Revisiting the 2007 Mila Water Pumping Leakage Induced-Swarm (NE Algeria): High Precision Relocation and Statistical Analysis

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Abstract
In December 2007, the Mila area in northeastern Algeria experienced an unusual seismic event, comprising a series of microearthquakes with magnitudes ranging from 0.8 to 3.9. These tremors were recorded by eight temporary seismic stations in addition to ten nearby permanent digital seismic stations.
Previous research identified two distinct bursts of seismicity: a smaller peak in August 2007 and a more intense peak in November-December 2007, both driven by water infiltration through preexisting fractures, faults, and karsts. This anthropogenic activity occurred during the transfer of water from the Beni-Haroun dam to the Oued Athemania reservoir. The smaller peak was associated with a pumping test, whereas the intense activity corresponded to a 55% water leakage through defective joints in a tunnel under the Akhal mountain.
This study addresses two main objectives: firstly, to overcome a limitation of the previous study, which excluded the first ten days of seismic activity due to the absence of the nearest station, leading to uncertainties and shifts in event depths. To address this, we conducted a detailed re-examination of the 2007 Mila earthquake swarm, employing high-precision relocation techniques based on cross-correlation. Secondly, we performed a comprehensive statistical analysis to characterize the seismicity pattern using the Deep Gaussian Process ETAS model, which allows for the assessment of the variable background rate and its uncertainties. The b-value analysis and inter-event time analysis were also assessed.
The results showcased a clear correlation between the seismicity rate, the water level of the dam, and water pumping. This confirms that the increase in the seismicity rate is due to water infiltration, which was also supported by a variable background rate indicating an aseismic process and a high b-value, typically found in seismic swarm activity. This study underscores the critical importance of understanding anthropogenic seismic activities by employing statistical methods, specifically parameterized using the confirmed water-driven sequence from the 2007 Mila event. This approach aids in studying sequences with unknown driving mechanisms, providing valuable insights for risk mitigation and future planning.

Migration Diffusivity as a Dontrolling Factor in the Duration of Earthquake Swarm

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Abstract
Earthquake swarms exhibit highly uncertain temporal behavior. Their duration ranges from a few days to indefinite periods of years, making the duration's controlling factors enigmatic. Hypocenter migration is often observed in earthquake swarms. The diffusivity of the hypocenter migration represents the characteristics of the spatiotemporal behavior of earthquake swarms. To clarify the controlling factors of swarm duration, we investigated the relationship between the swarm duration and the diffusivity of hypocenter migration for earthquake swarms in northeastern Japan. We estimated the diffusivity by fitting an isotropic fluid pressure diffusion model to the migration front for the moving time bins, defined by the 90th percentile distances from the spatial origin of hypocenters. We also estimated the duration as the elapsed time that the cumulative number of earthquakes reached 90% of the total.
Estimated diffusivities range from 10^{-2} to 10^{0} m^2/s, with corresponding swarm durations from 10^{3} to 10^{0} days. These results delineated a clear negative correlation between the diffusivity and swarm duration. The relation follows a power-law with an exponent of -0.5 to 1.0. Examination of previous studies confirmed that this relationship globally holds under various localities and tectonic environments. These results suggest that diffusivity, and by extension, crustal permeability and fluid viscosity, play a key role in controlling the duration of the fluid-driven swarms.

Seismic Analysis of the 2023, ML 5.7 Southern Carpathians Earthquake Sequence: Insights into Seismicity Patterns, Crustal Structure and Stress Dynamics

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Abstract

Seismic activity in the Eastern Carpathians Arc bend (ECAB), where strong subcrustal earthquakes, with magnitudes up to 7.9, occur in a narrow lithospheric body sinking into the mantle, generating 2–3 significant earthquakes (Mw ≥ 7) every century. The overlying crustal seismic activity, although more widespread, is less intense and mainly located towards the outer side of the ECAB, raising questions about upper mantle-crust coupling. Additional seismic clusters are found in the extra-Carpathian area, particularly in the foredeep region and western Romania. Weak to moderate earthquakes also occasionally occur along the Southern Carpathians, between its two sharp bends, urging further investigation to better understand the tectonic evolution of the entire Carpathians system.

Recently, Romania experienced an unprecedented crustal seismic sequence in the Gorj area, which began on February 13, 2023, with two major shocks (M_L 5.2 on February 13 and M_L 5.7 on February 14) and numerous aftershocks extending beneath the Southern Carpathians to the Moesian Platform. To gain new insights into this seismic sequence, we employed state-of-the-art inversion algorithms and analyzed seismic data from the Romanian Seismic Network and recently installed AdriaArray temporary stations. Our goals are to compute an accurate 1-D velocity model, determine stress parameters and moment tensor solutions for the small to moderate earthquakes, as well as to explore the local stress field.

Our results are consistent with previous studies, revealing a normal faulting regime with fault planes predominantly oriented WSW-ENE, consistent with both the epicenter distribution and major fault orientations. The stress drop exhibits notable variability for smaller events, with moderate values (2 to 45 MPa) typical for intra-continental tectonic areas. These findings shed light on the tectonic mechanisms driving seismic activity in the Southern Carpathians, enhancing our understanding of the dynamic tectonic processes shaping this region.

Preliminary Observations of Swarms and Remote Dynamic Triggering Along the Liquiñe-Ofqui Fault System in Southern Chile

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Abstract

The Liquiñe-Ofqui Fault System (LOFS) is a ~1000 km intra-arc transpressive fault structure in southern Chile, running roughly between 38ºS and 47ºS. The Aysen segment (44.5-47ºS) has been associated with M 6+ earthquakes in the past. For example, a M_w 7.7 event with an estimated source duration of ~190 s occurred 15 days after the 1960 May 22, M_w 9.5 Chilean earthquake, while an intense swarm sequence that began in January 2007 culminated in a devastating M_w 6.2 event in April of the same year. How the rheological features of the LOFS control the mechanics of such large events remains an open question, in part because the long-term seismicity rate and source properties along the Aysen segment are largely unknown. In this work, we will demonstrate how a comprehensive analysis exploiting all available data will investigate the driving mechanisms behind swarms and their interaction with mainshock-aftershock sequences in the region.

We will present preliminary observations of the 2018 swarm-like sequence that started on May 11th and lasted for roughly three months. Most events within the sequence have magnitude below ML 2.7 and the maximum magnitude was ML 3.5. Seismicity was detected and located using permanent stations of Sernageomin and CSN. Initial catalog-building efforts employed a coincidence trigger algorithm with subsequent enhancement by template matching over continuous recordings. The enhanced, relocated catalog shows seismicity that is aligned with mapped branches of the LOFS. Waveform cross-correlation of the relocated seismicity reveals at least three different event families. Focal mechanisms based on first-motion polarities for the largest events of each family suggest three dominant faulting styles along a NNW direction (normal, dextral, and sinistral strike-slip). The hypocentral distribution and variable faulting style are comparable to the 2007 swarm sequence, suggesting that swarm-like activity and fault interaction might be a recurrent phenomenon along this LOFS segment. A preliminary search of remote dynamic earthquake triggering reveals that the first events of the 2007 swarm sequence in the catalog by Mora et al. (2011) occurred a few days after the surface wave passage of a M_w 8.1 event in the Kuril Islands and shortly after an M_w 7.5 in Indonesia. The temporal correlation warrants a more detailed waveform analysis in the hours bracketing the passage of surface waves to detect local events that were missed by the catalog. Specifically, the subject of this future work will be aimed at detecting the onset of potential triggering as it relates to the initiation of the 2007 swarm.

Finally, permanent monitoring of regional M<2.5 earthquakes has been out of scope and challenging due to network coverage. We therefore propose a workflow using novel techniques (e.g., denoising, AI-based phase/polarity picking) on an aggregate waveform data set from

temporary and permanent stations from 2004 to present. Specifically, we aim to study long-term seismicity and source properties and to produce a refined earthquake catalog to study the fault mechanical properties of the LOFS in greater detail.

Investigating the Complexity of the 2010-2014 Pollino Seismic Sequence: A Comparative Study of Stress Drop Estimates Using Diverse Methods

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Abstract

Seismic activity in the Pollino area is strongly influenced by structural complexities and tectonic barriers resulting from the intricate geodynamic processes generated by the slow convergence of the European and African plates. These geological-structural characteristics are highlighted through: (i) a comparison of stress drop estimates obtained using different techniques, and (ii) the application of the same analysis to other seismic sequences in the Apennines, such as 2009 L'Aquila (Calderoni et al., 2013), 2016-2017 Amatrice (Calderoni & Abercrombie, 2023), 2013-2014 Sannio-Matese (Calderoni et al., 2023), and 2019 Northern Edge of the Calabrian Arc Subduction Zone (Calderoni et al., 2020), as well as to the 2019 Ridgecrest seismic sequence in California (Calderoni & Abercrombie, submitted).The study utilizes different approaches: spectral fitting, based on the assumption that path effects are constant over the spatial and temporal extent of the sources, and the spectral ratio, which assumes that a nearby, smaller event is subject to the same propagation effects. The latter method is applied with and without constrains on the stress drop of the smaller event. The main result of this study is that the geological context of a seismic region significantly influences the choice of method used to estimate stress drop. This is due to the significant influence that geological characteristics have on the propagation of seismic waves. Different geological settings can alter wave paths, attenuation, and other seismic properties, thereby affecting the accuracy and reliability of stress drop estimates obtained through various analytical techniques. Consequently, it is crucial to consider the specific geological features of a region when selecting and applying methods for stress drop estimation. By comparing different techniques, we can ensure more accurate stress drop estimates and reliable interpretations of the results. This comparative approach allows the identification of potential biases and limitations inherent to each method, facilitating a more comprehensive understanding of the stress regime in the area under study. In addition, the inclusion of regional geological characteristics in the analysis improves the robustness of the estimates and supports the development of tailored mitigation strategies for seismic hazards.

Anti-Repeating Earthquakes in Swarms and Complex Sequences

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Abstract
Conversely as well-known repeating earthquakes, which have overlapping rupture patches, similar focal mechanisms and magnitudes, anti-repeating earthquakes have been only recently found as earthquake pairs with reversed focal mechanisms at similar hypocentral locations. Both repeating and anti-repeating earthquakes can be detected, e.g. by template matching techniques, to reconstruct complex seismic sequences and swarms, based, respectively, on highly correlated or anti-correlated waveforms. In this work, we will first report about the observation of earthquakes with anti-correlated waveforms in different environments, such as volcano, induced and intermediate-depth seismicity, and later illustrate how anti-repeating earthquakes can also be identified using seismic catalogs, which confirm their occurrence in many different seismogenic regions. Some anti-repeating earthquakes occur as single event pairs. More often, however, they were reported during seismicity unrests, both in the form of seismic sequences and swarms. We review a number of conceptual models, which have been proposed in the literature to explain the reversed rupture type of anti-repeating earthquakes. The peculiar rupture geometry of anti-repeating earthquakes reveals stress perturbation transients or local stress heterogeneities, which are often controlled by fluid migration processes. Therefore, anti-repeating earthquakes can be used as indicators to identify the presence of fluids in the subsurface and to track their migration.

Low Magnitude Seismic Swarms in the Calabrian Arc (Italy)

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Abstract

During the last decades the Calabrian Arc has been affected by an overall low magnitude seismicity, with many earthquakes clustered in swarms which occurred both inland and offshore. Some earthquakes with magnitude up to M5.0 (Mt. Pollino, 2012) have occurred in many parts of the region. Some of them triggered a sequence of usually tens to hundreds of smaller earthquakes that occurred during the following weeks or months in a small source volume. In other cases swarms of low magnitude earthquakes occur without a mainshock-aftershock evolution, but rather with several earthquakes with similar magnitude. In this work we performed detailed analyses on some of these swarms, those well recorded by a high number of seismic stations. In particular, we computed the relative location and the focal mechanism of as many earthquakes as possible, also including very small earthquakes (M<1), in order to investigate the features of the seismogenetic volume. In many cases the relative location provided a useful constrain on the identification of the fault that produced most events of the swarm, especially when coupled with the solution found from the focal mechanism analysis. In other cases the relative location allowed for the identification of a small cloud of hypocenters without a planar shape geometry, thus indicating the occurrence of the swarm in a highly fractured seismogenetic volume. In all cases, we provide an estimation of the source volume through the relative location analysis, obtaining in many cases values smaller than 1 km^3 (e.g. Umbriatico 2022, valle del Mesima 2019, Molochio 2024), but still with an extension greater than the likely size of the mainshock rupture. In other cases the activated seismogenetic volume is much greater, more than 1000 km^3 (for example Pollino 2010-2014, Cirò 2024). In the case of Molochio swarm (2024), the relative location indicates that the earthquakes occurred on two different faults about 2 km apart from each other. Most of the analyzed swarms are characterized by normal kinematics, but strike slip and reverse kinematics are also found, in particular for swarms located offshore and near the coast. The timing analysis of relative located hypocenters does not show any evident migration of the sources, thus suggesting that the driving mechanism is not related with aseismic phenomena like fluid diffusion and stress waves.

Seismic Swarming in the Apennines: Insights into their Evolution

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Abstract

Seismic swarms pose significant questions and challenges for seismology, and the lack of a singular large event complicates prediction and forecast. The mechanisms behind seismic swarms are still not well known, and their detection and analysis have potential broad implications on the seismic process. In this study we focus on some examples of seismic swarms in the Apennines, exploring their causes and main features, including fluid migration, pressure changes, and the role of geological heterogeneities. Advanced monitoring technologies and computational models really help to analyze swarm behavior, offering insights into the complex interplay of many factors. Our results demonstrate that the rapid analysis of seismological data using machine learning (ML)-based techniques is highly effective in tracking the spread of seismicity following moderate-magnitude earthquakes on fault segments within the brittle upper crust. The ability to quickly generate extensive seismic catalogs and promptly identify fault activation is crucial for assessing and forecasting seismic scenarios, even in regions with sparse monitoring systems.

We show that seismicity can be significantly triggered on segments within a large volume around the hypocenter of moderate magnitude earthquakes, with pore pressure modulation being the primary driver of segment activation. The application of ML-techniques facilitates the rapid analysis of seismic sequences and provides early insights into fluid-related processes after moderate and large earthquakes.This approach enhances our understanding of the evolution of seismic sequences and improves our ability to respond to seismic events. By integrating ML-techniques into seismic data analysis, we can achieve faster and more accurate assessments, ultimately contributing to hazard mitigation.

Re-Activating a Natural Fault Zone in the Bedretto Underground Laboratory

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Abstract

The ERC-Synergy Fault Activation and Earthquake Rupture (FEAR) project aims to activate a natural granitic fault zone within the Bedretto Underground Laboratory for Geosciences and Geoenergies in the Swiss Alps (BedrettoLab). The goal is to induce seismic events of approximately magnitude Mw ~1.0 on a 100-meter scale.
This will enable researchers to observe and study earthquake rupture phenomena in a natural setting from unusually close distance on an exceptionally well characterized fault zone.
The BedrettoLab is a research laboratory in a 5km long tunnel in the southern Swiss Alps, with an overburden of up to 1.5km. At 2.4km into the Bedretto tunnel a natural fault zone approximately 2m thick has been identified. This fault zone consists of multiple distinct shear fractures containing quartz and biotite. Some of these fractures contain gauge layers that can be up to 5mm thick. The fault zone is favourably oriented for rupture in the estimated present day background stress field.
We are currently working on excavating a side tunnel that runs parallel to the fault zone for ~120m. This tunnel will facilitate the installation of a very dense multi-domain, multi-scale geophysical monitoring system, directly on and around the fault zone. The system combines seismic monitoring at various scales (using acoustic emission sensors, high sensitivity accelerometers and broadband sensors), strain and hydromechanical monitoring (pressure sensors, fibre optic cables and Fibre Bragg Gratings) and hydrochemical monitoring. After a detailed characterization of the fault zone and the host rock, and with the monitoring system in place, we plan to activate the fault via water injection in multiple injection boreholes, in a suite of experiments. If successful, the experimental setup will allow us to study a wide range of seismic and aseismic crustal deformation phenomena from up close, including rupture preparation and precursory signals, rupture nucleation, coseismic strain localization, rupture growth and termination as well as the post-seismic response of the fault zone.
In this talk we show the results of our first fault activation experiment, which took place a few hundred meters from the target fault within a well-instrumented volume and discuss the scientific potential of the suite of planned experiments in the coming 3 years. In April 2024, we tested an injection protocol designed to pre-condition the experimental volume, which included a 4.5-day period of injection below reactivation pressure (i.e., at 15 MPa), before changing to high pressure

injection (20 Mpa). The goal was to trigger a ML~0.0 main shock. The stimulation induced numerous micro-earthquakes and, after 16 hours of high-pressure injection, we triggered a Mw~-0.4 event which was 2 magnitude units larger than the largest induced event up to that point. The event triggered an aftershock sequence with >100 aftershocks in the first 3 seconds alone. The high-sensitivity and -resolution observations from our multi-scale and multi-domain borehole monitoring array facilitate the study of the hydromechanical processes that drive this complex sequence of induced earthquakes, showing that the main shock is embedded in a network of pre-existing geological structures.

Statistical Analysis of Earthquake Clusters in the 2016/17 Central Italy Sequence Identified with Machine Learning

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Abstract
In this study, we analyze the spatiotemporal variability of the magnitude–frequency distribution (MFD) during the 2016/17 central Italy earthquake sequence. We use a combination of three unsupervised machine-learning algorithms applied to four individual temporal periods separated by the largest events. Specifically, we use DBSCAN for event clustering, OPTICS for analyzing spatially nested dense zones, and PCA for identifying potential segments of complex fault surfaces. By incorporating only past data within each period, our approach mimics the information that is available in near real-time during an earthquake sequence.

DBSCAN clusters earthquakes based on density, revealing the emergence of active volumes over time; OPTICS provides insights into the spatial nesting of dense zones within these clusters, further refining our understanding of their structure; and PCA facilitates identifying complex fault surfaces by highlighting planar features within the high-density zones.

We demonstrate that the geometry of these clusters evolves over time and exhibit a different MFD. We characterize the MFD with the b-positive estimate, which is a b-value based on using only positive magnitude differences to circumvent a bias from short-term incompleteness especially after large earthquakes. In particular, the clusters located closest to the hypocenter of the largest earthquake (Norcia), are characterized by a strong variation of b-positive, reaching the highest value before the Norcia mainshock. To better explore the causes of such variability we zoom into a dense zone of this particular cluster before the Norcia mainshock, and we find a quasi-planar fault with a high dip angle together with sub-horizontal faults.

We further analyse the MFD of the high dip angle structure over time by estimating a weighted b-positive, in which earthquakes further away from the structure contribute increasingly less (1 / distance for distances > 500m). We find that before the Norcia mainshock, b-positive is around 1.0 (albeit with large uncertainty), which is characteristic for the tectonic background, whereas b-positive increases markedly after the Norcia mainshock on that specific tectonic structure.

These findings highlight the significance of spatially isolating seismically active clusters to resolve the fine-scaled variation of the b-value in a meaningful way. Our study showcases the potential of machine learning techniques to characterize the geometry and MFD of seismically active clusters during a sequence rapidly and reproducibly. It underscores the importance of integrating machine learning algorithms to analyze seismic sequences. This integration not only improves the resolution of seismically active clusters but also enhances the interpretative capabilities regarding their geometrical and dynamical properties. This capability may aid in better understanding the complex MFD variability during an earthquake sequence.

Seismic Swarms in the Azores: The Example of the February 2018 São Miguel Crisis

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Abstract
The Azores archipelago is located on the north Atlantic ocean, on the triple junction between the North America, Eurasia and African plates. The archipelago comprises 9 populated islands of volcanic origin. The geodynamic of the Azores is quite unique, displaying a complex interaction between the tectonic processes associated with the triple junction and magmatic processes associated with a hypothesized mantle plume that underlies the archipelago. This scenario renders the Azores a very active region both in terms of volcanic and seismic activity.
In this presentation we will start by characterizing the overall seismicity of the archipelago of the Azores. Instrumental catalogs show that both the a- and b- values of the Gutenberg-Richter law increase systematically from the east, near the oceanic transform Gloria fault, to the west, close to the triple junction and mid-Atlantic ridge, indicating a regional progression from dominantly tectonic to dominantly volcanic processes. The catalogs also show an abundance of swarm-like seismicity, often associated with episodes of volcanic unrest. Higher magnitude mainshocks sometimes occur at the beginning or within seismic sequences, but curiously sometimes also occur isolated, without noticeable aftershock sequences.
S. Miguel is the largest and most populated island, and the most seismically active one. In this work, we'll focus on the February 2018 seismic swarm, the most recent unrest episode in S. Miguel. We carried out an automated analysis of continuous waveform data. Our workflow includes detection and location using the back-projection of waveform-based characteristic functions, single-stations magnitude estimation, clustering based on waveform similarity and template matching to extend and complete the catalog. In addition, we computed tensor solutions for selected events. This workflow was completed with waveform spectral analysis.
We identified three clusters of earthquakes with similar waveforms. The first includes events that occurred during a 7-day precursory phase. The waveforms display high-frequency P- and S-waves, typical of brittle failure. A second cluster is activated on 12/February. On this day the seismic rate increases abruptly and the highest magnitude (Ml=3.4) of the swarm is recorded. The waveforms of this cluster have a lower frequency content than those of the first one. Finally, a third cluster is activated, with a much lower number of events. These waveforms have a more harmonic character.

Although the clusters have distinct waveforms, spectral analysis shows no significant differences between the three clusters spectra, implying a common earthquake seismic source.

From the first to the last cluster, earthquakes migrate slightly shallower (15 km to 10 km) and to the SE. Focal mechanisms indicate mostly normal faulting. We interpret the first cluster as brittle fracturing at depth, followed the triggering of shallower structures (2nd cluster), and finally by events that occur already in a fluid-rich environment (3rd cluster). Interestingly, this seismic swarm marked the beginning of a period of aseismic surface deformation that lasted over the subsequent 17 months. Such inflation periods associated with seismic swarms seem to be recurrent in the study region, indicating a persistent process that is activated episodically.

Seismic Migration Driven by Fluid-Induced Aseismic Slip in Natural Swarms and Anthropogenic Induced Sequences

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Abstract
Seismic swarms are clusters of seismicity without large mainshocks. They can happen naturally or be induced by human activities, particularly during hydraulic stimulations of reservoirs. A notable feature of seismic swarms is the migration of their hypocenters, providing insights into the processes driving the swarm. Initially, the seismic front was attributed to fluid diffusion. However, recent understanding points to the propagation of a fluid-induced aseismic slip as the underlying cause.
This interpretation is supported by a global analysis of migrating sequences, revealing two different, parallel behaviors in the scaling laws between migration velocity and duration: one linked to slow slips with high migration velocities and another related to fluid-induced processes with low velocities. These distinctions offer metrics for identifying the drivers of earthquake swarms.
For seismicity driven by a fluid-induced aseismic slip, seismic migration depends on the hydromechanical properties controlling the dynamics of aseismic slip propagation, rather than hydraulic diffusivity. Comparisons of numerical simulations with extensive earthquake catalogs suggest that the shape of the seismic front may indicate the initial stress state of faults where swarms occur. In this context, migration distance depends on the root-square of the volume, rather than elapsed time, which can help reconstruct injected volumes in natural swarms.
Additionally, a seismic back-front, delineating an area devoid of seismicity, is consistently observed in swarms of both natural or anthropogenic origin during the injection period. Conversely, post-injection back-fronts are rare and occur only when there is a rapid fluid pressure decrease at the injection point. The minimum magnitude of seismic events is observed near the injection point, and the vanishing seismicity behind the back-front results from the increase in earthquake nucleation length with increasing fluid pressure. Therefore, the seismic back-front during injection corresponds to the fluid diffusion front.
In summary, the new model for swarm seismicity driven by a fluid-induced aseismic slip, rather than direct fluid pressure effects, fundamentally modifies the interpretation of migrating patterns. This advancement improves the identification of swarm-driving processes and helps infer fault properties and hydraulic parameters.

Fluid-Driven Seismic Swarms in the Gripp Valley (Haute-Pyrénées, France)

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Abstract
An unusual seismic activity has recently occurred in the Gripp valley, located in the central part of the French Pyrenees. Since spring 2020, two new swarms appeared, clearly outside the usual location of the seismicity in this area. On 20 September 2020, almost concomitantly with the activation of the second seismic swarm, a hole suddenly opened in the bed of a local river, the Adour de Payolle. This hole drained the water from the river, which dried up over 500 m. We follow and study the spatial and temporal evolution of these clusters, using four temporary stations deployed a few days or months after the beginning of the crisis to complete the regional network. Using permanent broadband network, Rasberryshakes sensors and temporary seismic stations, we obtained additional data that lead to the construction of a comprehensive catalog of more than 4900 earthquakes, using both a template matching approach and a deep-learning based phase picking method to complete and improve the initial catalog available from the French seismological agency. This allows highlighting a slow and clear migration of the seismicity during 1 yr. Precise absolute and relative event locations reveal a dipping faulting structure, confirmed by the focal mechanism estimated for the highest magnitude event of the sequence (ML 3). During 2022 and 2023, the seismic swarm stopped and an old one was reactivated. We propose to explain the observed migration of the seismicity by deep fluids going up through a newly discovered faulting structure.

Swarm Seismicity as Indication for Magmatic Activity Along Ultra-Slow Spreading Ridges: Insights from a High-Resolution Earthquake Catalog Obtained from Gakkel Ridge Deep (Arctic Ocean)

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Abstract
Detailed seismicity analyses in a focused, localized area can provide insights into the physical processes active within it. This is especially true when seismicity deviates from classical mainshock-aftershocks behavior and exhibits swarm-like behavior. Such analysis is particularly valuable in regions where the physical processes driving swarm activity operate at scales too small to be detected by other methods, or where measurements are generally sparse.
In this work, we produce a high-resolution earthquake catalog that is further analyzed to study the physical processes active along a volcanic center at the Gakkel Ridge (Arctic Ocean). The Gakkel Ridge is one of the slowest spreading ridges on the planet, with spreading rates of ~5 mm/year and indications of seismicity from onshore seismic stations at regional distances.
We use a seismic dataset collected over a period of one year by a small-scale (interstation distances of ~15km) ocean bottom seismometer network. This network was deployed at water depths exceeding 3000 meters, positioned near a volcanic center in the sea-ice-covered waters at the Gakkel Ridge. We use a semi-automatic picking approach to identify phase arrivals of local earthquakes at different stations. These picks are then associated with seismic events for which we estimate absolute locations. This approach reveals abundant micro-seismicity within the study area despite increased ambient noise levels in the ocean. We then apply template matching to automatically rescan the dataset for events with amplitudes only slightly above the ambient noise level, which often go undetected by conventional methods. The latter step decreases the detection capacity by approximately one order of magnitude.
We then perform a subsequent statistical analysis of the resulting high-resolution earthquake catalog that reveals two dominant types of seismicity. The first occurs over a bulk of the duration of the experiment, with temporally random seismicity that does not exhibit discernable spatial organization. The low magnitude of completeness of the enhanced catalog allows us to identify the second population of small-magnitude ($M < 3$) earthquakes that occur over short time periods (hours to days) in dense spatial clusters, which are unrelated to the occurrence of a large mainshock. The small clusters exhibit signs of migration away from an aseismic area.
We will present interpretations of random seismicity resulting from large-scale tectonic stress release along the ridge, that producing a constant rate of seismicity over time without significant organization. We will also discuss the characteristics of the second population of organized

seismicity, and interpret swarm-type behavior as indicative of ongoing localized magmatic activity. The latter highlights that magmatism occurs even at the slowest spreading ridges.

Constraining Links between Seismicity and Eruptive Behaviour at Mt. Etna Before, During and After the 2018 Flank Eruption

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Abstract

Volcanic seismicity is a powerful indicator of activity at volcanoes worldwide, providing information on volcanic structures and subsurface processes such as magmatic fluid transport.Volcanic systems produce a range of eruptive styles and durations; determining whether future eruptions will be explosive or effusive is key for reducing the hazards faced by local communities. Mt. Etna is the largest volcano in Europe and is continuously monitored by a substantial seismic network; this provides an ideal location to quantitatively constrain links between eruptive styles and seismicity.

During periods of intense volcanic activity, many seismic events will go undetected. Repeating earthquakes are events that have identical waveforms, implying that they are from the same source origin and mechanism. A matched filter search identifies repeats of template events, including those which are hidden behind the noise, and can increase a seismic catalogue by a factor of 10. Separating seismicity into families of similar waveform properties, provides a way to monitor how the seismic signal evolves through time, building a framework that can be linked to subsurface processes and eruptive styles.

Here we focus on a flank eruption in December 2018 which saw a large increase in seismicity during the first few days of the eruption. We use 483 events detected by the INGV seismic catalogue in December 2018 as templates for a matched filter search over 2018-2019. We use a combination of relative and absolute location methods to further constrain hypocenter locations for the detected events. This is used to establish a framework that links subsurface processes and structures, providing a quantitative comparison with the vast and complex eruptive history of Mt. Etna.

Seismic Swarm and Graben Formation Preceding the Grindavík 2023 Eruption

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Abstract

The Reykjanes peninsula volcanic unrest started in March 2021 when a fissure eruption took place in the Fagradalfjall area and was followed in August 2022 and July 2023 by another two eruptions of the same volcanic dyke. All these eruptions were preceded by intensive seismic swarms and accompanied by surface deformation indicating extension and vertical movements due to the magma migration.

In October 2023 the seismic activity moved to the Grindavik/Svartsengi area where strong and episodic uplift has been observed since 2020. The seismic swarm activity started on 25 October and activated the oblique rift zone. On 10 November the seismicity trend turned and highlighted a narrow NE striking zone of about 15 km length, which was accompanied by a fast subsidence resulting in formation of a graben, 5 km long and 2 km wide. The following seismic swarm gradually decreased until 18 December when the first eruption of the ongoing series of eruptions started.

We analyze the space-time distribution of precise hypocenter locations of the seismic swarms and compare it with the geodetic measurements. We found multilateral migration of events whose character changed during the swarm evolution. However, a common feature of this migration was the fact that a few days before the eruption, an aseismic zone formed at depths above 5 km, adjacent to the site of the future eruption.

To understand the relation of the Grindavík seismic swarm, the graben formation, and the following eruption, we determined the focal mechanisms of majority of detected earthquakes and analyze occurrence of typical focal mechanisms during the activity evolution. Results indicate that the unrest was cause by a combination of transtensional setting of the plate boundary enforced by magmatic activity.

Machine-Learning Catalog Building Applied on the Campi Flegrei Caldera Swarm

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Abstract
Nowadays the use of neural networks and artificial intelligence in seismology provides high-resolution seismic catalogs including very small magnitude events that remained undetected by human analysts. In this study, we propose a workflow for earthquake-catalog building using machine-learning methods applied to the Campi Flegrei area struck by a seismic swarm and an increase in seismicity in the last few years. We extracted data recorded by 30 seismic stations from 1st January 2023 to 17th June 2024. We used the Deep Neural Network PhaseNet to detect P- and S- waves arrival times and GaMMA to associate the picks, obtaining at first 16,062 seismic events. We selected the best location with at least 4P and 2S arrival time to compute 1D-location and Double-Difference relocation. The rapid analysis with ML-methods helps constrain the evolution of seismic sequences and could support other types of analysis (using these data in a seismic tomography, for example). The pattern of seismicity distribution enables us to clearly define the main active structures and the role of ring faults in accommodating the deformation induced by the magmatic source at depth.

Recent VT EarthquakeEswarms in Campi Flegrei (Italy)

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Abstract

A strong increase of seismic activity has been recorded in the Campi Flegrei caldera during the last few years. Thousands of VT earthquakes, often occurring as swarms of tens of events, are located in the uppermost 3 km crustal layer in the middle of the caldera. The maximum magnitude observed to date (July 2024) is M4.4. Only a very few events can be classified as low frequency (LF) earthquakes since they have features different from the classic VT earthquakes, as shown by the spectral content of the recorded seismic signals. The possible occurrence of volcanic tremor has not been recognized yet in the (very noisy) seismic signals. In this work we computed the focal mechanism of most earthquakes with magnitude M>=2.8 occurred during the last two years. Results show that all types of solutions are found, with a predominance of normal kinematics (about 50%). The mixing of earthquakes with very different kinematics located very near to each other indicates that they occur in a highly fractured volume (as expected for a volcanic environment) subjected to a varying stress field. As the normal stress acting on a fault decreases a little, the fault can move under the shear stress, and this happens with an almost random character.

The full moment tensor inversion computed for the strongest events indicates that double couple (DC) is the most important component for the analyzed events, while CLVD and ISO components take smaller values. The search for earthquakes with similar waveforms does not identify large families of seismic events but it yields several clusters composed of a small number of very similar earthquakes. The spatial distribution of released energy was computed and the result shows that during the last two years the most of seismic energy has been released in the area around Solfatara crater, about 2 km east of the place where the maximum ground uplift is observed. A comparison with the structural setting of the inner part of the caldera shows a good agreement with the most important recognized structures. Source scaling has been investigated for earthquakes with M>=2 (M_0 >= 10^{12} Nm) and results show stress drop values around 1 bar with fault size smaller than 1 km of diameter in the assumption of a circular fault.

The results of our analyses indicate that the ongoing seismicity has all features typical of tectonic type earthquakes that occur on a lot of small and very small faults activated by the ground uplift that is the most important feature of the present volcanic activity. Only a very small percentage of non-VT earthquakes betrays the role of the volcanic environment in current seismicity.

Seismicity Acceleration and Clustering Before the Mw 7.9 Gorkha Earthquake, Nepal

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Abstract
Several observations of peculiar seismic and geodetic phases preceding large earthquakes have been documented. Despite being a-posteriori, these observations provide a better understanding of the processes involved in the nucleation of earthquakes. The analysis of several sequences of large earthquakes have shown an abnormal behavior of the seismicity preceding the mainshock. In particular, swarm-like sequences have been evidenced to occur (Tangshan earthquake, China, 1976, L'Aquila earthquake, Italy 2009, the 2016-2017 earthquakes in central Italy, the Iwate-Miyagi earthquake in Japan, or more recently, Noto earthquake, Japan 2024). These swarms are often related to the presence of fluids that increase the pore fluid pressure and reduce the effective normal stress, hence bringing a fault closer to failure and facilitating slip. They can also be accompanied by slow slip transients. Such deviation from the normal behavior of seismicity is better seen when micro-seismicity is analysed. In this study, we investigate the foreshocks and pre-seismic phase of the Mw 7.9 25 April 2015, Gorkha-Nepal earthquake by applying a matched-filter technique on its nucleation zone. We use the seismic signals of 1851 local earthquakes and the continuous signal recorded at the nearest station for the 6 years preceding the mainshock. The pre-seismic phase depicts a long-term increase of seismicity rate and several seismic swarms less than 20km away from the mainshock epicenter. The longest swarm occurs one month before the Gorkha earthquake, lasts two weeks and consists of 38 repetitive earthquakes located at the north western edge of the rupture zone. Another increase in seismicity rate starts six days before the mainshock and includes small foreshocks that develop at less than 10 kilometers from the future earthquake hypocenter. These observations suggest that the Gorkha earthquake was preceded by a pre-seismic phase related to a potential initiation of slow slip triggered by fluids at the northwestern boundary of the rupture zone.

Seismicity Patterns and their Source Regions at Krafla (N-E Iceland)

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Abstract

Krafla is one of the five central volcanoes of the Northern Volcanic Zone in north-east Iceland and has been utilised for decades for geothermal energy production. Thus, the volcano and its geothermal system have been monitored and imaged extensively with various geophysical methods to better understand this complex geological system not only for scientific, but also industrial interests. However, an unexpected encounter with magma at a relatively shallow depth while drilling the IDDP-1 borehole in 2009 proved, that the imaging of small-scale structures remains challenging in such heterogeneous geological settings.

With a ten-year dataset of 30.000 manually picked events from a local permanent 12 station seismic network owned by Landsvirkjun and operated by Iceland GeoSurvey, and a very dense temporary array of 98 seismic nodes deployed for one month in 2022 in the center of Krafla caldera, we performed a multi-scale analysis using local earthquake tomography to identify not only small-scale velocity structures, but also to improve the localisation of earthquakes.

The velocity structures retrieved in the high-resolution 3D models for P- and S-wave velocities offer a glimpse into the subsurface of the volcanic system with the two wave types being responsive to distinct rock/fluid properties and their phases. The relocated seismicity underscores active structures pinpointed through the tomography. The seismogenic zone hosting the largest, rather diffuse cluster of earthquakes at Krafla is located at the interface of high to low Vp/Vs close to where magma was repeatedly encountered by wells. Even though these events are located at the same boundary, their focal mechanisms vary widely from double-couple mechanisms with normal and thrusting earthquakes striking in different directions, to non-double-couple explosions and implosions. To decipher if events can be attributed to different sources, we use an unsupervised machine learning approach to cluster the events based only on the polarity of the P-onset, to make sure that path effects in the clustering are minimized. This work is still in progress, but the first results obtained on less complex clusters show that with our approach, events originating from diffuse seismicity clouds can be attributed to different sources, using the existing focal mechanisms only to validate the clustering.

By applying this method to the ten-year data set, we hope to gain a better understanding of when and where structures are active in an area which, because of its physical properties and its fluid content, is likely to generate seismicity. Comparing these results with additional data like GPS or production and injection patterns at the geothermal powerplant, can offer insights if volcanic

forcing such as inflation/deflation or external forcing such as regional seismicity and anthropogenic influence trigger certain seismicity patterns.

How Can Anthropogenic and Natural Swarms be Distinguished from Self-Driven, Epidemic-Type Earthquake Sequences?

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Abstract
Natural earthquake swarms are only loosely defined as spatiotemporal clusters of seismicity that do not exhibit typical mainshock-aftershock patterns. Earthquake swarms are usually associated with aseismic driving forces, such as fluid intrusion or slow-slip events, while aftershock sequences are explained by mainshock-induced stress, i.e., by earthquake-earthquake triggering, and the corresponding seismicity can be well explained by the Epidemic-Type Aftershock Sequence (ETAS) model. However, in addition to typical mainshock-aftershock patterns, ETAS simulations also show swarm patterns with the same parameters. These ETAS swarms are simply a random result of the same earthquake-earthquake triggering processes as the mainshock-aftershock sequences. Therefore, it is important to define swarm features that can distinguish “aseismically-driven” from “self-driven” swarms.

Here, I analyze a set of features ranging from commonly used parameters calculated from the magnitude time series to spatiotemporal features related to migration patterns. I compare the values of these features for natural and anthropogenic swarms with the corresponding values for a large set of ETAS simulations. The results show that most of the features are useless on their own to discriminate between aseismically-driven from self-driven swarms. Combinations of features are necessary to distinguish the observed swarms, where aseismic forcing is known or very likely, from ETAS-type clustering without external forcing.

Swarms in the Pacific Northwest of North America

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Abstract

The Pacific Northwest of North America includes a variety of tectonic regimes, resulting in all kinds of small-magnitude earthquake swarms. The subduction of the Gorda, Juan de Fuca, and Explorer oceanic plates beneath the North American plate is associated with volcanic swarms at active volcanoes and deep earthquake “nests” of uncertain origin. In addition, earthquake swarms at various depths within the crust, most likely related to fluid flow, occur repeatedly in specific geographic regions in the forearc and backarc and compressive and extensional settings. Despite the prevalence of small-magnitude swarms, the area appears to have low aftershock productivity rates. To gain further insight into the spatial-temporal behavior of seismicity in this region, we present a systematic study of various statistical quantities of the authoritative ANSS (Advanced National Seismic System) catalog to quantify earthquake clusters in space and time. We, and others, hypothesize that swarms show distinct parameter value ranges for descriptive statistical relations depending on the seismogenic process and, conversely, that swarms due to similar driving forces will show similar values. In addition, to investigate to what extent statistics of a routinely created earthquake catalog are representative, we compare the statistics of the standard catalog and a waveform cross-correlation derived catalog for Mt. Hood volcano in Oregon. Our goal is to describe observed patterns. We do not aim to create a forecast model; however, our results may inform such models.

The instrumental catalog in parts of the PNW with accompanying event-triggered waveforms covers the period from 1980 to now. Over time, the regional seismic networks used to create the catalog have changed significantly; we cannot assume the same level of completeness over time, nor in space. Similarly, the estimated earthquake locations and magnitudes have inherent uncertainties that exceed the formal uncertainties provided by the location and magnitude estimation programs. To complicate things, the location inversion and magnitude methods vary by regional network and over time. We try to account for the various uncertainties in the source parameters in the catalog when deriving the statistical relationships that describe the occurrence of the events in time and space. Imperfect input data does not prevent us from identifying and describing the robust features of the catalog. We identify spatially small clusters that reactivate over time at a wide range of depths, seismic zones that exhibit the more typical behavior of tectonic events, and many isolated events not readily associated with a particular structure or process.

Pre-Eruption 2021 Seismic Swarm at Fagradalsfjall, Iceland as a Sensitive Indicator of Volcano-Tectonic Movements

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Abstract

Iceland represents the onshore continuation of the Mid Atlantic Ridge separating the North American and Eurasian plates. It is the only section of the Mid-Atlantic Ridge exposed above sea level. The Reykjanes Peninsula in SW Iceland forms its active oblique spreading segment in place where the rift bends to its landward continuation. Such a setting produces transtensional tectonics characterized by increased seismicity, volcanism and high-temperature geothermal fields. The main tectonic features are expressed by a large number of NE-SW trending volcanic fissures and normal faults with grabens followed by several N-S striking faults from large earthquakes. The Fagradalsfjall volcanic system in the southern part of the Reykjanes Peninsula featured an increased seismic activity in late February 2021, which led to the first present volcanic eruption in this area on March 19, 2021. This eruption was succeeded by several other volcanic and tectonic unrests expressed by thousands of earthquakes, local and regional surface inflation, and four effusive eruptions over a span of three years.

We focused on the Fagradalsfjall 2021 pre-eruption seismic activity and interpreted seismic data recorded by local REYKJANET seismic network. The earthquakes with local magnitudes up to 5.3 (February 24, 2021) were located at depths 2-6 km and indicated activation of several fault segments related to dike and transform setting. Focal mechanisms and moment tensors with non-double-couple (non-DC) volumetric components of these earthquakes revealed complex evolution with three different regimes of faulting. They comprised (1) shearing at WSW-ENE trending strike-slip faults accompanied by north-south trending strike-slips, (2) collapses at normal faulting with negative volumetric components above or close to the magmatic dike with the same strike as the volcanic fissures and coinciding with the March 19 eruption, and (3) reverse faulting with positive volumetric components connected to magma movements and/or over-pressurized fluids migrating through the fractures. The spatiotemporal evolution revealed the interactions between tectonic and magmatic processes in this volcano-tectonic area.

Qseek: A Data-Driven Earthquake Detection, Localisation and Characterisation Framework

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Abstract

We present a data-driven method and the software framework qseek to automatically generate seismic catalogs from large seismic data sets with great accuracy and efficiency. The method is based on a stacking and migration approach in combination with machine learning phase arrival annotations to detect and locate seismic events in continuous data.

To efficiently detect and accurately locate seismic events, we developed an octree search algorithm, which iteratively refines the resolution towards the seismic source location. Our software framework integrates the Pyrocko and SeisBench platforms and offers feature extraction capabilities, such as moment and local magnitude calculation from peak ground motions. We extract and incorporate station corrections and source specific station corrections to enhance the location accuracy of the algorithm.

We demonstrate the robustness and scalability of the method by processing various large seismic data sets to generate seismic catalogs with high completeness which captured diverse seismic activities. These include volcanic swarm activity and tectonic earthquakes. The data sets include volcanic swarm activity on the Reykjanes Peninsula, Iceland, seismicity at Campi Flegrei caldera in Italy, four years of magma ascent beneath La Palma and seismicity at Vulcano, Italy.

The evolution and expansion of seismic monitoring networks has significantly amplified our observational capabilities. The developed efficient and automatic analysis workflow of large data sets for seismicity can offer insights into the dynamic processes within the Earth's crust and mantle. Here waveform-stacking methods and machine learning allows the detection of micro-seismic events in noise-dominant environments, this improves the detection sensitivity by emphasizing on the coherency of seismic energy and phase arrivals across networks.

Slow Slip in Earthquake Swarms on Oceanic Transform Faults? Lessons Learned from the Húsavík-Flatey Fault in North Iceland

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Abstract
More than half of the moment release on Oceanic Transform Faults (OTFs) is believed to occur in slow slip events with associated seismic swarms, rather than in large earthquakes. This has, however, been difficult to study in detail because of the inaccessibility of OTFs for geodetic observations. The location of the Húsavík-Flatey fault (HFF), a 100 km long OTF just off the northern coast of Iceland, provides a potential solution to this problem. The HFF has had multiple energetic earthquake swarms since 1995 (when accurate recording started) with thousands of recorded events of magnitude up to 6. These swarms have shown spatial complementarity with later swarms filling in gaps left behind by previous swarms, indicating stress interaction between different parts of the fault, which is difficult to explain without notable slow slip associated with the swarms. However, significant slow slip has not yet been confirmed by geodetic observations due to lack of continuous GPS (CGPS) stations close to the activity. In 2017-2020, we installed three CGPS stations on the north coast close to the offshore HFF swarm activity and they have been running since then. An energetic earthquake swarm took place in June 2020 with magnitude 5.4, 5.7 and 6.0 earthquakes. The M6.0 event was the largest earthquake to occur in North Iceland since 1976. The earthquake swarm caused clear displacements of up to 10 mm on the new CGPS stations as well as on several campaign GPS sites near the north coast. Our modeling shows that most of the GPS station movements can be explained by coseismic offsets of the three largest events, although some slow slip might have taken place during the earthquake swarm. Therefore, the results show that most of the moment in this seismic swarm was released co-seismically rather than by slow fault slip. Future earthquake swarms will reveal whether this is generally the case for the HFF or if slow slip plays a larger role in some cases.

Ground-Motion Analyses of Maurienne Swarm (2017-19)

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Abstract
Between August 2017 and March 2019, an intense seismic swarm was recorded in the Maurienne valley in the north of the Belledonne massif (Western French Alps). In order to study the spatiotemporal evolution of the Maurienne swarm, Minetto et al. (2022) created a high-resolution catalog based on template matching, double-difference relocation, and moment magnitudes. The catalog includes 71,064 events with a maximum moment magnitude of 3.5 and a magnitude of completeness of 0.7. Minetto et al. (2022) interpreted the seismic activity as reactivation of an N80 strike-slip fault system called Fond de France, and the presence of a shallower fault system with the same strike, but opposite dip direction and smaller size. The presence of two distinct fault systems was attributed to the observed variation of the b-value with depth. The seismicity migrated asymmetrically in all directions during the course of about 15 months. Shorter migrations lasting 2–3 days are also observed. In addition, the asymmetric migration of seismicity was inferred to be driven by several mechanisms, possibly a combination of pore-pressure diffusion and earthquake interactions. In this study, we performed statistical analyses of the Peak Ground Accelerations (PGA) and Velocities (PGV) of the 71,064 events recorded by a nearby broadband seismometer “A181A” of the AlpArray network. The analyses involved evaluating the swarm PGA/PGVs against the Ground-Motion Models (GMM) used in European Seismic Hazard Map 2020 (ESHM20). The GMM is updated via a Bayesian framework to extend its applicable magnitude range, and followed-up with a residual analysis. The residual analysis revealed remarkable spatial and temporal trends wherein; deeper events produced higher PGAs than shallower events of identical magnitude, events occurring in winter produced higher PGVs than those of identical magnitude occurring in summer. In addition, there appears to be dramatic spatiotemporal changes in PGA/PGV residual variabilities during different phases of the swarm. We are currently researching physical mechanisms driving such spatiotemporal trends in swarm ground-motions, and their relation to evolution of swarm seismicity. The analyses can be replicated on other swarms; with the intention of revealing robust and repeatable phenomena that can be modelled for ground-motion prediction, hazard and risk from larger, tectonic earthquakes.

Seismic Activity in Belgium: Characterizing Swarm-Like Patterns and Geothermally Induced Seismicity

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Abstract

Belgium, situated in a stable part of the European continent, exhibits a low to moderate seismic activity, but has experienced significant earthquakes over the last centuries. Historically notable events include the 1692 Verviers earthquake, which occurred on September 18th with an estimated magnitude of 6 ¼, causing considerable damage with an intensity of VI-VII on the EMS 98 scale. This earthquake is one of the most damaging in Belgian history, affecting a wide area. Earlier, a magnitude 6.0 earthquake in the North Sea on May 21, 1382, was felt in the region, highlighting early seismic awareness. In 1580, another magnitude 6.0 earthquake occurred in the Strait of Dover, or 1756, the Düren earthquake, with a magnitude of 5.7, also both caused significant damages.

More recent seismic events have generally been of lower magnitude but are still noteworthy. The 1983 Liège earthquake, with a magnitude of 4.7, caused massive damages locally and was significantly felt in the area. On April 13, 1992, a 5.4 magnitude earthquake struck Roermond, resulting in minor local damage and a felt intensity of IV-V. The 2002 Eschweiler-Alsdorf earthquake, with a magnitude of 4.6, was also felt broadly. Other significant tremors include the 1921 Geraardsbergen quake measured at 4.0 magnitude, the 1938 Zulzich-Nukerke earthquake with a magnitude of 5.0 that caused many chimneys to fall, and the 1755 Aachen earthquake with a magnitude of 5.2, highlighting the region's vulnerability to such events.

The country has also faced episodes of "swarm-like" seismic activity, such as the 1987 “Dour” sequence (60 events), the 1989-1990 Hautes-Fagnes sequence (452 events) and the more recent 2008-2010 Walloon-Brabant sequence (239 events). This last example reactivated an area that was affected by a swarm in 1953-1954, with comparable waveform characteristics. These swarms are marked by numerous, temporally clustered seismic events rather than isolated occurrences, without clear fore- or aftershock sequence around a major event. At the time of their occurrence, those sequences have been studied thoroughly to provide valuable insights into the fault zone geometries, fault mechanisms, etc. The 2008-2010 sequence location was compared to local geology and gravimetric data, suggesting a clear delineation of the responsible fault. The analysis of the focal mechanisms and stress regime can be explained by an analysis of the local stress tensor variation in central and north Belgium estimated from differences in the gravitational potential energy (geoid).

In addition to natural seismic activity, Belgium has recently encountered geothermally induced seismicity. The development of geothermal energy projects has inadvertently triggered numerous small magnitude events, primarily due to fluid injection processes. For example, the first injection test at the Balmatt-site in Mol triggered more than 740 events that could only be measured by 2 permanent stations (distance: 4 km). This required the adaptation and development of advanced tools for detecting and characterizing seismic events.

Improving Forecasts During Earthquake Swarms

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Abstract
Earthquake swarms present challenges for earthquake forecasting because compared to more common mainshock-aftershock sequences, they are more difficult to define and characterize. While the time decay of aftershock sequences can be modeled with the modified Omori law, it is difficult to forecast how long a swarm is likely to last or how seismicity rates may vary because the rate is controlled by the behavior of the external driving process (e.g., fluid migration, slow slip, or volcanic processes). The U.S. Geological Survey (USGS) has released earthquake advisories and forecasts during some swarms, such as the 2016, 2020, and 2021 swarms near the Salton Sea in California, a region of particular concern due to its proximity to the southern San Andreas fault. These forecasts have informed responses by local and state government agencies, as well as public discussion in news and social media (McBride et al., SRL, 2020). These experiences have demonstrated the need to improve both the models that are used to make forecasts during swarms as well as how these forecasts are communicated to the public and other stakeholders who may not be familiar with earthquake swarms.
Here we define a swarm simply as a sequence of earthquakes where changes in earthquake rates are driven by external processes in addition to typical mainshock-aftershock triggering. This definition allows a swarm to be described with a time-varying background rate term in the Epidemic-Type Aftershock Sequence model (Ogata, JASA, 1988), which is already used to produce aftershock forecasts in many regions. A swarm forecast can therefore be computed by adding a temporally varying background rate to the approach used for an aftershock forecast. Currently, the USGS forecasting method estimates this rate from the swarm so far observed and a swarm duration model based on past regional swarm activity (Llenos and van der Elst, BSSA, 2019). This procedure is applied using expert judgement when the inclusion of the extra rate improves the model. However, identifying swarms in real-time using more objective methods remains a critical challenge.

Seismic Swarms of the Cascade Volcanoes and Magma Replenishment

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Abstract

Shallow earthquake swarms are a well-known precursor to volcanic unrest that often leads to eruptions. Lesser-known are earthquake swarms that follow vigorous eruptions and occur deeper in the system and often follow an aftershock-like pattern decreasing in intensity over time. These swarms are often interpreted as rock failure around a deeper magma reservoir (> 3 km) due to stress changes caused by the rapid depressurization of reservoir during the eruption. Seismic swarms in this same deeper part of a volcanic system unrelated to an eruption also occur and have been interpreted as evidence for episodic replenishment of a mid to upper crustal magma reservoir. Such swarms come and go, perhaps over years or decades without an eruption.

In the last 50 years of seismic monitoring of the Cascade Range in the Pacific Northwest of the USA only four volcanoes experienced earthquake swarms; Mount Rainier, Mount St. Helens, Mount Hood and Lassen Peak. Of these four volcanoes Mount St. Helens has had an eruption precursory swarm, aftershock-like sequences and swarms associated with magma replenishment. In this latter case a complete cycle of eruption, replenishment and then eruption is well documented. There is evidence that magma replenishment is currently taking place but at a slower rate than during the previous cycle. This rate might imply a much longer time (several decades) before the next eruption.

There is weak evidence (locations somewhat distal to the volcano center) that similar swarms at the other three Cascade volcanoes with significant seismic activity are due to regional tectonic forces unrelated to the volcano. However, arguments can be made that these so-called “distal volcano-tectonic” earthquakes are the result of the interaction of tectonic stress and those due to magma replenishment. Efforts are currently underway to greatly improve the relative and absolute location of these swarm earthquakes using NonLinLoc-SSST (Source Specific Station Terms)+ Coherence. Comparing preliminary results with the routine catalog locations shows a tightening of earthquake clusters and a general shallowing of the deeper events. We plan to make this technique part of our routine volcano monitoring system with the hope that it will help to resolve the ambiguity between a purely tectonic source and one involving magma replenishment. This could lead to longer-term eruption forecasting than is currently done based on the shallow precursory seismicity that often precedes eruptions by no more than hours to a few weeks.

The Umbertide 2023 Seismic Sequence: Relative Velocity Variations, Ground Deformation and Role of Fluids

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Abstract

On March 9th 2023, a low-energy seismic sequence struck the town of Umbertide in the Umbria-Marche region (Central Italy), with three events with $3.8 \leq Mw \leq 4.5$ occurring in a time span of about 4 hours. We analyze data collected by the 6 seismic stations within a radius of 20 km from the largest Mw 4.5 earthquake, computing cross-correlations of seismic ambient noise in the oceanic microseism frequency band (0.1 − 1 Hz), and we find a significant seismic velocity drop associated with the time of the main coseismic events. We carry out a dynamic strain sensitivity analysis which suggests that the crustal damaging is mainly related to the shaking induced by the passage of seismic waves. In order to interpret the deformation processes associated with these earthquakes, we exploit the high temporal resolution (1 Hz) of the geodetic observations recorded by the recently installed Strainmeter ARray (STAR), together with the pore pressure measurements. We discuss the role of elastic strain and fluids in driving the deformation time evolution the study area went through during this seismic sequence. Overall, this study sets an example of how a combined seismo-geodetic analysis may help us to resolve low-intensity tectonic signals enhancing our capability of properly investigating the seismogenic mechanisms. We think that this abstract would fit best the session "Analysis of seismicity from waveform to catalogs and beyond", addressing in particular the topic "Multidisciplinary studies that integrate strain, strain rate and stress analysis, fluid redistribution and geochemistry to constrain the underlying physical mechanism of complex seismic sequences and swarms"

Flexible Objective Methods for Detecting Dwarms: the Cases of the Chilean Subduction Zone and the Complex Amatrice-Norcia Sequences

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Abstract
Swarm activity can be objectively discriminated from other (normal) seismicity patterns by measuring how the earthquake distribution departs from a null-hypothesis ETAS-like model. We discuss how this can be done at two very different scales: along the Chilean subduction zone, using regional data, and at the scale of a (complex) aftershock sequence comprising several mainshocks, namely the Amatrice-Norcia 2016 sequence. We show that the flexibility of the model, which formulation can be adapted to the specific challenges of a given target study, allows an efficient swarm detection. This approach is well adapted to modern high-resolution earthquake catalogs that are characterized by low to very low time-varying magnitude of completeness. We find that, for Chile, the swarms are either caused by large megathrust earthquakes (or occur shortly prior to them) or are structurally-controlled. In particular, a series of recurrent swarms is found where the Copiapo Ridge subducts, a zone that also hosts slow slip events. For the central Italy sequence, the small and dense swarms appear to be controlled by fluid pressure readjustement following the mainshocks, and are therefore delayed compared to 'normal' aftershock triggering.

Swarm-Like Seismicity on Basaltic Volcanoes: What We Can Learn from Taking into Account Damage and Stress Diffusion

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Abstract
On basaltic volcanoes, pre-eruptive seismicity often exhibits increases in earthquake rates in limited volumes surrounding a shallow-level magma reservoir; it constitutes an earthquake swarm, which ceased rapidly after the eruption and the depressurization of the reservoir that often occurs through a tensile dyke. Such pre-eruptive earthquake time series are often modelled by using an inverse Omori-Utsu law. We will show how this law can be understood in terms of damage, earthquake interaction and stress diffusion processes. We use Kachanov's definition of damage and continuity for representing both the loss of contact area above the magma reservoir, and the decrease of Young's modulus during the pre-eruptive period. We show how damage and continuity may be expressed using the earthquake number. Using this damage approach in a simple non-linear elastic model for the rock surrounding the pressurized magma reservoir allows modelling accurately the surface displacement from earthquake numbers. We show how using this damage approach and Charles (1958)'s law relating time-to-failure to the applied stress allows retrieving the inverse Omori-Utsu law. Basic hypotheses, limitations and eventual extensions of this approach will be discussed. Earthquake and surface displacement data from Piton de la Fournaise volcano (OVPF-IPGP) will be used.

The 8-Month Journey Towards the 2023 MW 7.8 Kahramanmaraş Earthquake: Persistent Seismicity Clustering and Anthropogenic Activities

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Abstract

A longstanding question in seismology concerns whether earthquakes do show a preparatory process and precursory seismic activity. Some models hold that in the intermediate term (from months to years), seismicity and/or aseismic transients in fault slip and in other fault properties occur. Nevertheless, the current body of knowledge from mechanical models, numerical simulations, experimental work, and field observations suggest that several processes can affect earthquake preparation on different temporal and spatial scales, ultimately yielding highly varying transient observations prior to mainshocks.

We analyze the transient deformation around the epicenter of the 2023, MW 7.8 Kahramanmaraş/Türkiye earthquake in the months to years prior to its occurrence. Using the catalog from a national agency (AFAD) derived with traditional techniques, we identify seismic precursory activity composed of isolated spatiotemporal clusters occurring in a complex fault network within 65 km of the future earthquake epicenter. Some of these clusters were identified to represent quarry blasts from anthropogenic activities and hence were excluded from the seismic analysis. The remaining clusters contributed to a substantial acceleration of seismicity rates in an area with R up to 50 km surrounding the future mainshock over a period of 8 months and contributed to a significant decrease in Gutenberg-Richter b-values. Using an enhanced seismicity catalog derived with artificial intelligence techniques for the same region and covering six years before the earthquake, we find that (1) the 8 months preceding the mainshock display substantially higher levels of clustered seismicity and thus earthquake interaction, (2) the epicenter displayed an increase in the background seismicity after the 2020 MW 6.8 Sivrice earthquake on the northern part of the East Anatolian fault, and (3) there was a period in 2017/2018 that shared some features with the period preceding the MW 7.8 earthquake, but did not lead to a large event. We also utilized a deep neural network and unsupervised clustering to analyze the lower-frequency band of the continuous seismic waveforms and detect any potential low-frequency signals related to the seismicity transients. We identify the enhanced occurrence of distinct low-frequency tremor-like signals during the six months preceding the mainshock. However, locating these low-frequency signals revealed that their source was related to anthropogenic activities on quarry sites and cement plants along the Narlı Fault, where the MW7.8 mainshock nucleated and the seismicity has a hybrid nature of tectonic and anthropogenic origins. These findings highlight the importance of understanding potential patterns detected by machine learning methodologies.

Our findings point towards an 8-month period of accelerated seismic activity, seismic clustering, and interaction around the future MW 7.8 earthquake. Moreover, this study opens the question of whether years of mass removal and quarrying activity could have altered the stress loading along the Narlı Fault.

Stress Heterogeneities Governed by Fault Structure and Stress Transfer: the 2016-2017 Central Italy Seismic Sequence

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Abstract
We analyze the spatial and temporal evolution of stress parameters from the 2016-2017 central Italy seismic sequence taking advantage of a deep learning catalog containing ~56.000 focal mechanisms. The density of the catalog allows us to invert focal mechanisms over distances of a few km and different time periods. We inferred a number of stress-related parameters, including the fault plane variability, the orientation of principal stress axes and maximum horizontal stress, the relative magnitudes of principal stresses and the variability of the stress field orientation with respect to regional stress. From the uniform regional stress field consistent with the extension of the Appeninnic Belt, we observe local stress heterogeneities that are driven by the structural features and the coseismic stress history. A variation of the principal stress magnitudes and regimes from pure normal faulting towards transtension with depth is observed. Stress discontinuities at the 1-10 km wavelength are observed at either side of two of the main regional fault structures. The reported stress results suggest a partial mechanical coupling and a strong interaction between the shallow normal faults and the detachment horizon at depth. Furthermore, distinct trends are observed in the stress parameters after the largest mainshocks, and before the M_W 6.5 Norcia mainshock, potentially indicating the high stress still available in the system after the M_W 6.0 Amatrice earthquake. Our analysis holds important implications towards (1) constraining stress magnitudes, (2) illuminating the interaction between the shallow normal faults and detachment horizons, and (3) tracking stress evolution during seismic sequence.

Deciphering the Spatiotemporal Complexity and the Stress State Evolution of the 2021 Arkalochori (Crete) Foreshock Swarm with a Deep-Learning Catalog

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Abstract

On September 27th, 2021, a damaging earthquake of M_w6.0 occurred in central Crete (Greece), close to Arkalochori village, being the strongest earthquake ever recorded in this area during the instrumental period. The mainshock was remarkably preceded by an intense foreshock swarm that lasted almost four months. The spareness of the seismological network close to the activated area constrained the capabilities of conventional event-detection methods to provide a comprehensive seismic catalog for the foreshock swarm that would allow the study of its spatiotemporal evolution and statistical properties. To enrich the seismic catalog and to further enlighten the dynamics of the foreshock swarm, we exploited waveform data from the operational seismological stations of the Hellenic Unified Seismic Network (HUSN) in Crete and employed a deep-learning model to automatically detect and pick additional earthquake phases during the foreshock period. A Bayesian Gaussian Mixture Model (GaMMA) was then applied to associate the automatic P- and S-wave picks with specific event origins, followed by single-event location with a local 1D velocity model. With this procedure, a new deep-learning catalog was constructed, enriching more than tenfold the published seismic catalogs and reducing the magnitude of completeness from 2.8 to 1.1. By using the new catalog, the spatiotemporal evolution of the foreshock seismicity was examined, showing the occurrence of moderate-size events with low aftershock productivity that culminated with a major M_w4.9 foreshock on July 24th, 2021. A small cluster of events was finally triggered near the mainshock's epicenter, only days before its occurrence. Furthermore, we studied the spatiotemporal evolution of the b-value to detect possible variations that could act as insightful stress state indicators in the seismogenic area. The analysis showed persistent lower b-values than the background during the foreshock sequence, with lowest just before the occurrence of the major M_w4.9 foreshock. The spatial distribution of b-values further showed that both the M_w4.9 foreshock and the M_w6.0 mainshock occurred in low b-value zones, suggesting a critical accumulation of stress in the epicentral areas of the strongest events.

Intersection Between Tectonic Faults and Magmatic System Promotes Swarms with large Magnitude Earthquakes Around the Tengchong Volcanic Field, SE Tibetan Plateau

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Abstract
Volcanic regions commonly host swarms comprising small to moderate-sized earthquakes while tectonic faults mostly host mainshock-aftershock sequences which can include very large earthquakes. At the southeastern Tibetan Plateau, large tectonic faults formed by the collision between the Indian and Eurasian plates intersect with the intraplate Tengchong Volcanic Field (TVF), and the seismic behaviour of such environments remains unclear. Here, we built a deep-learning-based high-precision earthquake catalog for TVF and found that (1) ~59% of the seismicity occurred as swarms but on faults aligned with the regional tectonic stress field; (2) All swarms contained migration fronts resembling fluid diffusion with some occurring where high CO_2 emissions have been detected, and (3) A year-long swarm including two M_L 5.2 earthquakes within two months in 2011 revealed complex fluids-faults interaction. Combined with the historical occurrences of M>6 earthquake swarms around TVF, our observations suggest potential increased likelihood of swarms with large magnitude earthquakes in regions where large tectonic faults and magmatic system intersect.

Discriminating Between High-Hazard and Low-Hazard Faults through Cluster Analysis: A Case Study of Induced Seismicity at the Geoven Deep Geothermal Energy Site, Strasbourg, France

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Abstract

In June 2021, a M_L3.9 earthquake struck the city of Strasbourg, France. This earthquake occurred about 6 months after the interruption of fluid injection operations, which were intermittently carried out from March 2018 to January 2021 at the Geoven deep geothermal energy site. To understand the triggering processes of the seismicity and the properties of the activated fault systems that led to the largest event of the sequence, we used template matching and double-difference relocation to build a high-resolution seismic catalog for the period between January 2018 and September 2023. This new catalog contains 2409 earthquakes.

A large portion of the seismicity (70%), including the largest events, occurred along well-defined planes. These clusters of seismicity are well-oriented relative to the direction of the maximum horizontal stress, but show different effective stress drop (i.e., different total seismic moment for the same area). High effective stress drop clusters have low b-value, large maximum magnitude (M_{max}), and closely follow the Gutenberg-Richter law. In contrast, low effective stress drop clusters have high b-value, low M_{max}, and are better fitted by a tapered Gutenberg-Richter law.

We attribute these differences in frequency-magnitude distribution and effective stress drop between clusters to differences in their rupture process. The observed clusters result from multiple bursts of seismicity, occurring either during or after injection. With each burst, seismicity migrates along preferential directions (appearing discontinuous in distance-time plots but continuous in distance-event index plots), while previously active regions remain inactive. However, the size of the area ruptured during a burst varies between clusters. Clusters whose total area is the combination of small ruptured areas have low M_{max} and effective stress drop, whereas clusters whose total area is the combination of large ruptured areas have high M_{max} and effective stress drop. This suggests the presence of mechanisms that can either inhibit or promote large rupture sizes, regardless of the total fault size and orientation.

Moreover, the rupture behavior of each cluster tends to remain constant over time. This raises the question of whether the rupture process is an inherent property of a fault system, at least in the short term, and if hazardous faults can be identified early through proper cluster identification.

Using Earthquake Time Series to Characterize Seismicity in the Mount Cameroon Region

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Abstract

Mount Cameroon is an active volcano rising to almost 4100 m above sea level on Cameroon's south-western coast on the Gulf of Guinea. Over the past century, it has experienced 7 major volcanic eruptions, the most recent of which occurred in 1999 and 2000. Its volcanic eruptions are usually preceded by a major seismic crisis, with seismicity rising from an average of 30 events in the quiescent period to over 100 events per month as an eruption approaches. At the end of the year 2010, over a period of almost 3 months, we witnessed an increase in seismicity, with a peak of just under 200 events reached in September, yet no eruption followed. In order to better understand the physical phenomena behind this crisis, we therefore proposed to use a seismological statistical approach, in this case the non-stationary ETAS model and the analysis of the magnitude distribution, to characterize this seismicity. The b value, considered as one of the important parameters representing the nature of earthquake occurrence and characterizing the state of stress in the crust, was found to be high. The background rate, obtained from the inversion of the non-stationary ETAS parameters, reveals a slow transient deformation with gradual onset. The computation of the forcing rate shows so far that almost 55% of the seismicity is due to an external process like fluid intrusion.

The Role of Fluids in Driving the Pollino Swarm-Like Sequence

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Abstract

The role of fluids in driving the 2010-2014 Pollino swarm has been suggested since the first published works on this sequence. In the last six years, the effort of our research group has been focused on characterizing the seismogenic volume involved in the sequence and to assess the role of fluids in the development of this seismic swarm. Travel-time, attenuation and focal mechanisms tomographies, performed using a high-quality selection of seismic events from this sequence, all agree in highlighting over pressurized fluids in the highly fractured crustal medium involved in the sequence. Velocity anomalies reveal a trust-and-fold interface between the two lithologic barriers in the Pollino area, i.e. the ductile Apennines Platform overlaying on the brittle Inner Apulian Platform, where the strongest event of the sequence occurred. Clusters of events of similar waveforms have been revealed, and new focal mechanisms of small magnitude events have been computed and employed in computing the local stress field for the swarm area. Fault structures, imaged through seismic scattering, act as barriers for fluid migration, confined at focal depth, reaching pore fluid pressures well beyond the hydrostatic value. In addition, employing a nonstationary ETAS model on a new template-matching high-resolution catalog for Southern Italy, we suggest a slow-slip event and fluid interplay as the main aseismic forces in triggering and developing the Pollino swarm-like sequence.

Seismo-Volcanic Earthquake Swarms – Source Mechanisms and Forecasting Potential

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Abstract
Volcano seismology is an established discipline within seismology, however, there are fundamental differences between purely tectonic and volcanic events. This contribution will focus on different volcanic source processes and their interpretation in terms of volcanic-tectonic and so-called low-frequency events. We cover real-time monitoring aspects in an operational volcano observatory as well as data processing steps necessary to reveal the true nature of the source process and conclude with a check list of how to minimise misinterpretations of seismic signals.

Deciphering Earthquake Preparatory Processes: Perspectives on Subcritical Fracture Growth and Similarities in Rupture Growth Phases in Anthropogenic Seismic Swarm Activity

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Abstract
This study leverages acoustic emission (AE) data from laboratory stick-slip experiments on naturally pre-fractured rock samples to explore the behavior of subcritical fracture growth velocity and the clustering factor of seismo-mechanical fracture increments under evolving loading stress. Our goal is to identify seismicity-based parameters that serve as proxies for stress and phases of damage across local to system-size scale. We analyzed AE data, ranging from Mw -7 to -9, collected from Westerly granite sample characterized by high initial roughness, representing strongly segmented and roughness faults (Goebel et al., 2012). Five stick-slip experiments consistently exhibited a characteristic signal in the evolution of parameters before large slip events, enabling the tracking of preparatory processes leading to significant slip occurrences. Based on these observations, we developed a physics-based model of system-size damage, integrating the damage models proposed by Main et al. (1993) and Lei (2006), characterized by five phases: primary, secondary, nucleation, hardening, and failure.
We test this damage model on anthropogenic seismicity data from reservoir impoundment – seismic swarms related to the Pertusillo Lake in Italy and the Song Tranh 2 Reservoir in Vietnam, mining activity – seismicity in Rudna Copper Mine in Poland, and geothermal energy production – The Geysers geothermal field in California, USA. The study reveals that accelerating subcritical deformation consistently precedes major seismic events by several days to weeks. This acceleration is evident in the clustering factor within the dTdRMw probabilistic space, where a minimum value is detected shortly before large slip events, indicating that seismo-fracture increments become more internally similar. Our findings show that the larger the magnitude of the event, the longer the duration of the final damage stage. Additionally, we identified two dynamic regimes in the earthquake parameters' patterns, characterized by different fracture growth dynamics. The faster mode is linked to the onset of stage V before large slip events in mining, while the slower mode corresponds to pore pressure-related large slip events.
This study highlights the significance of detecting two distinct precursory modes, suggesting further investigation into whether this is a common feature of anthropogenic seismicity or specific to certain technological activities. Furthermore, we found that seismicity contributing to the earthquake preparatory process (EPP) is typically localized within an average radius of 0.3Mw. Our findings underscore the value of analyzing evolving kinematic and dynamic variables of system-size damage to enhance forecasting strategies and mitigation efforts for anthropogenic seismicity. Understanding the deformation phase allows for controlling technological processes to reduce stress, thereby minimizing earthquake risks in reservoir impoundment, geothermal projects, and mining.

Contrasting Anthropogenic-Induced Swarms and Natural Swarms

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Abstract
A swarm by definition is a seismic sequence without a clear mainshock. There are several hypotheses about the forces driving these sequences including fluids, weak crust, and stresses associated with aseismic energy. While not commonly characterized as swarms, anthropogenic-induced seismic sequences also often occur without clear mainshocks. However, in the case of induced earthquakes, we usually know more about the driving forces. In this study, we characterize induced sequences from (1) stimulation and circulation activities at the Utah Frontier Observatory for Research in Geothermal Energy (FORGE), a fluid-driven environment and (2) long-wall coal mining from the Wasatch Plateau and Book Cliffs in central Utah, a volume extraction process. We compare the development and progression of these two cases with naturally occurring swarm sequences from the University of Utah Regional Seismic Catalog. For direct comparison with Utah FORGE, we will focus on a zone of recurring natural swarms located to the east of FORGE in the Mineral Mountains and an energetic natural swarm sequence located ~ 20 km to the south. For a more general comparison to both FORGE and mining induced seismicity, we will analyze other swarm sequences identified in the Utah Regional Seismic Catalog, including two sequences where it appears that a mainshock later triggered a swarm sequence. The goal here is to see what we can learn about the evolution of natural swarms from the more controlled experiments of induced swarms.

Unraveling Hydro-Fracturing Mechanism: Is the Analysis of Induced-Seismicity Alone Sufficient?

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Abstract

Induced seismicity is recorded during controlled experiments where high pressurized fluids are injected following a prescribed protocol for flow rate and pressure to build a reservoir via intense fracturing. In Enhanced Geothermal System the goal is to create fluid circulation pathways for the heat production. Injection experiments are designed to induce hydro-shearing, where the fluid over-pressure induces either seismic and aseismic slip on favorably oriented pre-existing fractures; or hydro-fracturing where instead the fluid over-pressure exceeds the minimum principal stress and create tensile fracture that can propagate from the borehole injection point. The seismicity triggered during hydro-shearing is representative of failure of asperities on fault structures, while in hydro-fracturing the fracture opening is aseismic and seismicity is triggered at the expanding edges of the tensile crack. A further mechanism to trigger earthquakes consists of slip on fractures induced by a diffusive front of high pore-pressure triggered by the fluid injection. However, even in designed injection experiments with a good knowledge of the stress field and rock properties, the fracturing response of the host rocks can vary and do not fully comply with the intended protocol.

The analysis of induced seismicity can indeed help to single out one or more of the above mechanisms at play. We here have focused on the 2022 injection experiment performed at the Utah Frontier Observatory for Research in Geothermal Energy (FORGE). We have analyzed a post-processed and high-resolution catalog of earthquakes recorded during the stimulation test at FORGE 2022. We performed a clustering analysis of the spatial and temporal features and the geometric distribution of the seismicity cloud with respect to the in-situ stress field. We additional fit to the earthquake migration front (space-time data) three models: 1) aseismic/seismic slip on a fault where earthquake front distance is dependent on the injection volume, 2) an expanding tensile crack filled by the injected volume and where the seismicity is triggered at the leading edges of the crack; 3) a 1D diffusion model where high-pore pressure reduces the effective normal stress on faults allowing seismic slip to occur. The three models almost equally fit the earthquake migration front, but the model fit alone cannot resolve on the source triggering mechanism. In addition, the spatial distribution of the earthquakes analyzed with respect to the local stress field and slip susceptibility indicates the hydro-fracturing as the most likely underlying mechanisms. However, we cannot fully rule out hydro-shearing and slip on existing faults. The take-home message is that - beside the analysis of seismicity - is important to measure deformation to better nail down the mechanisms at play during injection experiments.

Swarm-Like Microseismicity in the Northeastern Italy: Some Hints From a Decade Monitoring of the Collalto Seismic Network

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Abstract

The high-quality seismic monitoring carried out by the National Institute of Oceanography and Applied Geophysics - OGS at two underground gas storage facilities in Northern Italy allows us to investigate, in addition to the seismicity potentially induced by anthropic activities, the local seismogenic processes, up to a spatial scale and low magnitudes that are not comparable with the ones obtained by of the regional and national seismometric networks existing for Civil Protection purposes.

In particular, the Collalto Seismic Network, in Northeastern Italy, since 2012, has gathered a catalog of nearly 4000 microearthquakes with M<3 located approximately within 30 km distance from the gas storage reservoir. These seismic events allow an unprecedented imaging of deep seismogenic structures which integrates and strengthens the structural model linked to surface geological evidence. In addition, in August 2021 an extremely productive seismic sequence took place in this area, near the village of Refrontolo at about 9 km depth; in a single month we identified and localized 407 microearthquakes which represent about 20 times the average monthly rate of events detected in the last decade; no event was felt by the population (main earthquake MW2.4). These earthquakes, mostly identified by automatic procedures, were post-processed by manual picking of P, S-phases and polarities, and localized by different techniques, to obtain the best possible imaging of the source.

We suggest that this sequence has ruptured pre-stressed patches near to failure of subvertical faults on a small SE dipping volume, antithetically oriented with respect to the brittle surface previously depicted by microseisms and assigned to the NNW dipping Montello Thrust.

This episode was crucial for strengthening the automatic microearthquake detection and location procedures; jointly with other minor swarm-like sequences identified a-posteriori by the catalog analysis, we believe it is of greatest interest for deciphering the seismic potential of this area too, and for testing the hypothesis that the Montello system has a relevant aseismic component.

Complex Microseismic Sequences in Complex Geo-Tectonic Environments: A Challenging View into the Subsurface

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Abstract

In seismology, seismic swarms are frequently interpreted in the context of fluid propagation and mainshock-aftershock sequences with the rupture of tectonic faults. While this fundamental dualism is often valid, many examples challenge a clear distinction between the two sequence types and also their underlying processes. Such “complex” or “hybrid” sequences can include mainshocks that trigger swarm activity or sequences that experience multiple, equally sized mainshocks.

In this work, we want to discuss the occurrence of microseismic sequences in the southern and eastern Alps and Central Utah. While located in very different tectonic regimes, the two study areas share a scattered, inhomogenous, and moderate to low seismicity. In both regions, swarms, mainshock-aftershock sequences, and complex/hybrid sequences occur in proximity. This presentation encourages an open discussion about the possibilities and limitations of learning about the underlying subsurface processes by analyzing, for example, the spatio-temporal patterns, waveform similarity, and rupture mechanisms under challenging circumstances. Microseismicity is often the only way - or at least the most cost-efficient one- to learn about subsurface structures and processes. However, in areas of low to moderate seismic activity monitored by sparse regional networks, the interpretations of such sequence analysis must carefully consider all methods' resolution limits.

Hydrology Drives Crustal Deformation and Modulates Seismicity: Case Studies from the Matese Massif and Eastern Southern Alps (Italy)

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Abstract

The natural water cycle induces changes in the amount of continental water storage and redistribution of groundwater. These processes can generate both horizontal and vertical deformation, induce crustal stress perturbations, and then modulate seismicity rates.

There are two mechanisms by which hydrological processes can modulate earthquake occurrence: variations in pore fluid pressure at hypocentral depths and direct stress on the fault plane. They can be distinguished by analyzing the time lag between the hydrological forcing and seismicity rates: while direct stress on the fault plane has an instantaneous effect, so that no time lag between the hydrological and seismological signals is recorded, pore pressure variations take time to propagate, and then a time lag is recorded.

Here we present two examples of how variations in water storage and redistribution have caused centimetric deformation in short time intervals (a few weeks) and affected seismicity rates. The first study is carried out in a karstic mountain range on the edge of the Adriatic-Eurasian plate boundary system in northern Italy. Here, the presence of high permeability geological structures and deeply rooted hydrologically active fractures concentrate groundwater fluxes and pressure changes, generating perturbations of crustal stress up to 25 kPa at seismogenic depths. The background rates of seismicity appear to be correlated, with no apparent temporal lag, with the estimated changes in groundwater storage in the Piave River hydrological basin. In the absence of evidence for pore pressure propagation from the hydrologically active fractures, seismicity modulation is likely to be influenced by direct stress changes on the fault planes.

The second area analyzed is the Matese massif, located in the Italian Southern Apennines. We find that this area is characterized by the concurrent action of two hydrologically driven processes: the first is the deformation, detected by the Global Navigation Satellite Systems (GNSS) data, in the shallowest part (above the elevation of the major springs) of the Earth crust, in phase with the hydrological forcing; the second is the triggering of seismicity at depth with a time delay that suggests a downward diffusive process. The displacement signal is well correlated and in phase with the flow of the largest spring of the region, which we consider as a proxy of the water content

of the massif. This indicates that the main source of horizontal deformation is the water content fluctuations in the shallow part of the Matese aquifer, in particular within fractures located in correspondence of the main mapped faults. Finally, we infer the second process by observing the correlation between the background seismicity and the spring discharge with a time lag of 121 days. In our interpretation, downward diffusive processes, driven by variations in the water content of the aquifer, propagate pore pressure waves that affect the strength of the fault, favoring the occurrence of microearthquakes. This is supported by the values of hydraulic diffusivity $\left(1.5\frac{m^2}{s}\right)$ and rock permeability $\left(3.2 - 3.8 \cdot 10^{-13} m^2\right)$, which are compatible with those observed in karstified limestones.

We think that this abstract would fit best the session “Analysis of seismicity from waveform to catalogs and beyond”, addressing in particular the topic “Multidisciplinary studies that integrate strain, strain rate and stress analysis, fluid redistribution and geochemistry to constrain the underlying physical mechanism of complex seismic sequences and swarms”.

High Resolution Earthquake Catalog Characterizing Faults Geometry and Source Mechanisms in a Complex Extensional Fault System: the Altotiberina Fault Case Study

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Abstract
Recent advances in machine learning (ML)-based detection and location techniques, combined with dense seismic networks, have dramatically increased the quantity of low-magnitude earthquakes that can be recorded and accurately located.
We analyze the seismicity of the Northern Apennines (Italy) using data from the Alto Tiberina Near Fault Observatory (TABOO-NFO), an ideal site for applying modern detection techniques due to intense microseismic activity involving complex fault systems and deep fluid circulation.
We construct an earthquake catalog for the TABOO area from 2010 to 2023 through an ML-based workflow tailored to this region.
Our approach employs an enhanced PhaseNet model, including polarity estimation and improved detection of close-in-time events, trained on locally recorded waveforms with manually labeled P, S, and polarities. We demonstrate that ad-hoc training enhances the accuracy of S-phase picking and polarity determination. The extensive phase dataset, comprising tens of millions of P and S detections, is associated with the GaMMA algorithm. Absolute hypocentral locations are obtained with a probabilistic location method (HypoSVI) in which the forward model is based on a physics informed neural network trained to solve the Eikonal equation. The location procedure incorporates source-specific station terms (SSST) that vary with source position, enabling better correction for unmodeled velocity structure compared to traditional static station corrections. Finally, the catalog is relocated using a Double-Difference method (DD) based on differential traveltimes and waveform cross-correlations resulting in ~420k earthquakes.
The resulting spatial distribution of seismicity provides detailed insights into geometrical features related to crustal faults and associates with independent lithological information, suggesting structural and lithological control. Seismicity patterns exhibit pronounced along-strike migration characteristics, potentially indicating widespread fluid diffusion processes.
To constrain the kinematic characteristics within different portions of the Alto Tiberina fault (ATF) system we analyze the distribution of focal mechanisms estimated from ML polarities and moment tensor inversion of P-wave amplitudes.

Unraveling Seismic Patterns: A Deep Dive into Earthquake Sequences and Swarms in Northeastern Algeria through a Dual Method Approach

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Abstract

In nature, there are two main types of seismic sequences: the first involves mainshocks followed by aftershocks, exhibiting a temporal decay in line with the Omori-Utsu law, typically with the mainshock initiating the sequence. The second type consists of earthquake swarms, deviating from Omori-type decay, where events of significant magnitude often occur in the middle or towards the end of the sequence. In the northeastern region of Algeria, seismic sequences often involve more than two main earthquakes, featuring both temporal and spatial migrations. Clarifying and categorizing these sequences is crucial for understanding the triggering mechanisms governing this seismicity.

In the current study, two methodologies were employed to detect seismic swarms. Firstly, we determined the spatio-temporal ETAS model parameters for the entire region, incorporating a bootstrap approach to assess uncertainties. Subsequently, using these parameters, the region was divided into grid cells of dimensions 0.2 x 0.2, and transformed time was calculated in each grid cell. Finally, the '1σ criterion' introduced by Nishikawa et al. in 2017 was applied. A total of 21 clusters were identified, encompassing 312 swarm events.

For the second method, skewness and kurtosis of the moment release time series were computed for each cluster after identification using the CURATE method. In total, 621 events exhibited swarm-like behavior. The two swarm catalogs were merged, as both techniques are independent of each other. In all, 762 events were accepted as swarm after applying additional criteria, such as ensuring the difference between the largest event and the second largest event in each cluster is less than 1. From this catalog, interpretations were made based on the tectonic setting of the region and the geological area to understand the factors responsible for these earthquake swarms.

A special emphasis was placed on the 2010 Beni-Ilmane seismic sequence, characterized by three shocks with magnitudes ≥ 5.3 within ten days. The non-stationary ETAS model, alongside b-value analysis and tomography, was employed to characterize the sequence, revealing the involvement of static stress transfer and fluid intrusion, which were responsible for the triggering process.

Real-Time Modeling of Injection-Induced Seismicity: Results from the DEEP Project

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Abstract
The challenge of controlling and modulating the induced seismicity has become nowadays a major objective for the scientific community. This is particularly true for geoenergy application such as EGS since they require high-pressure stimulation to achieve the desired fluid circulation at depth. The DEEP (Innovation for De-risking Enhanced geothermal Energy Projects) project is an international collaborative research environment whose goal is to establish a full-scale real-time test bench for innovative seismic monitoring and processing, seismicity forecast modelling, and risk assessment using the so-called Adaptive Traffic Light System (ATLS), a fully probabilistic seismic hazard and risk study that is updated continuously as new data arrive. This contribution will present the current development of real-time forecasting model and their use for hazard and risk calculation. Results include applications at both the 2022 and 2024 stimulation activities at the DOE'S Frontier Observatory for Research in Geothermal Energy (FORGE) in Utah (USA).

Numerical Modelling of the Seismicity Induced by Propagating Hydraulic Fractures

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Abstract
Hydraulic fracturing is a fundamental fluid transport mechanism in the earth's elastic-brittle crust. Hydrofractures are opening cracks containing fluids, propagating by fracturing the rock at the leading crack tip; they can be driven by overpressure at the injection source, by the buoyancy of the fluid they contain, by external stress gradients, or a combination of these factors. Hydraulic fracturing is relevant to a number of geological and industrial processes, including magma ascent by diking, degassing of hydrothermal systems and human-made fluid injections to enhance crustal permeability. Hydraulic fractures propagating in heterogeneous stress fields are expected to form tortuous pathways, as e.g. observed for some magmatic dykes propagating below volcanoes with complex shapes. Hydraulic fracture propagation is usually accompanied by seismic swarms, which can be very energetic in the case of km-scale magmatic dykes. By combining a three-dimensional model for the propagation of hydraulic fractures in a heterogeneous stress field and models for the generation of seismicity due to stress changes, we simulate the evolving shape of a hydraulic fracture, the stresses it induces in the host rock and the seismicity it is expected to generate. We apply our study to dyke events from the last decades and to hazard evaluation of possible future pre-eruptive magma ascent at Campi Flegrei caldera, Italy.

Fault Linkage and Distributed Deismicity

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Abstract

In recent years, high-resolution analysis of time-space evolution of seismic sequences highlighted a strong connection between fault zone structure, rock rheology and seismicity distribution. Here we explore this topic using the 2009 L'Aquila Mw6.1 seismic sequence (Central Italy).

This seismic sequence occurred along the Paganica-San Demetrio fault system (PSDFS), consisting of multiple sub-parallel N133°E-trending normal faults extending for 20 km of length. We constructed a set of 12 geological cross-sections to characterize the long-term PSDFS throw and the degree of fault segment interaction. The along-strike throw profile highlights a central throw deficit, suggesting that the PSDFS results from the interaction of two main fault segments. In coincidence of this deficit, the extension is partitioned among different interconnected small fault segments resulting in a zone of hard linkage between the two main segments.

The PSDFS has also been studied via 2 km-spaced seismological cross-sections perpendicular to the strike of the mainshock. This analysis shows two kinds of seismicity, on-fault and distributed seismicity. On-fault seismicity is characterized by earthquakes aligning along a SW-dipping structure, from 4 to 9 km of depth, illuminating the structure that hosted the mainshock. The distributed seismicity is instead characterized by earthquakes highlighting a sub-horizontal volume located at shallow depth (1-4 km) and corresponding at the surface with the area of fault linkage.

Together with geometrical differences, on-fault vs. distributed seismicity show different time evolution. The seismicity rate of the on-fault seismicity shows an Omori-like decay together with relatively low b-values (1.01) whereas distributed seismicity shows higher b-value (1.21) and a bimodal distribution of the seismicity rate. We observe a typical Omori decay followed by a further increase of the seismicity rate about 15 days after the mainshock. This second pulse of seismicity is associated with a temporal increase of Vp/Vs ratio occurring in the same time window and documented in previous studies. To better investigate the bimodal distribution of this distributed seismicity, we employed the ST-DBSCAN algorithm to cluster the events and to highlight the possible presence of small structures. The seismicity rate of the clustered events exhibits multiple increases and decreases over time in a swarm-like evolution. In contrast, the seismicity rate of non-clustered events decreases with time after the mainshock in agreement with the Omori's law. Furthermore, the clustered events show higher b-value (1.32) than non-clustered events (1.27).

We interpret the distributed seismicity at shallow depth as the result of two different mechanisms, mainshock induced stress change responsible for non-clustered seismicity, and pressurized fluid diffusion causing clustered seismicity. Because this distributed seismicity is in correspondence with the PSDFS segments linkage zone, we propose that its immature structural complexity (i.e. distributed damage and fault branching at shallow depth), represents a preferential pathway for fluid flow, promoting post-mainshock fluid migration and favouring the observed distributed seismicity with swarm-like evolution of the seismicity rate and higher b-values. Our results suggest that fault

zone structure and associated structural complexities can play a primary role in seismicity distribution and crustal scale fluid flow.

Source Properties and Clustering Styles of the Recent Seismicity at the Campi Flegrei Volcanic Complex (Italy)

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Abstract

Over the past two decades, the Campi Flegrei (CF) volcanic complex (Italy) experienced a persistent ground uplift of up to 15 mm/month, accompanied by seismicity of increasing magnitude, rate, and spatial extent. While there is consensus about the intimate relationships between ground deformation and seismicity, a still pending question regards whether those phenomena are directly driven by the transfer and emplacement of magma at shallow depths, rather than by the thermo-poro-elastic response of an over-pressurized hydrothermal system. We contribute to the debate by investigating the source mechanism and clustering properties of the CF seismicity. For the 2014-2024 time span, the catalog includes more than 11000 earthquakes that are relocated using a custom velocity structure and a probabilistic, non-linear inversion procedure. Completeness and maximum magnitudes of this catalog are Md~0.1 and Md=4.4, respectively. For the larger (Md>3) earthquakes occurring since 2022, P-wave amplitudes and polarities are inverted for the Full Moment Tensor. Fault plane solutions are consistent with activation of the ring fault system bordering the inner sector of the caldera. Non-Double-Couple components are not sufficiently resolved to unambiguously demonstrate the role of subsurface mass migration into the earthquake source mechanism. Source parameters (seismic moment, source size, stress drop) for Md>1.5 earthquakes are evaluated from the inversion of S-wave displacement spectra, permitting the definition of a scaling relationship between Moment and Duration Magnitudes. The clustering properties of the catalog are investigated using nearest-neighbor-distance (NND) analysis, in which the correlation between event pairs is quantified using a space-time-energy metric. During the early stage of the unrest, NNDs are distributed according to a typical bimodal pattern, corresponding to [i] Poissonian, background seismicity occurring at large inter-event times and distances, and [ii] clustered events separated by short temporal and spatial ranges. As the sequence evolves, the relative contribution of these two components varies significantly, likely mirroring changes in the factors which control the seismogenic process. The hypocenter cloud spreads with time, exhibiting a pattern which is reminiscent of diffusive processes, in which the expansion of a pore pressure front triggers seismicity by reducing the effective normal stress and/or changing the friction coefficient of the rock mass. Taken all together, these results suggest that magma does not play an active role in the earthquake generation process; rather, seismicity would be mainly controlled by stress concentration related to the ground uplift and fault weakening induced by pore pressure diffusion of hydrothermal fluids.

Silent Subsurface Variations in Seismic Secordings

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Abstract

While some mechanical and structural changes in the subsurface might trigger seismicity, others are aseismic and occur silently, unnoticed in seismic recordings. Understanding aseismic changes is also important for comprehending the ongoing physical processes in the crust. Seismic noise interferometry provides a non-invasive method to quantify these subsurface variations by analyzing the seismic noise generated by ocean wave interactions. In this talk, we explore several applications of this technique across various geological contexts characterized by intense seismic activity.

First, we will delve into the results from a volcanic eruption in the Canary Islands, where magma migration before the eruption caused an intense seismic unrest along its path. This eruption was extensively studied using numerous instruments, which allowed for the identification of five distinct pre-eruptive phases. By analyzing variations in the elastic properties of the subsurface through seismic noise recordings, we are able to identify those pre-eruptive phases as well as other different processes that had not been previously observed.

Furthermore, we will explore a different geological scenario at the Hengill geothermal field in Iceland, which is characterized by an intense seismic activity. This geothermal field, with over 100 deep boreholes (>1 km), presents a complex seismic environment with several clusters of both natural and induced seismicity. Here, we investigate the seismic velocity structure and its long-term variations with seismic noise interferometry. We observe seismic velocity alterations that result from factors such as reservoir depressurization, cooling, and steam accumulation.

The 2019-2022 Sequence of Induced Seismicity below the city of Strasbourg, France: Insights from Large-Scale Reservoir Modeling

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Abstract

Between November 2019 and November 2022, a series of seismic events were felt by the population of the city of Strasbourg, France. The first main event (MLv 3.0) that occurred on November 12, 2019, was part of a seismic swarm (the southern cluster) that has been initiated a few days before, lasted four months, and was located by the BCSF-Rénass (EOST), below La Robertsau area at a depth of 5 km. In October 2020, after a new series of hydraulic tests, second cluster of seismic events with more felt earthquakes (the northern cluster) developed closer to the geothermal wells (<1 km) below the La Wantzenau area. It includes the largest event (MLv 3.9) that was induced on June 26, 2021, 6 months after the shut-in of the wells. Two important features of the induced seismicity were unexpected : the large distance to the wells of a cluster of seismic events (4-5km) and the occurrence of the largest event Mlv3.9 at the bottom of the wells, six months after shut-in. To better understand the mechanisms of seismicity, we develop within the framework of the DT-GEO project, a large-scale model (8kmx8kmx6km) of the area. We aim at performing in-silico experimentation to reproduce the geophysical responses of the geothermal reservoir. The model is based on the MOOSE/GOLEM framework (finite element approach) and integrate the public regional geological model GEORG that includes major lithologies and large-scale faults of the area. We will discuss the preliminary of coarse-grained simulations of the natural fluid circulation and fluid injections in light with the high resolution monitoring of the seismicity.

How Can We Develop New Models for Seismogenesis using Advances in the Laboratory?

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Abstract
Advances in seismic and geodetic methods have painted a rich picture of deformation in and around tectonic boundaries in the Earth's crust. In the upper lithosphere, fault zones are thought to host deformation that spans a wide range of spatial and temporal scales, from localized and rapid seismicity to broad and slow aseismic deformation. In some cases, there is clear evidence that seismicity rate and aseismic moment release accelerate in the vicinity of eventual hypocenters of larger events. This behavior is thought to be associated with a preparatory phase of earthquakes; however, we currently lack integrated models that can reconcile these end-member observations of deformation.
We present results from compressive rock failure tests in triaxial conditions that are complemented by a novel pairing of two technologies: (i) acoustic emission (AE) sensors to study the seismic response, and (ii) fiber optic-based distributed strain sensing (DSS) systems that maps the heterogeneous surface strain forming on the specimen. Some similarities can be drawn with field-scale observations: Initially, localized aseismic deformation accumulates in the specimen as determined by the DSS array. Once a macro-fracture begins to form, AE rate increases and becomes more clustered in space and time. At this stage, AEs occur predominantly in regions of the rock that localize strain. This was attributed to the development of a system-size macro-fracture that begins to dominate the brittle failure sequence.
These quantitative observations allow us to discuss nuanced differences in the brittle failure sequences in different lithologies (e.g. sandstone and granite). Clear patterns emerge in the seismicity (e.g., changes in the frequency-magnitude distribution, focal mechanisms and triggering) and appear to be connected to the distributed strain and strain rate in the bulk of the sample. We are currently building and validating more accurate physics-based computational models that explain regions predisposed to seismogenesis while also matching the strain field observed on the samples' surface.

Rock deformation tests produce seismicity ranging from Mw -10 to -6 and have been instrumental in developing more refined theories to support the "what we know" about mechanisms controlling seismogenesis. With improved insight into complex failure process – even at µm to cm-scales – we can deepen our understanding of the physics controlling the interplay between seismic and aseismic deformation. Fundamental questions we are investigating include:

- What patterns of large-scale deformation drive local seismicity (and vice versa)?
- When (if ever) does seismicity begin to dominate the precursory phase of larger earthquakes?
- How do fluids, temperature, and geology affect strain distribution and seismogenesis in rocks subjected to compressive failure?

The answers to these questions will still require some validation at larger scales. We outline a methodology to upscale our integrated models in the Fault Activation and Earthquake Rupture (FEAR) project at the Bedretto Underground Laboratory for Geosecience and Geoenergy (BULGG) in Switzerland. In this setting seismicity ranges from Mw -6 to 1 and the rock mass is monitored using similar technologies (AE + DSS), making it a perfect testbed for new theories.

Multidisciplinary Analysis of Near Fault Observatory Data: Example from the Alto Tiberina Fault (Northern Apennines, Italy)

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Abstract

Geodetic measurements, such as those provided by the Global Navigation Satellite System (GNSS) or Interferometric Synthetic Aperture Radar (InSAR) techniques, are key tools for studying the spatial and temporal evolution of transient deformation associated with seismic swarms or seismic sequences. However, these signals can be smaller in magnitude than non-tectonic deformation signals, such as those related to the hydrological cycle, and may be characterized by a poor signal-to-noise ratio. This is especially true in slowly deforming tectonic environments, where the subtlety of the deformation signal tests the precision and accuracy limits of space geodetic techniques.

In this context, we will discuss examples of how geodetic data have been successfully utilized to study deformation associated with low-energy seismic swarms in Italy. We will also explore how geodesy can help quantify the temporal and spatial characteristics of other deformation processes, enhancing our ability to detect smaller tectonic deformation.

In this regard, Near Fault Observatories (NFOs) play a crucial role in monitoring the broad spectrum of fault slip modes by offering spatially and temporally dense, high-precision near-fault data. However, integrating and interpreting datasets from various disciplines, including geodesy, seismology and geochemistry presents challenges. These datasets often consist of time-series depicting the temporal evolution of different parameters and sample a wide range of temporal and spatial scales and depths, representing the distinct or cumulative effects of various multiscale processes.

Here we will present primary outcomes from a multidisciplinary project showcasing an approach designed to analyze, integrate, and extract knowledge from the EPOS NFO TABOO. This NFO features a dense network with an average inter-station distance of ~5 km between multidisciplinary sensors, including seismological, geodetic, geochemical, hydrological, and borehole strain stations. The project's core objective is to unravel the interconnections between different observables and explore the causal relationships among them.

Complex Seismic Sequences Originated from the Collective Behavior of Asperities: an Experimental Approach

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Abstract

Faults can slip with diverse behaviors by accommodating the large-scale, far-field, slow tectonic loading: from aseismic creep to seismic slip. Such diverse slip behaviors of a fault are mainly controlled by the frictional stability of the rough fault interface, where a complex set of real contacts are established by numerous discrete asperities. These asperities control the initiation and evolution of the fault slip, especially the transition from aseismic to seismic slip, since they offer greater than average resistance to the imposed shear stress. Investigating the intrinsic relationships between the collective behavior of local asperities and the frictional stability of the macroscopic fault enables a better understanding of the mechanical evolution of a fault and the physical process of resulting seismic sequences.

Here we develop a novel analog fault model to overcome the difficulty of imaging an exhaustive spatiotemporal variability of a natural fault interface at depth and the limited computational efficiency of the numerical models when heterogeneities span a large time and space domain. Specifically, numerous identical rigid spherical PMMA (poly-methyl-methacrylate) beads (with a number of around 175), which are used to model the discrete frictional asperities, are embedded with height variations and random spatial distribution in a soft viscoelastic silicone block to establish numerous micro-contacts with a thick transparent rigid PMMA plate on the top. During the entire shear process of such a heterogeneous fault interface, not only the subtle motion of each local asperity can be directly measured by the high-resolution optical monitoring system, but also the seismic characteristics emitted from slow transients that occurred at local asperities can be captured by the acoustic monitoring system.

Integrating the temporal evolution of the slip of each asperity and the continuous acoustic signatures, we link the mechanical response of the macroscopic fault with the collective behavior of local asperities. The synchronization of the local rapid slips at all asperities is responsible for the unstable system-size stick-slip of the macroscopic fault that generates the large amplitude energetic acoustic event. Unlike only limited foreshocks detected conventionally just right before the mainshock, it is interesting to observe that complex seismic activities initiate much earlier during the interseismic phases, which could represent a long-term preparatory stage with abundant complex seismicity. Such interseismic seismicity have small-to-moderate amplitudes concerning the mainshocks, and essentially they are destabilizing transients at the local asperity scale that originate from spatiotemporal interactions of limited local asperities. These transients are determined as slow slip events by estimating their overall rupture speed, whereas the detected acoustic events prove the existence of elastic waves radiated from local dynamic ruptures during these slow transients. We quantify the partitioning of the resolved slip taking place on the asperities as dynamic events to interpret the nature of these complex seismicities from the fine asperity scale. Our results provide

insights into a better understanding of the physical processes leading to the occurrence of foreshocks and complex seismic sequences.

Micro-Earthquakes Induced by Fluid Injection: Distinctive Characteristics of Dynamic Rupture Models and Near-Source Recorded Observations

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Abstract
Understanding the dynamics of microearthquakes is a timely challenge to address current paradoxes in earthquake mechanics but also to investigate earthquake ruptures induced by fluid injection. However, our understanding of earthquake rupture processes is generally limited by the resolution of available observations. The ERC-Synergy project FEAR (Fault Activation and Earthquake Ruptures), conducted within the Bedretto Underground Laboratory for Geosciences and Geoenergy (BedrettoLab), offers a pioneering approach to investigate these intricate processes and governing mechanics. In this study, we leverage this opportunity to perform 3D simulations of spontaneous dynamic rupture caused by fluid injection and generate $Mw \leq 1$ seismic events. We adopt different spatially variable normal stress and stress drop resulting from varying profiles of pore-fluid pressure change. Indeed, during the hydraulic stimulation, the local stress field around the injection borehole is perturbed potentially influencing in different ways the characteristics of induced seismicity. Through the variability of fault strength parameter S, that is, high ratio between strength excess and dynamic stress drop we identify two end-member classes: self-arresting earthquakes characterized by spontaneous rapid rupture deceleration phase, and run-away earthquakes with a continuously accelerating front. In faults with high S values (i.e., low rupture potential), we find that even minor variations in dynamic parameters have a substantial effect on the rupture propagation and on the ultimate size of the events. The spatial gradient of effective normal stress impacts the variability of frictional strength and stress drop, leading to differences in features observed during accelerating dynamic ruptures compared to those seen during deceleration in a self-arresting earthquake. In spontaneous arrest models, the residual slip velocity decreases to nearly zero implying that an initially crack-like rupture turns pulse-like. Our findings highlight the complex dynamics of small induced earthquakes, which are partially contrasting with established crack-like models of earthquake rupture. Analyzing the spectra of modeled waveforms, we examine the differences in the frequency content and provide an estimation of source parameters obtained through spectral inversion. These estimations are then compared with dynamic forward models and provide critical insights into radiated spectrum, the potential contribution of near-field terms and attenuation.

Finally, we describe and interpret the seismic events recorded during the "M0" FEAR experiment, which was designed to induce a maximum magnitude event around zero and activated multiple aligned fractures in the BedrettoLab. These methods together with the upcoming FEAR stimulation experiments can provide a controlled setting to study the intricate details of earthquake mechanics closely and can create an ideal environment to improve our current understanding of earthquake physics.

The Influence of Lithology and Fault Source Volume on the Magnitude Frequency Distribution of Earthquakes

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Abstract

The earthquake Magnitude-Frequency-Distribution is usually modelled with the Gutenberg-Richter law, where the b-value controls the relative rate of small and large earthquakes. b-value shows an inverse dependence on differential stress, it increases with fault roughness and in areas with fluid involment in faulting. b-value analyses have been also applied to infer temporal evolution of the stress state along active faults or to discriminate between foreshocks and aftershocks. For the Mw 6.5 2016–2017 Central Italy seismic sequence, we show that: 1) away from the major earthquake faults, b-values are controlled by lithology and style of deformation; 2) the absolute number of the b-values depends on the adopted magnitude scale and catalogue, but differences induced by lithology are preserved; 3) the selection of the fault source volume can strongly influence b-value changes in time, highlighting some complexities on the applicability of the b-value as fault stress meter.

The Evolution of Seismic behavior in the Bucaramanga Earthquake Nest, Colombia

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Abstract

Intermediate-depth earthquakes occur in subduction slabs where extremely high pressures and temperatures make frictional slip unlikely. Understanding the mechanism potentially reveals a mechanical state of the fault zone and the origin of magma in subduction zones. Using a systematic methodology established for shallow earthquakes, we explore for the first time the fine-scale spatiotemporal evolution of intermediate-depth earthquakes within the Bucaramanga earthquake nest to obtain new insight into the physical mechanism from their recurrence intervals and locations. We first construct a high-resolution earthquake catalog through matched-filter detection using the largest 100 earthquakes as template waveforms and continuous waveform data in six years (2016-2021) from 13 stations operated by the Servicio Geológico Colombiano (SGC). Our catalog detects 71,621 events classified into smaller clusters based on the cross-correlation coefficients between the template and continuous waveform. Subsequently, we apply the second round of matched-filter detection for one cluster that records the largest number of detections in the first round. We observe a multi-year evolution of different earthquakes characterized by the number of events in one template family. Relocation of these hypocenters highlights a spatial migration over several kilometers toward the plate interface over several years, highlighting a continuously evolving forcing that drives earthquake activity within the Bucaramanga nest.

The Fingerprints of Swarms in the San Jacinto Fault Zone

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Abstract

The broader area of the San Jacinto Fault Zone (SJFZ) of the San Andreas Fault Zone system in Southern California hosts many seismic clusters that do not behave like classical aftershock sequences. Recent studies alluded that some of these sequences might be swarms driven by fluid diffusion. However, since swarms are primarily driven aseismically, the lack of this evidence renders their confirmation elusive. To identify the aseismic presence and confirm these swarms as a major part of the seismic activity in the SJFZ, we built a detailed fifteen-year catalog (2008-2022) using cutting-edge deep learning methods. Using statistical modeling and other simple statistical methods, we confirm the existence of these ever-so-present swarms by computing the background rate as a function of time along the sequence's evolution. Our observations indicate these sequences have transient aseismic forces active continuously for years and even observed over cycles. The sequences range from almost all aseismic triggering to a mixed pattern. Their location and depth of origin paint a story about the crustal fluid flow underneath this major fault zone.

Off-Fault Triggered Swarms after L'Aquila 2009 and Central Italy 2016-2017 Seismic Sequences

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Abstract

Earthquake swarms, a series of seismic events occurring in a local area lasting from days to years, have recently been the subject of intense study. The primary causes of these swarms are believed to be transient aseismic fault slip and slow or sudden pulses in hydraulic pore pressure. A combination of these features is frequently suggested to explain complex seismicity patterns. This study delves into the intricacies of off-fault swarms, likely triggered by large seismic sequences. We focus on two significant seismic events in the Central Apennines: the L'Aquila event in 2009 and the Central Italy sequence in 2016-2017. These powerful seismic sequences activated a high level of off-fault lower magnitude seismicity in an area of approximately 400 km² from 2009 to the end of 2017. This region, close to Campotosto, experienced several earthquakes with magnitudes greater than 5 and a persistent and long-lasting high level of lower magnitude seismicity.

High-resolution earthquake catalogs provide a rich dataset for analysis and offer unique insights into the mechanisms driving earthquake swarms. From these catalogs, clusters of events were selected for further study and classified based on migration velocity, duration, and total moment released. The swarms that followed the two primary sequences did not overlap in space. The seismicity activated after L'Aquila 2009 is prevalent in the western sector, while after Central Italy 2016-2017, many swarms are observed in the easternmost part. The analysis revealed variable durations ranging from a few days to months and migration velocities from kilometers to meters per day. These findings suggest an interplay between fluids, aseismic, and seismic slip affecting minor faults. Interestingly, swarms are generally located at depths of less than 10 km and have multiple events with $M<3.5$. In some cases, these swarms anticipated $M>5$ foreshock-mainshock sequences. We compare observations with well-known natural and anthropogenic swarms, providing new case studies and insights into their mechanisms and evolutionary styles.

Multi-Depth Dpatiotemporal Evolution of the Sora Seismic Sequence (M_W4.8, Central Apennines)

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Abstract
The central-southern Apennines of Italy is a high seismic risk area undergoing Quaternary extensional tectonics at low rates in the SW–NE direction. The background seismicity is mainly located at upper crustal depths (<12-14 km), and the focal mechanisms of the significant earthquakes show an SW–NE trending nearly horizontal T-axes consistent with the regional stress field. Seismic events occurring along the westward limit of the extensional domain are thought to be caused by tectonic loading or overpressurized CO2 reservoirs. This sector of the Apennines, near Sora town, experienced four significant events during the last ~700 years: 1349 (Mw 6.8), 1654 (Mw 6.3), 1915 (Mw 7.1), and 1984 (Mw 5.8) earthquakes. Notwithstanding, except for the 1984 seismic sequence, whose aftershocks helped to constrain the geometry of some active segments, this area was not affected by other significant or minor earthquake up to the 2009 L’Aquila mainshock.
In this tectonic context, on the 16th of February 2013, a normal fault event of M_W 4.8 occurred a few kilometers west of Sora town at a depth of ~ 20 km. Enhancing the catalog, we found 25 foreshocks ($-0.2 \leq ML \leq 1.6$) located at the same depth range one day before the main event. This seismic sequence shows a complex spatiotemporal evolution. It is composed of three clusters about 5 km apart, sequentially occurring. The first developed at depths between 17-21 km, the second at 11-16 km, and the third at upper crustal depths 8-11 km. The first and second cluster shows a highly asymmetric time-magnitude distribution (seismic sequence behavior). In contrast, the time-magnitude for the third cluster is characterized by many earthquakes of similar size (swarm behavior). The Vp/Vs ratios, computed with the modified Wadati diagram, are relatively high. Our preliminary results show a complex evolution of this seismic sequence where fluids could have played a significant role in triggering the main shock and controlling the up-dip migration of the foreshocks.

Dynamic Triggering of Earthquakes in Yunnan, China: Insights into the Influence of Distant M>6 Earthquakes and Geothermal Fluids

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Abstract
This study delves into the phenomenon of dynamic triggering of earthquakes in Yunnan, China, a region renowned for its abundant geothermal activity. Through an extensive analysis spanning from 2006 to 2021, we unveil the impact of 13 distant M>6 earthquakes on seismic clusters in the region, emphasizing the unique clustering of these seismic events at specific fault-related locations. Advanced methods, including the Epidemic-Type Aftershock Sequence (ETAS) model, were employed to identify the spatiotemporal patterns of seismic activity before and after these distant M>6 earthquakes. Noteworthy observations highlight the preferential distribution of earthquake clusters at specific fault-related locations, such as fault ends, bends, intersections, and fault step-overs. Some earthquake clusters exhibit clear fluid diffusion processes, validated by increased water temperature in nearby wells. The applied ETAS model underscores a high proportion of forced seismic activity, elucidating the subtle relationship manifested as delayed triggering effects. The results of our study emphasize the association of dynamic triggering with specific fault-related locations, emphasizing the potentially significant role of subsurface geothermal fluids in this process. This research deepens our understanding of seismic activity patterns in the Yunnan region, revealing the intricate interplay between distant M>6 earthquakes, fault dynamics, and geothermal fluid activity.

Understanding and Managing Trailing-Induced Seismicity: A Quantitative Analysis of Influencing Factors

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Abstract

Fluid injection into the subsurface can activate faults, leading to induced seismicity. Of particular concern are trailing-induced earthquakes, which occur after the cessation of injection operations. Understanding the physical mechanisms behind these trailing events is crucial for predicting and managing their associated risks. This study focuses on analyzing the factors controlling trailing-induced seismicity, specifically in Enhanced Geothermal Systems (EGS), by examining both industrial injection operations and seismic activity characteristics.

We utilize six aftershock decay models to quantitatively describe the decay rate and duration of trailing-induced seismicity: the Modified Omori Model, Exponential Model, Stretched Exponential Model, Cut-off Power Law Model, Gamma Model, and Hill Sigmoid Model. These models are applied to fit global cases of trailing-induced seismicity resulting from EGS injection operations.

The fitting parameters obtained from the best-performing models, namely the decay rate and corner time, are used for risk assessment. We investigate the factors influencing the decay time, analyzing both injection operation parameters and seismic characteristics. Key factors from injection operations include injection rate, wellhead pressure, duration of injection, and hydraulic energy. From the seismic activity perspective, we consider hydraulic diffusivity and triggering distance.

To identify the primary factors controlling the decay time of trailing seismicity, we employ machine learning models. These models are trained and validated on the fitted parameters to forecast the decay time, providing insights into the relative importance of various operational and seismic factors.

Our findings indicate that both injection operations and seismic characteristics significantly influence the decay time of trailing-induced seismicity. The machine learning approach successfully identifies the key control factors, enabling better prediction and management of trailing-induced seismicity risks. This study provides a comprehensive framework for understanding the decay dynamics of induced seismicity, contributing to more effective risk mitigation strategies in industrial fluid injection operations.

The Pahala Sill Complex Swarm Illuminates Magma Dynamics in the Mantle

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Abstract

Patterns of magma flux in the mantle can influence a volcano's eruptive behavior, but magma dynamics below the crust are usually aseismic and difficult to observe directly. We leverage advances in earthquake monitoring with deep learning algorithms to image the structures underlying a major mantle earthquake swarm of nearly 200,000 events that rapidly accelerated under Hawai`i after the 2018 Kīlauea caldera collapse. At depths of 36 to 43 kilometers, we resolve a 15-kilometers-long collection of near-horizontal sheeted structures that we identify as a sill complex. Swarms in the sills exhibit diffusive spatiotemporal behavior over multiple years that we interpret as evidence of magma intrusion. The onsets of swarms are contemporaneous with eruptions at Kīlauea volcano, suggesting a high degree of hydraulic connectivity between the mantle and the surface. We invert for full moment tensors of sill earthquakes and identify predominantly shear mechanisms with persistent tensile faulting components; slip occurs in-plane with the sill structures. Together, these observations suggest that magma flux through the sill structures generates seismicity by increasing pore pressure and promoting slip. Our results suggest that mantle swarms at Hawai`i may be useful for observing magma flux deep in Hawai`i's magmatic plumbing system and improving our understanding of melt pathways between the hotspot and the surface.

Automated Detection and Characterization of Swarms and Mainshock-Aftershock Sequences in Southern Mexico

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Abstract
Earthquakes in Mexico are frequent and dangerous. Over the last decade, there have been a dozen major earthquakes including two larger than M7.5. The Mexican subduction zone is considered a natural laboratory for studying slip processes due to the relatively short trench-to-coast distance which brings broad portions of the seismogenic megathrust inland. Using an automated detection algorithm that identifies clusters of events using the nearest neighbor distances in the space-time-energy domain (Zaliapin and Ben-Zion, 2013), we were able to detect and ~700 sequences from 2012 to 2020 for characterization. Traditional methods are time-consuming and biased due to the number of events and human perception, so we developed an automated strategy to evaluate sequences on a spectrum of swarm to mainshock-aftershock (MS-AS). The automated algorithm uses quantitative forms of these attributes: 1) magnitude difference between the largest event and next largest events, 2) percentage of the sequence after the largest event, 3) slope of seismicity rate over time, 4) ratio of magnitude range to the number of events and, 5) rate of maximum magnitude decay over time. The automated method yields similar results to manual characterization and is effective at identifying average properties when there are discrepancies among manual ratings for complex sequences. We found twice as many swarms as aftershock sequences despite the prominence of large megathrust MS-AS sequences over the past decade. Temporally, some swarm sequences show an interesting pattern where the seismicity shuts on or off depending on nearby megathrust activity. Spatially, swarms help define a vertically dipping fault in the upper plate indicating a strike-slip sliver fault may be closer to the coast than previously thought. Additionally, a cluster of swarm sequences in Juchitan de Zaragoza appears to reveal a normal fault zone that accommodates the offset of the sliver fault in Oaxaca from the sliver fault in Chiapas. We anticipate that by standardizing the swarm detection and characterization process will provide opportunities for more in-depth studies of their driving processes.

Earthquake Swarms in JapanTriggered by Upward Fluid Migration following the 2011 M9 Tohoku Earthquake and the 2024 Mw7.5 Noto Peninsula Earthquake

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Abstract

Since the 2011 M9 Tohoku earthquake, Japan has experienced frequent earthquake sequences that appear to be caused by fluid involvement. In this presentation, I will introduce the appearance and interesting features of those activities.

Immediately after the Tohoku earthquake, several earthquake swarms occurred in the crust of eastern Japan. The swarm activation there was enigmatic, given that the Tohoku earthquake released the accumulated strain. By studying the details of the three earthquake swarms, we found that: (1) All of these swarms became active after a time delay (approximately 1 to 4 weeks) from the Tohoku earthquake; (2) their source regions are distributed beneath paleovolcanoes or calderas, and seismic low-velocity regions and S-wave reflectors are located below; and (3) the earthquake hypocenters migrated from deep to shallow via multiple sharp planes. These suggest that these swarms were triggered by upward fluid migration via existing faults. The deformation and shaking caused by the Tohoku earthquake probably allowed the upward movement of fluid trapped deep in the crust.

More than ten years after the Tohoku earthquake and approximately three years before the 2024 Mw7.5 Noto Peninsula earthquake, an intense earthquake swarm occurred in the Noto peninsula. No volcanic activity has occurred in this region since the Middle Miocene (15.6 Ma). We investigated the cause of this activity based on the spatiotemporal evolution of earthquake hypocenters and seismic reflectors. We found that these earthquakes migrated upward, activating a complex network of faults. The initiation of this swarm occurred at a locally deep depth ($z = 17$ km). A distinctive S-wave reflector existed in the immediate vicinity, below which a low-velocity region was located. Moreover, a high helium isotope ratio and a low-gravity anomaly were observed at the surface. These characteristics are similar to those of the swarms in Tohoku above, although the relationship between fluid movement and the Tohoku earthquake is unclear in this case. These observations demonstrate that fluids can trigger swarm earthquakes even in areas without modern volcanic activity.

An Mw6.2 earthquake occurred in this swarm region in 2023. By examining the rupture process of the Mw6.2 mainshock and the hypocenters of small earthquakes, we found that the mainshock rupture was initiated near the shallow end of the largest swarm fault. The mainshock rupture propagated farther updip, followed by aftershocks in the shallow extension. Updip fluid flow likely caused systematic upward earthquake migration from a depth of 18–5 km.

Moreover, the 2024 Mw7.5 Noto Peninsula earthquake was initiated on the same swarm fault. The initiation location coincides with the destination of the upward migration of a deeper earthquake cluster via several smaller faults. Fluid flow, small earthquakes, and aseismic slip likely triggered

the mainshock, leading to the first major rupture at a nearby asperity, propagating further to both the east and west sides, resulting in the Mw7.5 earthquake over 100 km in length. These observations indicate that fluid supplied from depth can trigger swarm earthquakes to Mw7.5 earthquakes, depending on the states of fault and stress in the crust.

Correlations and Change Points Identification in Crustal Anisotropy, b-value and vp/vs, Time Series during Seismic Swarm Occurrences in the Alto Tiberina Fault zone (Italy)

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Abstract

We computed different seismological parameters from the analysis of the waveforms recorded during the seismic swarms activity occurred along the Alto Tiberina Fault (ATF) and surrounding regions in the period 2010-2015: crustal anisotropy (in terms of time delay between the two S-waves generated by the shear wave splitting), b-value of the Gutenberg-Richter law and vp/vs ratio. We obtained three time series of the corresponding measures for each station of the Italian Seismic Network operating in the study area. However only three of them show enough points along the entire 6-year period to obtain robust time series. Due to the sparse presence of values in the time series we thus apply a weighted likelihood approach to homogenize them, and finally we looked for both correlations and change points in their temporal trends. The times corresponding to aforementioned variations in one or more parameters/stations are then tested to highlight the statistical significance of their occurrence. We merge all observations for getting a more constrained interpretation of the ATF seismicity evolution. The statistical approach presented in this study for comparing seismological time series could more generally find application in comparing other types of time series, and is especially suitable for those derived from unevenly sampled measurements.