See volcano, we systematically revisited all seismic activities in the EEVF since 2018, computing a new, high-precision earthquake catalog and moment tensor solutions. Although the EEVF is not typically characterized by extensive swarm activity, our analysis reveals tens of tiny other swarm sequences over the past years. We present multi-disciplinary insights into the Laacher See swarm sequences, and investigate swarm occurrences in spatial proximity to recently mapped crustal velocity anomalies, interpreted as inherited upper-crustal magmatic systems from the past eruption. Notably, the locations of suspected reservoirs beneath the EEVF correlate well with those of deep low-frequency earthquakes.

*Speaker

Keywords: Eifel, swarm, volcano

Spatio-temporal Evolution of Seismicity in the Northern Apennines: Insights from a High-Resolution Earthquake Catalog

Giulio Poggiali * [1], Lauro Chiaraluce [2], Monica Sugan [3], Alessandro Vuan [3], Zachary E. Ross [4], Chris Marone [1]

[1] Università degli Studi di Roma "La Sapienza" – Italy
[2] Istituto Nazionale di Geofisica e Vulcanologia - Sezione di Roma – Italy
[3] Istituto Nazionale di Oceanografia e di Geofisica Sperimentale – Italy
[4] Seismological Laboratory, California Institute of Technology – United States

The Alto Tiberina Fault (ATF) system in the Northern Apennines is an ideal natural laboratory for observing the interplay between high-pressure CO2 and fault mechanics.
Using a 13-year high-resolution earthquake catalog and density-based clustering, we identify over 70 clusters exhibiting distinct migratory behavior within the ATF hanging wall.
Direct observation of their spatio-temporal evolution reveals migration patterns spanning multiple scales, from localized bursts to regional transients, which we characterize by both diffusive and linear migrating fronts.
We observe an intriguing trend between maximum magnitude and diffusivity, suggesting a feedback loop where larger events may increase "coseismic permeability," allowing faster fluid migration and triggering broader seismicity. Our diffusivity values are comparable to injection-induced and natural swarms, and lower than Apennines mainshock-aftershock sequences (M> 4).

Scaling analysis of migration speeds, durations, and magnitudes indicates a strong prevalence of fluid-induced processes throughout the ATF hanging wall volume. However, the observed effective stress drop range suggests that while fluids trigger activity, the resulting deformation includes noticeable aseismic creep.
Furthermore, we characterize each cluster by the prevalent hosting lithology, indicating different behavior in terms of duration and migration speed.

Our analysis also extends the timeline of the 2013 Gubbio swarm, revealing that migration initiated in late 2012. This observation reframes the 2013-2014 aseismic slip event as part of a broader, fluid-driven swarm context.

Finally, fluid volumes linked to expanding seismic fronts are estimated and then compared to the maximum expected moment from established literature relationships.
Our results demonstrate that modern high-resolution catalogs, enabled by novel techniques and dense instrumental networks, represent more than a simple quantitative upgrade; they are a qualitative necessity for decoding the mechanical behavior of complex fault systems.
By resolving micro-seismicity across multiple orders of magnitude, we can observe fault dynamics at a breadth of scales previously obscured.

*Speaker

Seismic signatures of dike propagation and their discrimination from tectonic seismic crises

Eleonora Rivalta * [1,2]

[1] GeoForschungsZentrum Potsdam (GFZ) – Helmholtzstrasse 7 14467 Potsdam, Germany
[2] Departiment of Physics and Astronomy, University of Bologna – Italy

Seismic swarms are commonly observed in volcanic regions and often represent a key feature of interest in volcano monitoring. In many cases, hypocenters within a swarm align approximately along a plane, suggesting clustering on a pre-existing fault or along the trajectory of a propagating magmatic dike. Determining the physical driver of such swarms, i.e. whether they are triggered by the migration of magma or originate from purely tectonic processes, can be challenging, particularly when geodetic constraints on ground deformation are sparse or unavailable.
I present a review of a range of well-documented dike intrusion events and examine the seismic swarms associated with their propagation. By comparing these case studies, I identify a set of recurring characteristics in the temporal evolution, spatial migration, and geometric organization of seismicity that are diagnostic of dike-driven processes. We discuss how these features differ from those typically observed during tectonic seismic crises and evaluate their usefulness as practical indicators in situations where deformation data are limited. The criteria outlined here provide a framework for distinguishing magmatic intrusions from tectonic seismicity during real-time monitoring as well as constraining the physical processes at play during magma migration.

Keywords: volcanic seismicity, magma migration, dike propagation, ground deformation, stress field, focal mechanisms, moment tensor.

*Speaker

Illuminating magmatic and tectonic processes during the 2024 unrest at Kīlauea volcano with a high-resolution earthquake catalog

Alicia Rohnacher *† [1], Federica Lanza *

[1], Ninfa Bennington *

[2]

[1] Swiss Seismological Service [ETH Zurich] – Switzerland
[2] U.S. Geological Survey, Hawaiian Volcano Observatory – United States

Kīlauea on Hawaii is one of the most active volcanoes worldwide and frequently experiences major volcanic eruptions and tectonic activity. Here, we present a high-resolution earthquake catalog derived from a three-month deployment of a dense nodal array with 116 station locations in the East Rift Zone. Using the qseek machine-learning-based detection and localization framework, we detect and locate seismicity with substantially improved completeness compared to routine monitoring catalogs.

The enhanced catalog illuminates previously under-resolved regions, particularly in the lower East Rift Zone, revealing detailed spatiotemporal patterns of earthquake hypocenters. The catalog captures the 2024 Nāpau volcanic crisis, including three dike intrusions, the last one culminating in an eruption on 16 September. Examining the spatial and temporal evolution of earthquakes allows us to infer the characteristics of magma transport within the ERZ during the pre- and co-eruptive phases. In addition, we detect clusters of earthquakes along the south flank following dike emplacement, highlighting the interaction between magmatic intrusions in the rift zone and tectonic activity at the decollement.

Together, these observations underline the potential of dense nodal networks along with deep-learning catalogs to improve our understanding of magma migration and volcano-tectonic processes.

Keywords: Kīlauea, magma intrusion, Nāpau eruption, earthquake catalog

*Speaker
†Corresponding author: alicia.rohnacher@sed.ethz.ch

Recurrent shallow slow slip and seismic swarms on the Copiapo ridge, Chile

Anne Socquet *† [1], Jannes Münchmeyer [2], Diego Molina [1], Mathilde Radiguet [1], David Marsan [1], Marcos Moreno [3], Juan Carlos Baez [4]

[1] Institut des Sciences de la Terre – Institut de Recherche pour le Développement, Institut National des Sciences de l'Univers, Université Savoie Mont Blanc, Centre National de la Recherche Scientifique, Université Gustave Eiffel, observatoire des sciences de l'univers de Grenoble, Université Grenoble Alpes – France
[2] German Research Centre for Geosciences - Helmholtz-Centre Potsdam – Germany
[3] Pontificia Universidad Católica de Chile = Pontifical Catholic University of Chile [Santiago] – Chile
[4] Universidad de Chile = University of Chile [Santiago] – Chile

Like earthquakes, slow slip events release elastic energy stored on faults. Yet, the mechanisms behind slow slip instability and its relationship with seismicity are debated. We use a seismo-geodetic deployment to document a shallow slow slip event in 2023 on the Chile subduction. The slow slip initiation is driven by structurally-confined fluid overpressure, as evidenced by seismic swarms next to a subducted seamount, migrating along the interface and activating splay fractures. The seismic rupture of a permeability seal allows slow slip to accelerate and expand. Historical earthquake swarms highlight the persistent structural control and recurrent nature of such slow slip events. Our observations show that interactions between slow slip and seismicity are controlled by creep on a fluid-infiltrated fault with fractally distributed asperities.

*Speaker
†Corresponding author: anne.socquet@univ-grenoble-alpes.fr

Fluid-driven faulting and earthquake sequences in elastic-plastic numerical models

Guy Simpson * [1]

[1] Department of Earth Sciences, University of Geneva, Switzerland – Switzerland

It is well established that fluids may drive earthquakes and induce slip on faults in the upper crust. Field evidence suggests that fluid overpressures may generate complex mesh-like fault structures, while earthquake swarms have been sometimes been interpreted to result from the episodic passage of fluid through such structures, linked to fault-valve behaviour. Despite this, most models of fluid-driven earthquakes prescribe slip to occur on a single, predefined fault. Here I consider a more advanced model that enables fluid-driven earthquakes occur on faults that emerge spontaneously and rupture episodically. The model is based on two-dimensional plane strain conditions with an elastic-plastic (Coulomb) material coupled to porous fluid flow. The permeability is prescribed to decrease as a function of depth, while it also rapidly increases on a fault during sliding before slowing decaying once sliding has ceased. I consider a scenario in which the upper crustal layer is initially understressed with respect to frictional sliding. The models are subjected to slow lateral tectonic loading while fluids are sourced at a constant rate at the base of the model (10 km depth), which is considered as a proxy for water released from metamorphic reactions in the underlying mid crust. This leads to fluid overpressures at the base of the elastic-plastic crust, which eventually induce localised shear failure. The increase in permeability on a fault relaxes the fluid overpressure at the rupture site, while upward fluid transfer pressurises the overlying rocks, potentially inducing failure there, which continues in a cascade-like manner. Thus, faults and seismicity propagate upward in waves in response to the passage of fluid overpressure pulses. In some cases, these pulses ascend along isolated faults, while in others they occur on multiple structures that evolve synchronously. The resulting earthquake sequences are complex in space and time, the details of which depend on the coseismic fault permeability and permeability healing time scale, the basal fluid flux and the background stress state. I am currently exploring the relevance of the models to earthquake swarms and the operation of faults at low stress levels.

Keywords: earthquakes, faulting, fluids, overpressure, swarms

*Speaker

Swarm-Like Volcano-Tectonic Earthquakes and Magmatic Inflation at Akutan Volcano, Alaska (2004–2019): Insights from a Deep Learning-Based Earthquake Catalog

Zilin Song * [1], Zhenkai Bo [1], Nanzhe Wang [1], Ahmed Elsheikh† [1]

[1] Heriot-Watt University [Edinburgh] – United Kingdom

Volcano-tectonic (VTs) and long-period (LPs) earthquakes are commonly associated with volcanic unrest and eruptions, yet their identification within continuous seismic waveforms remains challenging, as conventional monitoring methods are labor-intensive and difficult to capture the full spectrum of seismic activity, particularly during swarm episodes. In this study, we develop an integrated workflow based on deep-learning phase pickers and classifiers to automatically detect and classify VTs and LPs at Akutan Volcano, Alaska. We first employ EQTransformer, pre-trained on volcanic seismicity (Zhong & Tan, 2024), to analyze continuous waveforms from local stations (2004–2019). This process results in 5,223 earthquakes, over 3 times the number within the analyst-provided catalog (Power et al., 2019). We then categorize detections into VTs and LPs using TabPFN (Hollmann et al., 2025), a lightweight deep-learning classifier. By training on local labels, the classifier achieves an F1 score of 0.96 within the test dataset, suggesting robust classification consistency with manual labeling. Analysis of this enhanced catalog reveals that VT swarm-like seismicity is preferentially elevated during inflation episodes, with a subset of VT clusters extending to depths approaching the Moho beneath the inferred magma reservoir. Meanwhile, preliminary results for LPs suggest that while the number of detections is substantially increased, deep LPs potentially associated with magma activity remain underdetected relative to catalogs enhanced by template matching, likely due to the scarcity of such events in the training data. A similar data dependency is also observed in cross-domain experiments, where models pre-trained on volcanic data show greater transferability to induced seismicity detection (F1: 0.9-0.93) than those trained on pure tectonic data (F1: 0.75-0.88), suggesting that training data diversity may play an important role in model generalization across different seismic domains. Overall, this study demonstrates that combining deep-learning-based detection with classification models can substantially enhance earthquake catalogs in volcanic regions automatically and systematically. The spatiotemporal association between swarm-like VTs and magmatic inflation further highlights the potential of deep learning applications for volcano monitoring and eruption forecasting.

*Speaker

†Corresponding author: A.Elsheikh@hw.ac.uk

Keywords: Volcano, tectonic earthquakes, Long, period earthquakes, Deep, learning applications

Enhancing Long-Term Seismic Analysis of Swiss Seismic Sequences through Waveform Similarity

Tania Toledo * [1], Verena Simon [1], Toni Kraft [1], Tobias Diehl [1]

[1] Swiss Seismological Service [ETH Zurich] – Switzerland

The Swiss Seismological Service (SED) operates one of the densest national seismic networks in the world, enabling routine monitoring of seismicity across Switzerland. Earthquakes are routinely detected and located down to magnitudes near the completeness level of approximately Mc ≈ ML 1.0 across most of the country. Detailed analyses of routinely detected earthquakes are presented in the SED annual reports, often applying advanced techniques such as relative relocation to resolve active fault structures and to provide insights into the tectonic processes driving seismicity.

Despite this high-quality monitoring, the number of detected events in many Swiss microearthquake sequences remains relatively small. This can limit the ability to fully resolve the space-time evolution and statistical characteristics of these sequences, and therefore to clearly identify seismicity patterns and their underlying driving mechanisms. The earthquake catalog of the Swiss Seismological Service is influenced by changes in network configuration and sensitivity over time. Since the introduction of the Swiss digital broadband network in the early 2000s (completed 2002), improvements in station coverage, instrumentation, and detection capabilities have progressively lowered the magnitude of completeness, introducing temporal variations in earthquake detectability. While the overall evolution of seismic sequences can often still be inferred, these variations may obscure finer details and, in some cases, bias the apparent development of seismic activity. As a result, interpreting the long-term evolution of earthquake sequences and their interaction with subsurface fault structures remains challenging. In particular, complex processes such as fluid-fault interactions may not be adequately resolved by conventional earthquake catalogs, highlighting the need for improved methods to analyze seismic sequence evolution.

To address these limitations, we introduce QuakeMatch (QM), a waveform-similarity-based toolbox designed to enhance earthquake catalogs through template matching and cluster analysis of repeating signals. Starting from a manually revised catalog, QM detects previously missed events using waveform similarity, refines magnitude estimates, relocates detected seismicity, and enables statistical analysis of seismicity evolution.

We demonstrate the workflow and performance of this approach using the Réclère seismic sequence in the Swiss Jura fold-and-thrust belt. QM is applied to reconstruct a homogeneous, high-resolution earthquake catalog spanning from 2014 to the present day, significantly improving our ability to track the long-term evolution and migration of the sequence. We further

*Speaker

illustrate the near-real-time application of QM and its potential to support operational monitoring of seismicity by providing more reliable, consistent, and sensitive earthquake catalogs.

Keywords: waveform similarity, earthquake catalog enhancement, seismic sequence evolution, seismic monitoring

A multi-method approach for characterization of low-to-moderate magnitude earthquake sequences and seismic sources along the Africa–Eurasia plate boundary (Southern Italy)

Cristina Totaro * [1], Thomas Mancuso *

[1], Simone Cesca [2], Francesco Grigoli [3], Debora Presti [1], Barbara Orecchio [1]

[1] University of Messina, Italy – Italy
[2] GFZ Helmholtz Centre for Geosciences, Germany – Germany
[3] University of Pisa, Italy – Italy

The Africa–Eurasia plate boundary, extending along the southern Tyrrhenian Sea in the Sicilian offshore, represents a tectonically complex region predominantly characterized by a compressional to transpressional regime. Deformation is unevenly distributed along the margin, and seismicity mainly consists of low-to-moderate magnitude earthquakes. The large offshore extent of the area, combined with locally unfavorable seismic network geometry, often limits the resolution of traditional seismological analyses and hampers robust seismic source characterization. In this study, we investigate recent seismicity along the southern Italy portion of the Africa–Eurasia plate boundary, aiming to improve the characterization of active seismic sources and their kinematics through advanced, multi-method seismological approaches. Our investigation comprises: (i) a regional-scale clustering analysis of earthquakes recorded between 2010 and 2025, and (ii) a detailed characterization of recent seismic sequences in the south-eastern Tyrrhenian Sea and Northern Sicily. At the regional scale, we apply a density-based spatial clustering algorithm using a space–time distance metric to a high-resolution relocated earthquake catalog. Seismic clusters are subsequently classified as swarm-type or mainshock–aftershock sequences using statistical descriptors of the seismic moment distribution over time. This analysis enables us to identify spatial variations in seismic release patterns and to infer differences in fault segmentation, loading conditions, and stress transfer along the plate boundary. At the local scale, we focus on a set of onshore and offshore earthquake sequences and present an integrated workflow specifically designed to enhance seismic source characterization. The methodology combines Bayesian absolute hypocenter location, machine-learning-based phase picking and event detection, distance geometry solvers for relative relocation, and probabilistic moment tensor inversion. This approach resolves source geometry, fault orientation, and slip kinematics despite non-optimal network conditions, providing robust constraints on active fault planes. Overall, our results demonstrate that advanced, integrated seismological methods sig-

*Speaker

nificantly improve the characterization of active seismic sources along the Africa–Eurasia plate boundary, offering new insights into fault behavior and deformation processes in offshore and structurally complex tectonic settings.

Keywords: Low to moderate magnitude sequences, Seismic source characterization, Africa Eurasia plate boundary

Subducting Seamounts and Fault Heterogeneity: the Effect on the Earthquake Cycle

Roos Verwijs * [1], Camilla Cattania *

[2]

[1] Department of Earth, Atmospheric and Planetary Sciences [MIT, Cambridge] – United States
[2] Massachusetts Institute of Technology – United States

Seamount subduction is thought to strongly influence the slip behavior of megathrust earthquakes, yet its role in hosting earthquakes and slow transients remains controversial. Seamounts alter fault stress, fluid flow, and upper plate structure, introducing heterogeneity to the subduction system.
Here we investigate how a subducting seamount affects the earthquake cycle by modulating normal stress along the megathrust. We use the efficient boundary element model FDRA, which simulates earthquake cycles with rate-and-state friction.

We account for frictional heterogeneity along the fault by implementing a hierarchical slip-weakening distance profiles. We define three classes of slip-weakening distance profiles based on asperity number, width, and spacing. While Class 1 serves as a baseline, Class 2 features a 3.5-time increase in asperity density with similar asperity sizes. In contrast, Class 3 doubles both the number and the size of asperities relative to Class 1.

Our results show that seamounts consistently promote slow slip in the region of reduced normal stress updip of the seamount and increase earthquake activity at the stress shadow's edges, regardless of the asperity spacing and size. This increase in slow transients is a direct effect of the reduced compression; slow transients occur if the normal stress contrast exceeds a critical value, which is controlled by the nominal nucleation dimension and the seamount width. The increase in earthquake activity can be explained from a fracture mechanics perspective: seamounts can host partial ruptures if the fracture toughness, modulated by normal stress heterogeneity, overcomes the stress intensity factor after nucleation.
Furthermore, we consider the different realizations of heterogeneity and discuss their effect on the frequency-magnitude distribution and earthquake clustering. Our work demonstrates that seamounts can produce complex slip patterns including slow slip, microseismicity, and a broad range of rupture dimensions.

Keywords: seamounts, seamount, subduction, numerical modelling

*Speaker

West Bohemia seismic swarms - relocations and seismic slip distribution to map fault reactivation segments

Josef Vlcek *† [1], Tomas Fischer [1], Eva Kaldy [1]

[1] Přírodovědecká fakulta, Univerzita Karlova [Praha, Česká republika] = Faculty of Sciences, Charles University [Prague, Czech Republic] – Czech Republic

Seismically active area of West Bohemia/Vogtland is instrumentally monitored since 1980s but more reliable data are available since 1990s. We took all available manual readings of P- and S-waves made by Institute of Geophysics, Czech Academy of Sciences and applied two different techniques of refining the hypocenter locations. First common step of data processing was use of NonLinLoc absolute location followed by 1) refining method applied was use of Growclust software (1) for event relative relocation and 2) NonLinLoc option to calculate Source Specific Station Terms (NLL-SSST, (2)) to get better accuracy of the absolute locations. In this contribution we will shortly discuss pros and cons of both techniques and compare their results on the total number of more than 33.000 events (ML> 0) processed for the time span of 1991-2026 in West Bohemia area. This amount of data gives us a wide range of hypocenters to be compared from different points of view, but also regarding the separate swarms appearing through time. Consequently, spatial changes of cumulative slip distribution (3), its difference and time variations will be compared among the swarms to map the migration of seismicity and filling of empty gaps on the steeply dipping fault plane. Results show interesting migration patterns and consequent swarms jumping into empty gaps on the activated fault plane creating almost uniformly covered 2-D shaped planar structure. Proportions of newly activated versus repeatedly activated fault sections are compared showing interesting behavior of different swarms that will be discussed more in detail also for more recent seismic activity in the area.

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*Speaker

†Corresponding author: josef.vlcek@natur.cuni.cz

Keywords: West Bohemia, slip distribution, relocation

What controls the upper magnitude of swarm-like seismicity under long-term fluid injection?

Zhiwei Wang *† [1,2], James Verdon [3], P. Martin Mai [4]

[1] Université de Strasbourg - CNRS – Université de Strasbourg, CNRS – France
[2] Tohoku University – Japan
[3] University of Bristol – United Kingdom
[4] King Abdullah University of Science and Technology (KAUST) – Saudi Arabia

What controls the upper magnitude of swarm-like seismicity remains an open question in induced and fluid-driven earthquake sequences, particularly given that similar injection conditions can produce markedly different magnitude outcomes. While fault instability and operational parameters are often invoked as primary controls, it is still unclear why some swarm sequences produce moderately large events whereas others remain limited to small magnitudes.
Here, we investigate long-term injection-induced seismicity at The Geysers geothermal field (California) to examine the physical conditions under which larger-magnitude events emerge within swarm-like sequences. We combine relocated seismicity, detailed injection records, and a focal-mechanism–based instability index to assess the joint roles of fault orientation, cumulative injection volume, spatial separation from wells, and time-dependent effects on earthquake magnitude.

We find that most larger events (Mw $\geq$ 2.5) nucleate on mechanically favorable fault segments that are typically located several kilometers away from active injection wells. Fault instability thus appears to be a necessary but not sufficient condition for larger ruptures, as many smaller events occur under similarly unstable conditions. Instead, cumulative injection volume and spatial separation exert a stronger influence on magnitude trends, particularly in the upper tail of the distribution.

A consistent delay of several months between peak injection and the occurrence of the largest events points to delayed triggering processes, such as pore-pressure diffusion, aseismic slip propagation, or stress redistribution within extended fault networks. Interpretable machine-learning diagnostics further indicate that commonly used operational and geometric descriptors alone are insufficient to explain the largest magnitudes, highlighting the role of unresolved physical controls.
Together, these results suggest that maximum magnitude in swarm-like seismicity emerges from the interplay between long-term fluid loading, fault-network geometry, and delayed mechanical responses, rather than from local instability alone. This perspective has implications for seismic hazard assessment in geothermal and other subsurface energy operations, where distal and time-lagged fault activation may dominate the largest events.

*Speaker
†Corresponding author: wangzw90th@gmail.com

Keywords: Induced seismicity, Maximum magnitude, Fluid injection, Delayed triggering, Fault instability, Geothermal systems

Multi-scale Growth of an Mw 7.0 Earthquake via Hierarchical Cascading Rupture from an Mw 3.7 Repeating Event

Keisuke Yoshida *† [1], Satoshi Ide [2], Yihe Huang [3]

[1] Tohoku University – Japan
[2] The University of Tokyo – Japan
[3] University of Michigan – United States

Earthquake swarms are seismic sequences that lack a distinct mainshock and are often viewed as temporary increases in the background seismicity rate. However, as demonstrated by the 2024 Mw 7.5 Noto Peninsula, Japan, earthquake, these clusters can escalate into major events, where the earlier activity is reclassified as foreshocks. To understand how a large earthquake grows from within such clusters, we investigated the 2021 Mw 7.0 Japan Trench earthquake. In this source region, the afterslip of the 2011 Tohoku-oki earthquake significantly increased the background loading rate, resulting in a large number of events occurring over a short time period. Within this highly active area, a previous study by Yoshida et al. (2022) showed that earthquakes with magnitudes ranging from Mw 5.1 to 6.1, as well as the Mw 7.0 earthquake, initiated near a nest of small (Mw $<$ 4) repeating earthquakes. Here, we conducted a detailed analysis of P-waves and found that the Mw 7.0 earthquake initiated in a manner identical to a local Mw 3.8 repeating event. By performing deconvolution analysis, we then tracked the sequential growth of this rupture: we observed it first breaking the Mw 3.8 source area within 0.1 s, expanding into Mw 5–6 zones at around 2 s, and then involving the main area between 3 and 6 s. While four Mw 5.0–6.1 events had previously occurred nearby, the main asperity remained unruptured for years. This suggests that the readiness of the asperity dictated the arrest of those earlier ruptures. We propose that these locked areas, which normally act as barriers, instead facilitated large-scale slip once they reached a critical state under continuous loading. In this case, we identified the Mw 3.8 event as the ultimate trigger. Ultimately, our findings underscore that while asperity readiness constrains the final sizeof an earthquake, the growth process itself is fundamentally realized through a multi-scale cascading rupture.

Keywords: Cascading rupture, Rupture initiation, Repeating earthquakes, Hierarchical Structure

*Speaker
†Corresponding author: keisuke.yoshida.d7@tohoku.ac.jp

An integrated view of seismic swarms: seismicity, geodesy, and seismic velocity variations

Piero Poli * [1]

[1] Geoscience department, univerity of Padova – Italy

An integrated view of seismic swarms: seismicity, geodesy, and seismic velocity variations
Among the many geophysical expressions of seismic swarms, the increase in earthquake occurrence, together with their spatiotemporal evolution, is the most striking and has led to an incredibly detailed understanding of swarm dynamics. The integration of geodetic observations has additionally revealed the aseismic component of swarms, further constraining their underlying physics.

In this contribution, we combine the high-resolution view provided by enhanced seismic catalogs with the geodetic signatures of swarms and measurements of seismic velocity variations derived from ambient seismic noise. Although challenging, resolving very small velocity variations associated with seismic swarms is possible through a precise modeling approach that minimizes the influence of non-tectonic contributions.
Our results show that strain-induced velocity changes can be extreme and point to unusual physical properties of rocks in swarm-prone areas. We further demonstrate that these material changes, which also occur on seasonal timescales, play an important role in modulating so-called background seismicity along seismogenic faults.

Keywords: Seismology, swarms, geodesy, rocks physics

*Speaker

Non-stationarity of the magnitude distribution is diagnostic of swarminess and foreshock potential in a differential triggering cascade

Nicholas Van Der Elst * [1]

[1] U.S. Geological Survey – Pasadena, CA, United States

Earthquake magnitude as defined by Richter is a fundamentally differential measurement, as it is defined relative to a reference earthquake. That does not stop us from treating it as an independent and identically distributed random variable within a cascade (aftershock sequence or swarm). What impact might it have on our cascade models if we treat magnitude as a differential variable, assigning *differences* along the cascade? If the magnitude (difference) distribution is unbounded, then there is no difference between the approaches. However, if there is a maximum differential magnitude dMmax, then the statistical behavior of the cascade varies dramatically as a function of productivity and dMmax. By varying these parameters, sequences can be generated with the character of aftershocks, swarms, or explosive sequences. The problem can be restated in terms of a random walk with controlling parameter equal to the average magnitude drift per generation dMgen. For sequences with high productivity but low dMmax, the whole-sequence magnitude distribution steepens over successive generations of the cascade, ending with a high terminal b-value. Such sequences may have tightly restricted magnitude difference distributions while still having unbounded maximum magnitudes. In such a context, new sequence begins with a b-value that is low relative to the 'background' and increases with time. Non-stationarity of the magnitude distribution may thus be characteristic of structural/tectonic regimes with highly stressed but immature faults, prone to foreshocks and outbursts. In the context of the random walk, swarm-like seismicity (with high productivity and high b-value) emerges when the magnitude drift per generation approaches zero.

Keywords: magnitudes, non, stationary statistics, swarms, foreshocks, aftershocks

*Speaker

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