Book of abstracts

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Physics-based estimates of the maximum magnitude of induced earthquakes in the Groningen gas field

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Abstract

Induced seismicity in the Groningen gas field, The Netherlands, has led to public concern and comprehensive investigations to assess future seismic hazard. One of the main challenges is to estimate the maximum possible earthquake magnitude (Mmax) that could be induced by gas extraction. Here, we estimate Mmax in the Groningen gas field through a novel physics-based approach, based on the dynamic fracture mechanics theory, constrained by field and laboratory observations. The method provides estimates of the along-dip rupture width, along-strike rupture length, and slip of potential maximum earthquakes for each of the more than 1000 mapped faults in the reservoir, at any given time in the production and post-production histories. The rupture widths are constrained by the along-dip two-dimensional fracture mechanics theory, and the rupture lengths by the three-dimensional fracture mechanics theory of dynamic ruptures with large aspect ratio. These two theoretical elements are extended, combined and validated in this study. The estimated Mmax is time-dependent due to the gas extraction history. It saturates at a value that depends on the friction parameters of fault rocks and on the pre-production tectonic stresses. Applying the physics-based rupture model, while accounting for plausible ranges of key parameters, yields an estimate of Mmax in the Groningen gas field. While there are considerable uncertainties in some parameters, such as dynamic friction coefficient and pre-production stresses below the reservoir, these may be reduced through future focused efforts. The proposed approach is a practical step toward physics-based seismic hazard assessment for other gas fields worldwide. Ongoing extensions of the model to include ruptures across multiple faults will be discussed.

*Speaker

The predictive skill of global and regional earthquake forecasting models for California, New Zealand, and Italy

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Abstract

The increasing availability and quality of geophysical datasets, including earthquake catalogs, geological records, and interseismic strain rates, has enabled the creation of global and regional earthquake forecasting models that can underpin probabilistic seismic hazard analyses. Regional models provide detailed seismicity forecasts given the high resolution of their input data, while global models offer greater testability of the large damaging earthquakes due to the more frequent seismic activity observed around the world. Quantitative comparisons between global and regional models can be useful to assess the performance of global models at regional scales, identify regional discrepancies that require further investigation, and better inform seismic hazard programs. Here, we prospectively evaluate the ability of the Global Earthquake Activity Rate (GEAR1) model, developed by Bird et al. (2015), and nineteen regionally calibrated models to forecast earthquakes in California, New Zealand, and Italy from 2014 through 2021. We project GEAR1 onto these testing regions, previously defined by the Collaboratory for the Study of Earthquake Predictability (CSEP), and scale its M5.95+ rates to a magnitude threshold of 4.95 assuming a b-value of unity. We then use comparative and consistency likelihood tests implemented in the CSEP's pyCSEP Python toolkit to contrast the performance of each regional model with that of GEAR1 and to evaluate the consistency between forecasts and observations. In addition, we compute Gini coefficients for each forecasting model to measure the absolute spatial localization of their predicted earthquake rates and to interpret the spatial test results. The testing dataset contains thirty-eight M4.95+ earthquakes in California, including the 2019 Mw 7.1 Ridgecrest earthquake, forty-seven M4.95+ earthquakes in New Zealand, including the 2016 Mw 7.8 Kaikōura quake, and eleven target events in Italy, including the 2016 Mw 6.6 Norcia earthquake. Comparative test results show that, in California, a model that adaptively smooths the locations of small earthquakes is the most informative, while GEAR1 outperforms all other regional models. In Italy, only amodel based on relative seismic intensities and two models based on adaptively smoothed seismicity can be considered statistically more informative than GEAR1. In New Zealand, GEAR1 is the most informative model, obtaining information gains per earthquake of about 0.5 over a fault-based and a smoothed seismicity model, respectively. These results provide evidence that GEAR1 is a robust first-order model to forecast M4.95+ seismicity in California, New Zealand, and Italy. When analyzing the spatial dimension of the models, we find that those that provide forecasts that are either too dispersed (low Gini coefficients) or too localized (high Gini coefficients) are the worst

*Speaker

performing models. Thus, we recommend applying an ”intermediate” smoothing procedure, e.g. adaptive smoothing, to improve the forecasting capacity of these models. Finally, we note thatthe New Zealand models obtain, overall, the highest spatial likelihood scores per earthquake, followed by the models for California and Italy, which could indicate a possible link between the tectonic setting and the spatial distribution of earthquakes.

Keywords: Statistical seismology, prospective model evaluation, global and regional models

Monitoring the criticality of the crust over a decade near Ridgecrest, CA, with temporal clustering and tidal triggering of microearthquakes

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Abstract

Earthquakes occur in the brittle part of the earth's crust to release the strain produced by tectonic loading over long time scales. Observing that earthquake sizes are power-law distributed, that relatively small stress perturbations (kPa) seem enough to trigger earthquakes, or that earthquakes temporal clustering follows fractal statistics, it appears that the crust is at or near a critical state. In this study, we built a decade-long catalog of microseismicity before the M7.1 2019-07-06 Ridgecrest earthquake. We systematically study the spatial and temporal evolution of the strength of temporal clustering and the sensitivity of seismicity rates to tidal stresses. We discuss how these observables relate to the mechanical state of the fault zone, and thus we produce new observations of the mechanical evolution of the crust over long time scales and prior to a large earthquake.

*Speaker

Change point analysis to fit time variable parameters of the ETAS model

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Abstract

This study uses change points based analysis to detect and fit potential temporal variation observed in the parametrisation of the stationary Epidemic Type Aftershock Sequence (ETAS) model. A series of fit-test steps are applied to account for possible time-varying background seismicity rate and earthquakes triggering parameters. Specifically, the standard ETAS model is fitted to a series of time periods identified by change points at one or both of their interval limits, while testing is applied to assess the goodness of fit between different ETAS models obtained by combining different fits at adjacent subperiods. For the Central Apennines (Italy) seismicity, two change points are detected in the time period 2005-2017. They depict starts of apparent quiescence occurred before the Amatrice M6 (2016) earthquake and activation observed around Campotosto M5.5 (2017) earthquake, respectively. Subsequently, a three-stage ETAS model is proposed to fit seismicity, with time varying parameters. A new time variable ETAS model fitting procedure is proposed and tested with an increasing background seismicity rate and significant temporal variation of the earthquakes triggering parameters in the three detected adjacent subperiods.

Keywords: ETAS model. Change point analysis. Central Apennines.

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A Bayesian model selection approach to estimate the distribution of earthquake magnitudes (including below completeness)

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Abstract

The statistical distribution of seismicity is described by the so-called Gutenberg-Richter law where the distribution of magnitudes p(M) follows an exponential law p(M) = b exp(-bM). The slope of this law, called "b-value", is used to compute seismic hazard maps. A well-known problem is that small events are often not detected, and the actual Gutenberg-Richter law thus needs to be corrected for small events. This can be done by multiplying the exponential law by the probability q(M) of detecting an earthquake of magnitude M. In this way, the distribution of observed magnitudes writes p(M)= q(M)*b exp(-bM). Characterizing the detection function q(M) is crucial as it allows to estimate the number of earthquakes that are missed at small magnitudes. This is particularly useful when analyzing aftershock sequences at early times, when the detection function threshold varies quickly.
Here we propose a Bayesian approach to jointly estimated all parameters that define p(M), i.e. the b-value as well as the parameters of the detection function q(M). Different detection functions, described by different number of parameters, are tested. Of course, a better fit is achieved as more parameters are used to describe q(M). We show how a Bayesian model selection approach can be used to compare different detection functions with different levels of complexity, to properly estimate q(M) and the b-value, together with associated uncertainties.

Keywords: Gutenberg Richter Law, Bayesian inference, b value, microseismicity

*Speaker

Towards Network Resilience: a collective effort by the expert community to define "good" seismic data quality using New Zealand specific ambient noise models

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Abstract

New Zealand National Seismic Network (NZNSN) totaling some 53 stations is managed by GeoNet and underpins earthquake, volcano, and tsunami monitoring. GeoNet provides free and open data in support of national and international research into geophysical research as well as natural hazard risk analysis and loss modeling. Data quality affects every application/purpose in these domains and yet little is known about whether it meets stakeholder and data user needs. Having a definition of "good" in a common language and in data-terms offers a practical, quantitative reference for end-users and network operators to support communication and decision-making. Funded by GNS Science, the "Towards Network Resilience" project has aimed to investigate this fundamental matter at a national level in three stages: the first stage was to establish a "feedback style" consultation model to define what constitutes "good" seismic data quality collaboratively with the New Zealand expert end-user communities. The second stage was to develop New Zealand specific reference models based on the community consensus in data terms and formalize it as a common standard for seismic data quality in New Zealand. This reference took the form of ambient noise models like those produced by S. J. Rastin (2012). The final stage was to explore how well historic seismic station data compares against our reference and how such comparisons could inform key performance indicators for network management and stakeholder relations. Ultimately we hope to integrate this work with geological hazard monitoring operations in New Zealand to build the capability of data-driven decision-making, empower network managers with awareness and understanding of station health, and to engineer processes for a high degree of network resilience.

Keywords: New Zealand, Ambient Noise Models, GeoNet, Seismic Networks, Data Quality

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Spatio-temporal evolution of foreshock sequences in the damage zone

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Abstract

Fault zones comprise multiple fractures which can generate seismicity in response to mainshocks, tectonic loading, or other stress perturbations, and in turn modify the stress state on the main fault. The physical processes controlling seismic swarms, and their implications for the time-dependent seismic hazard posed by the mainshock fault, are not fully understood. Here we study the precursory phase of large earthquakes in a fault zone comprised of a rough (fractal) fault surrounded by damage, represented as a collection of smaller faults with a power-law decay of density with distance from the main fault. We model seismic cycles assuming uniform velocity-weakening rate-state friction, and loading by a uniform far-field stressing rate.

We find that during the interseismic period between large ruptures on the main fault, seismicity takes place predominantly in the damage zone, and it is clustered in episodic swarms. Seismicy rates increase prior to the mainshock and exhibit a clear migration towards its hypocenter, both along strike and across the fault zone; in other words, seismicity becomes more localized in the final phase of the seismic cycle. This coalescence is controlled by two processes: 1. recovery of negative stress changes imparted by the previous mainshock, which are largest in the near field; 2. a triggering cascade in which each successive event is more likely to occur closer to the main fault, due to the power-law increase in fracture density towards the main fault.

In addition to foreshocks, simulations exhibit aseismic slip in subparallel secondary faults. We find that the mainshock is triggered by stress changes from both foreshocks and aseismic slip in the damage zone, and occurs earlier than it would have on a planar fault without damage.

*Speaker

Potential correlation between intraslab intermediate-depth and shallow earthquakes in Japan and Chile

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Abstract

An increase of both shallow and intraslab intermediate-depth seismicity has been observed days to years before some great subduction earthquakes, as before Tohoku-oki (Mw 9.0, 2011), Maule (Mw 8.8, 2010) or Iquique (Mw 8.2, 2014) earthquakes (Bouchon et al., 2016, Jara et al., 2017). These observations suggest that a link exists between these deep and shallow foreshocks, but it is still poorly understood and not characterized in a systematic manner. Some studies have attempted to address this lack of systematic characterization by using a statistical approach (Delbridge et al., 2017).
The aim of this study is to systematically and statistically identify and characterize the potential correlations between deep and shallow seismicity. We want to assess whether or not such interactions exist. If they exist, we plan to characterize when and where they occur, at what frequency, their characteristic duration, and with what spatial pattern.

For this purpose, we develop a statistical method to assess the relevance of deep-shallow interactions, that allows to identify statistically significant correlations between deep and shallow seismicity. We focused on the seismicity of the Japan trench and the Chile trench subduction zones, during the decades prior to the Tohoku-oki and Iquique earthquakes respectively, because deep-shallow interactions were identified there, and because we can test the events picked by our method against the correlations highlighted in published papers (Bouchon et al., 2016). The correlation values between the deep and shallow events are calculated on various sliding-windows with durations from days to months. These correlation values are then compared to the ones obtained using parts of catalogs far in time and therefore uncorrelated, and the significance of the correlation is calculated.

Some windows show a strong correlation. The dependence of our results to different parameters, such as the completeness magnitude, the length of the window or the smoothing are evaluated. The spatio-temporal analysis of the seismicity on maps for these windows is also explored. While the results are still preliminary, we believe that this method has the potential to systematically and quantitatively assess the current presumptions on the link between deep and shallow seismicity, that would lead to a better understanding of the mechanisms leading to megathrust earthquakes.

*Speaker

Regressions of moment magnitude on local magnitude in the New Zealand earthquake catalogue for the revision of the National Seismic Hazard model

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Abstract

Earthquake catalogues are by nature heterogeneous over time due to changes in network configuration and seismic processing. Statistical studies, including probabilistic seismic hazard analysis (PSHA), require homogeneous data to study changes in seismicity rather than changes in data processing. PSHA requires earthquake size estimates in the form of moment magnitude to be consistent with modern ground motion characterisation models. In New Zealand, routine moment magnitude calculations were introduced in 2007, although some earlier estimates for larger earthquakes are also available. The most prevalent magnitude in the New Zealand earthquake catalogue is a New-Zealand-specific local magnitude, *MLNZ77*, which has been consistently calculated for the earliest instrumental records in 1931 until 2011. The *MLNZ77* scale is known to estimate larger values compared to moment magnitude for moderate-sized earthquakes in the range 4.5–6.0.

A new seismic processing software, which allows for different magnitude-type calculations, was introduced in New Zealand in 2012. Routinely calculated magnitudes include a local magnitude *MLSC3* and a summary magnitude *M*, which is a mix of *MLSC3* and a broadband magnitude mB. Recently, a new local-type magnitude has been derived, *MLNZ20*, that is calibrated against New Zealand moment magnitude and is applicable for earthquakes of magnitude 5.5 and less. We have calculated *MLNZ20* for more than 250,000 earthquakes using more than 2 million individual waveforms with sufficient quality from before and after the introduction of the new processing software. We have derived regressions of *MLNZ20* on the existing local magnitudes, *MLNZ77* and *MLSC3*. These regressions allow us to derive moment-magnitude-consistent size estimates for more than 99% of earthquakes in the earthquake catalogue.

Here we present the updated earthquake catalogue and some of its features.

Keywords: Magnitude regression, moment magnitude, PSHA, New Zealand

*Speaker

Insights and lessons from more than a decade of public earthquake forecasting in New Zealand

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Abstract

Researchers from New Zealand have engaged in developing and testing earthquake forecasting models for more than four decades. They participated in the establishment of the Collaboratory for the Study of Earthquake Predictability (CSEP) in the late 2000s and set up a New Zealand earthquake testing centre. The existing earthquake forecasting models can be classified into three categories, (1) short-term or aftershock models that describe the decay of the earthquake occurrence rate following a large event, (2) medium-term models that aim to forecast upcoming large events, and (3) time-invariant models.
Aftershock models include the Short-Term Earthquake Probability (STEP) model, initially developed by Matt Gerstenberger for California, and the Epidemic Type Aftershock Sequence (ETAS) model, first developed by Yoshi Ogata and implemented in New Zealand by David Harte. The medium-term models are variations of the Every Earthquake a Precursor According to Scale (EEPAS) model that was developed by David Rhoades based on the observation that the size and frequency of earthquake occurrence tends to increase in the vicinity of an upcoming large earthquake. There is a suite of time-invariant models, mostly based on smoothed seismicity but also including other factors such as strain-rate and proximity to mapped faults.

In 2010, following the M7.1 Darfield earthquake that initiated the Canterbury earthquake sequence, GNS Science began to provide earthquake forecasts to the public. Initially, the forecasts were derived from the STEP model only. As the sequence continued with reactivation by a series of M6 plus earthquakes for more than one year, hybrid models including EEPAS and time-invariant models contributed to the forecast.

There were several further earthquake responses over the years. Social science research has helped in understanding what different stakeholders expected from forecasts and in fine-tuning the communications.

By the time of the 2016 M7.8 Kaikoura earthquake, the hybrid had evolved to include both the STEP and ETAS models, two versions of EEPAS, and a mixture of three time-invariant models. For automatic earthquake forecasting, a Hybrid Forecasting Tool (HFT) has been developed.
In this presentation, we review the progress of providing earthquake forecast to the New Zealand public and other stakeholders over the last decade. We conclude with some insights and lessons.

*Speaker

Keywords: Earthquake forecasting, New Zealand, large earthquakes, public communications

Exploring Afterslip and Aftershock Co-migration, Following no Evidence Afterslip Drives Aftershock productivity

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Abstract

Aseismic afterslip (transient, gentle fault readjustment) has been proposed as the principal driver of aftershock sequences. Evidence of this relationship includes observations of similar Omori-type decays, spatio-temporal co-migration, and explanatory mechanical models (e.g. rate-dependent brittle-creep afterslip). However, as this evidence is typically case-study based, first-order relationships between sequence-scale aftershock behaviours and afterslip abundance are not well-constrained. Given that relative afterslip moment (Mrel, afterslip moment/coseismic moment) can vary $< 1\%$ to $> 300\%$ for different earthquakes, we first look for robust correlations between Mrel and aftershock sequence characteristics, to support or rebut a global driving relationship. We select aftershock sequences from the global PDE catalog using three methods, for 41 mainshocks with available afterslip models, and find that Mrel does not correlate with aftershock productivity (number relative to an Utsu-Seki prediction, relative cumulative moment, or number relative to the background rate), b-value, Omori decay exponent (p) or the background-rate itself. Furthermore, we find that adding afterslip moment to the mainshock moment does not improve predictions of absolute aftershock number. Whilst data bias and uncertainty mean we cannot refute a weak relationship, our results do not support afterslip as a major driving mechanism of aftershocks globally. We then explore whether afterslip might control specific spatio-temporal characteristics of aftershock sequences, and whether we can support evidence that afterslip is an important aftershock triggering mechanism in specific case-studies (just not ubiquitously). We investigate the spatio-temporal migrations of afterslip and aftershocks for several case studies in California, including the 2004 Parkfield and 2014 South Napa earthquakes, using high resolution afterslip distribution models and regional seismic catalogs with better completeness.

Keywords: Afterslip Aftershocks Triggering

*Speaker

Linking fault roughness and earthquake behavior

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Abstract

It remains an open question how earthquake behavior may be influenced by the physical properties of a fault. The 2016-2019 Cahuilla, California earthquake swarm allows for high-resolution mapping of fault roughness, b-values, and stress drop. The sequence comprises 18,250 earthquakes (M-0.27 to M4.4) that ruptured across a 4-km by 4-km fault plane at 4-9 km depth. We first estimate roughness using 2D fault profiles – 150 m-wide bins in the along-strike and along-dip directions of the fault plane. Roughness is estimated from the residuals to a line fit to the profiles. We find that the fault is, on average, 50% rougher in the slip perpendicular direction than parallel to slip. Next, 3D mapping of fault roughness, estimated from residuals to a plane fit to moving subsets of events, suggests roughness varies by a factor of 6 over length scales of _˜500 m. Similarly, b-values determined using the b-pos method vary by a factor of 2 across the fault. In general, we find that b-values are weakly positively correlated with fault roughness. However, following the largest earthquake (M4.4), we observe a distinct population of earthquakes with low b-values occurring in an area of high roughness values. While stress drops also vary across the fault, we find no correlation between roughness and stress drops. We infer that earthquake sequence behavior is partially controlled by fault roughness, especially at low driving stresses.

Keywords: fault roughness, b value, stress drop

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Statistical relations between global earthquake magnitudes and parameters of seismograms

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Abstract

It is relatively straightforward to determine the magnitude of an earthquake after it has happened. However, it is unclear if an earthquake 'knows' its final magnitude before rupture ends. We are interested in whether earthquakes are deterministic: whether features of the initial stages of an earthquake make accurate predictions about the earthquakes' final size. A number of approaches have been taken to investigate determinism. For example, Olson and Allen (2005) found a relationship between the final magnitude and predominant period of the early stages of an earthquake. However, the results remain controversial, partly because Olson and Allen (2005) and subsequent researchers analysed only moderate numbers of earthquakes: of the order of tens or hundreds of events. The increase in data availability and quality over recent years allow us to re-investigate this issue in a more statistically robust way.

We examine the beginning of thousands of earthquakes from around the world. We quantify predominant period, average period, integral of velocity squared (IV2) and delay time for each of these earthquakes, and investigate these parameters' relationship with magnitude. We find that IV2 and predominant period scale better with final magnitude than average period.

The thousands of earthquakes used are now allowing us to also robustly analyse smaller groups of events, such as those grouped by depth or tectonic setting. We are also attempting to relate differences in the fits of these parameters to their physical basis, allowing us to better understand earthquake rupture processes.

Keywords: earthquake determinism

*Speaker

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Detection of small slow slip events by means of deep learning

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Abstract

Detecting small Slow Slip Events (SSEs) is still an open challenge. It is a crucial issue for the characterization of the slip spectrum and for the understanding of the mechanics of active faults. The difficulty in revealing low magnitude events is related to their detection in the geodetic data, notably subduction zones where tremors cannot serve as a proxy for the slow slip detection. It is therefore necessary to provide new observations by employing more powerful equipment or to develop novel methods to perceive potential bursts of slow slip. Unlike seismic data, geodetic observations provide the sole direct access to slow slip deformation, which need to be analyzed within a large time span (weeks to years). Moreover, they contain spatiotemporal information, which needs to be considered to consistently constrain the slip evolution. However, the detection of small potential events is still debated and hard to automatize. Traditionally employed methods rely on the visual inspection of the data and dedicated modelling methods with a fine-tuning of the parameters (e.g. Ozawa et al., 2001, 2013; Hirose & Obara, 2005; Wallace & Beavan, 2010; Radiguet et al., 2011, 2016; ; Wallace et al., 2016; Socquet et al., 2017; Bletery & Nocquet, 2020; Wallace, 2020; Itoh et al., 2022). Here we develop a method based on deep learning for the systematic detection of SSEs, which may outperform traditional techniques. We focus our analysis on the Cascadia subduction zone, where a link between slow slip and bursts of tremor activity has been established (Rogers & Dragert, 2003). In this direction, tremor catalogues can be used to validate potential SSEs detections against the spatiotemporal distribution of tremors. Moreover, a catalog of SSEs has been recently assessed by (Michel et al., 2019), providing an additional benchmark to our analyses. Nevertheless, the number of available labelled events is still scarce and does not allow for an adequate training of deep learning models. Therefore, we make use of synthetic data by generating synthetic slow slip events obtained from synthetic dislocations (Okada, 1985) and by means of the slab2 model. Each SSE template, assumed as a sigmoidal-shaped transient, is further added to a window of noise obtained from real GNSS data.

*Speaker

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We develop a method based on deep learning, using a Convolutional Neural Network (CNN), followed by a Transformer model, to detect small slow slip events in GNSS data. The CNN extracts features from the input GNSS time series by learning optimal convolution filters, while the Transformer focuses on specific parts of the input window thanks to a self-attention mechanism. We test our method both on synthetic and real position time series from Nevada Geodetic Laboratory (NGL). Results on synthetics are promising and show a detection trade-off between the SSEs location, magnitude and the density of the GNSS network. The model is further compared against real data and tremor catalogues, proving that it exists a magnitude threshold, which depends on the source parameters, down to which the model can reliably (90% confidence) detect slow slip events. The spatio-temporal information is thus taken into account, showing that our model is able to correctly learn the network geometry and exploit the temporal dependencies in the data, which is indeed the key feature to explore the slow slip variability and to address the detection of very small slow slip events.

Keywords: geodesy, seismology, machine learning

Declustering an earthquake catalogue in moderate seismicity context : strengths and weaknesses of existing methods

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Abstract

We present an analysis of the declustering and of the completeness of an updated earthquake catalogue for France. This catalogue was prepared by merging the former FCAT-17 version (Manchuel et al., 2017) with more recent catalogues from RESIF and from neighboring countries. It covers the 250 – 2020 AD period and is composed of events with magnitude greater than 2.0. This dataset was produced in a seismic hazard assessment perspective and will be used in a future update of the seismic hazard map previously produced by Drouet et al (2020) for France. This update will mobilize more recent and state-of-the -art methods and models. Our objective is to provide seismic hazard-oriented end-users with a turn-key dataset for the estimation of (Poissonian) seismicity rates in any region of France.
We compare the outcomes of several declustering techniques in the aftershock removal process for this long-term catalogue in a low-seismicity context. We discuss the efficiency of two approaches (Gardner and Knopoff, 1974; Zaliapin and Ben-Zion, 2020) for this removal operation and discuss the preservation of the Poissonian character of (declustered) seismic activity. We also revisit completeness periods for France in distinct magnitude bins from the outputs of several methods (Stepp, 1972; the slope method; Daniel et al., 2011).
These results and this updated catalogue for France (both original and declustered versions) will be made available to the community.

Keywords: France, Seismicity, Declustering, Catalogue Completeness

*Speaker

What injection-induced earthquake sequences tell us about natural earthquake swarms ?

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Abstract

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Whether they are due to natural processes or to fluid injection at depth (wastewater storage, geothermal activities, etc.), earthquake swarms are singular sequences that present insightful similarities. For instance, it has been observed for both types of sequences that seismicity migrates with time or that the seismic moment release is weak compared to the spatial extent of the seismic cluster. If aseismic slip has been observed in a few earthquake swarms, its observation is limited by the depth, low deformation and long duration of those sequences. Moment, duration and migration velocity scale in a similar way for both types of sequences, indicating that dynamics of injection-induced and natural swarms result from the same processes. As injection-induced and natural swarms seem to follow the same physics, we take advantage of what we know on the former to better understand the latter. Indeed, for decades, studies have tried to relate seismicity to injection operational parameters, especially seismic moment with injected fluid volume. We develop two new methods to relate fluid volume to seismic moment for injection-induced sequences considering the aseismic contribution and validate them statistically on a set of injection-induced catalogs. We can then propose, for the first time, a precise estimation of the fluid volume circulating during different natural earthquake swarms. This sheds a new light over the processes occurring at depth during those episodes, and opens promising perspectives to better understand their evolution.

Keywords: Earthquake swarms, Fluid injection, Aseismic slip

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Flexible and Scalable Earthquake Forecasting

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Abstract

Seismology is witnessing an explosive growth in the diversity and scale of earthquake catalogs owing to improved seismic networks and increasingly automated data augmentation techniques. A key assumption in this community effort is that more detailed observations should translate into improved earthquake forecasts. Current operational earthquake forecasts build on seminal work designed for sparse earthquake records that combines the canonical statistical laws of seismology. This parsimonious approach is remarkably robust and stubbornly difficult to improve upon. Advances in the past decades have mainly focused on the regionalization of the models, the recognition of catalog peculiarities, and the extension to spatial forecasts; but have failed to leverage the wealth of new geophysical data. Here, we develop a neural-network based earthquake forecasting model that leverages the new data in an adaptable forecasting framework: the Recurrent Earthquake foreCAST (RECAST). We benchmark temporal forecasts generated by RECAST against the widely used Epidemic Type Aftershock Sequence (ETAS) model using both synthetic and observed earthquake catalogs. We consistently find improved model fit and forecast accuracy for Southern California earthquake catalogs with more than 104 events. The approach provides a flexible and scalable path forward to incorporate additional data into the earthquake forecast.

Keywords: Earthquake forecasting, machine learning, temporal point processes

*Speaker

Analysis of seismic migrations highlight that natural swarms and injection-induced seismicity are both driven by fluid-induced aseismic slip

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Abstract

Seismic swarms are characterized by a high rate of small to moderate earthquakes clustered in time and space and they occur in a large variety of natural contexts. They are also induced by anthropogenic fluid injections in geological reservoirs, such as in enhanced geothermal systems or for shale gas extraction. In both cases, the driving mechanism required to maintain a seismic activity for days or years is still an open question. Moreover, despite similarities in the behaviors of anthropogenic and natural swarms, it is still not clear if they may share common driving mechanisms.
Classically, fluid pressure diffusion or slow-slips were proposed as driving mechanisms, but recent models suggest that swarm seismicity is rather triggered by fluid-induced aseismic fault slip. Here, using a catalog of natural and anthropogenic swarms, we observe that duration, migration velocity and total moment scale similarly for all swarms. This underlines a common aseismic slip driving process for both types of swarms, and allow a new possibility to discriminate fluid-induced swarms from aseismic slip triggered seismicity.

Moreover, one specific characteristic of seismic swarms is the migration of the earthquake hypocenters. Instead of being directly induced by the fluid pressure diffusion, the seismic front may map the shear stress concentration at the tips of propagating aseismic slip that is primarily induced by the fluid pressure increase. In this case, seismic migration depends on the hydromechanical properties that control the dynamics of aseismic slip propagation rather than the hydraulic diffusivity.
Using synthetic seismic catalogs computed from the hydromechanical modeling of a slip-weakening fault response to a fluid injection, we show that the shape of the seismic front in a distance-time plot depends on the initial fault criticality to failure, and not on the hydraulic properties. We then extrapolate this numerical result to injection-induced earthquake swarms. The seismic front has a diffusive behavior when the aseismic slip is directly driven by the pressure increase, either at the swarm beginning or later if the faults are not initially critically stressed. On the contrary, an accelerating seismic front indicates a high-criticality stressed fault, on which the aseismic slip runs away from the fluid pressurized area. Therefore, the migration behaviors of seismicity prove to be a useful indicator of the swarm driving process as well as of the stress state of faults over which the swarms occur.

*Speaker

The asymmetric seismic moment tensor in micropolar media

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Abstract

Seismic events produced by block rotations about vertical axis occur in many geodynamic contexts. In this study, we show that these rotations can be accounted for using the proper theory, namely micropolar theory, and a new asymmetric moment tensor can be derived. We then apply this new theory to the Kaikoura earthquake (2016/11/14), Mw 7.8, one of the most complex earthquakes ever recorded with modern instrumental techniques. Using advanced numerical techniques, we compute synthetic seismograms including a full asymmetric moment tensor and we show that it induces measurable differences in the waveforms proving that seismic data can record the effects of the block rotations observed in the field. Therefore, the theory developed in this work provides a full framework for future dynamic source inversions of asymmetric moment tensors.

Keywords: seismic moment tensor, asymmetric, micropolar media

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Joint Bayesian estimation of b-values and Mc : application to spatio-temporal variations

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Abstract

The statistical distribution of seismicity is described by the so-called Gutenberg-Richter law which tells us that the logarithm of the probability of having an earthquake of energy larger than M0, P(M > M0), decreases linearly with increasing energy, M0, such that log(P (M > M0)) = bM0 + a. The slope of this law, the so-called "b-value", is investigated to map different seismic regions and is used to compute seismic hazard maps so it has strong society implications. The way the b-value is currently estimated relies on the determination of a magnitude of completness Mc which defines the magnitude above which every earthquake is detected. The estimation of Mc is done independantly of the estimation of b while it can strongly affect the estimation of b. Moreover, as a result any study of seismicity requires to first remove all the earthquakes with a magnitude below Mc which implies loosing a lot of information. Instead we propose here to revisit this problem of determining b-values by jointly inverting for b and Mc using a Bayesian formalism and including the statistical modeling of the events below Mc. We also go further by extending the method to

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analyze spatio-temporal variations of b and Mc with a Bayesian formalism which provides the probability of any temporal or spatial changes in these parameters. The algorithm is tested on synthetic data, and then applied to a 20 years long catalogue of Japan including the Tohoku earthquake for which we detect temporal variations of b before and after Tohoku.

Keywords: bayesian, seismicity statistics, b value, Mc, spatio, temporal variations

Overview of Earthquake Rupture Forecasts for the 2023 USGS NSHM update

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Abstract

On behalf of a very large working group, this presentation provides a summary of anticipated improvements for the time-dependent Earthquake Rupture Forecasts (also known as seismic source characterizations) for the 2023 update of the USGS National Seismic Hazard Model. The main goals are a more uniform application of methodologies across the country, a more complete representation of epistemic uncertainties, and establishing a basis for an eventual operational earthquake forecasting capability nationwide. Efforts also include a better representation of multi-fault ruptures and the ability to apply variable degrees of segmentation throughout each fault system (e.g., a wider range of models than applied previously in California). The presentation also summarizes updated geologic constraints, deformation models, statistical seismology components, efforts to operationalize various computer codes, hazard and risk sensitivity analyses (e.g., for logic tree refinement), and any loose ends that continue to pose a challenge.

Keywords: System Level Earthquake Forecast

*Speaker

Seismicity under a dormant volcano: identification of an active crustal fault below Piton des Neiges

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Abstract

Volcanic environments frequently exhibit seismic phenomena. This is the case for the two major volcanic edifices on La Reunion Island (Piton des Neiges and Piton de la Fournaise), where significant seismic activity is recorded. If the seismicity at Piton de la Fournaise can be easily explained by its volcanic activity (more than three eruptions per year since 2014), the seismic activity of Piton des Neiges (inactive for about 27000 years) is still poorly understood. Following several earthquakes that have been detected and felt by the population under the north flank of Piton des Neiges, several seismic stations have been deployed in the area. Here, we use template matching and double-difference relocation to build a high-resolution catalog of the region since 2013. Our results reveal that the seismicity is densely clustered on a northeast dipping fault located in the oceanic crust, under the volcanic edifice. The orientation of this planar structure is consistent with the analysis of focal mechanisms indicating reverse fault activity. We also investigate variation in seismicity after correcting for apparent variations due to changes in the completeness of the catalog (following the densification of the seismic network since 2016). Preliminary analysis suggests that there is no significant variation of the b-value over time. The absence of intense seismic swarms suggests an origin that is not directly related to transient magmatic transfer (contrarily to what is observed at Piton de la Fournaise). However, some moderate changes in seismicity rates are observed over the studied time-period and remain to be explained. These results are intended to contribute to the understanding of deep seismicity (i.e., at depth between 5 and 30 km bsl) under dormant volcanoes. As far as La Reunion island is concerned, they constitute a first step towards an explanation of the seismicity at the scale of the island.

Keywords: Dormant volcanoe, crustal fault, seismicity rate

*Speaker

Seismic Clusters Growth and Underlying Triggering Mechanisms

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Abstract

Migration of hypocenters is a common attribute of induced injection seismicity and of earthquake swarms, which usually distinguishes them from aftershock sequences. Spreading of the triggering front is usually examined by fitting the square-root time dependence of hypocenter distances from the origin by the pore pressure diffusion model. The earthquake migration patterns however often exhibit not only spreading envelopes, but also fast-growing streaks embedded in the overall migration trends. It also turns out that when distance-event index plots are used instead of distance-time plots, the originally non- linear and interrupted migration front becomes linear and continuous. This is consistent with a front-rupture model where the new ruptures are triggered at the edge of previous ruptures, due to stress transfer supported by the fluid flow in the newly opened pore space. By simulation of the seismicity caused by pore-pressure diffusion and by the front-rupture growth we succeeded to reproduce the distance-time and distance-event index plots constructed for the observed earthquake swarms. We apply the new model to selected swarms from Iceland, California and West Bohemia and to injection induced seismicity. The seismic clusters are identified semi-automatically in the migration plots and the dependence of the activated area and total seismic moment are compared with the models of crack growth and front-rupture growth. The results allow distinguish between different types of seismicity growth and suggest the background triggering mechanisms of the observed seismicity.

Keywords: Statistical seismology, fluid induced seismicity, earthquake interaction, seismicity migration

*Speaker

The symptomatic spatiotemporal clustering of low-frequency earthquakes and tectonic tremor

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Abstract

Tectonic tremor and their constituent low-frequency earthquakes often accompany slow fault slip on plate boundaries. While tectonic tremor are difficult to pin down due to emergent waveforms without identifiable seismic phases, low-frequency earthquakes can be precisely located in both time and space with impulsive P- and S-waves. The characteristic feature of low-frequency earthquakes is that each seismic source emits many repeating events through time. We will show evidence that the evolution of these repeating sources follow a well-defined power-law distribution (e.g. clusters of activity) and are powerful indicators of aseismic fault motion along plate boundaries. The amplitude distribution of low-frequency earthquakes during spatiotemporal clustering suggests that clustered activity is driven by an underlying process, rather than event-to-event interactions as is the case for classic mainshock-aftershock sequences. We will also highlight similar clustering behavior driven by underlying processes in volcanic long-period seismicity. Systematically generated earthquake catalogs with a stationary detection capacity are what make the above observations possible and interpretable. We will thus conclude with recent work on developing a new approach to detecting tremor with a "single-station array". We implement an AI-based framework to learn how to detect and locate seismic sources from the records of a single seismic station based on the knowledge previously inferred from a dense seismic array. This allows us to detect and locate tectonic tremors with a uniform detection capacity over the entire lifespan of a single station. We demonstrate a proof-of-concept of this method in northern Cascadia, allowing us to explore the spatiotemporal distribution of tremor activity over more than two decades and 20 major slow slip events.

*Speaker

From the Izu-Bonin to the north of Hokkaido : how did the M9.0 Tohoku earthquake affect the Pacific plate seismicity ?

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Abstract

The last twenty years have seen a number of large, devastating earthquakes on subduction zones. In many ways, the M9.0 Tohoku-oki earthquake was bewildering for the seismological community. It occurred on a previously identified coupled area but ruptured a larger zone than expected and, above all, the large amount of near-trench coseismic slip was a surprise. Because Japan is one of the best area instrumented in the world, the 2011 Mw 9.0 Tohoku-oki earthquake is one of the world's best-recorded ruptures. Many studies have analyzed with great details the pre-seismic, co-seismic and post-seismic phases of the Tohoku earthquake. Researchers also focused on the triggering of on-land seismicity following the mega-thrust earthquake. However, no study zoom out and considered the consequences of this earthquake on

the Pacific plate in this area.In this study, we analyzed the Japanese Meteorological Agency seismic catalog over ten years of data to assess the consequences of such large mega-thrust earthquake over the Pacific plate from the Izu-Bonin area to the north of Hokkaido island.

*Speaker

We studied the seismicity from 0 to 700km depth, taking advantage of one of the most complete subduction zone catalogue.
Our results show that the seismic rate south of Japan experienced a decrease at the time of Tohoku about 30% and an increase of 20% underneath the Hokkaido island. The subduction zone that is downdip Tohoku doesn't seem affected by the megathrust earthquake. While it is difficult to understand and to model such large scale effects of the Tohoku earthquake on the Pacific plate, we think it is primordial to observe and detail them with precision.

The machine learning-based algorithm NESTORE for strong aftershocks forecasting in seismic clusters becomes a free available software: application to Italy

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Abstract

After an intense earthquake, the forecasting of strong subsequent events is strategic for civil defense purposes because already weakened structures may suffer further damage, increasing the risk of collapse and casualties. NESTORE (Next STrOng Related Earthquake) is an algorithm for probabilistic forecasting of clusters in which a strong mainshock is followed by at least one aftershock of comparable magnitude. More specifically, NESTORE labels clusters as type A if the magnitude difference between the mainshock and its strongest aftershock is less than or equal to 1, otherwise as type B. The goal of NESTORE is providing a near real-time estimation of the probability that the ongoing cluster is type A.
Some earlier versions of the algorithm have been successfully applied to California and Italian seismicity (Gentili & Di Giovambattista 2017, 2020, 2022). The new version, due to accurate statistical analysis of the results and the possibility of being applied to regions of higher completeness magnitude, is more robust and provides more reliable results. After the occurrence of a strong mainshock, the latest version of the NESTORE software, called NESTOREv1.0, analyzes nine selected seismicity features at increasing time intervals after the occurrence of the mainshock, through a multiparameter pattern recognition approach based on one-node decision trees. The main issues concerning this type of application are essentially two. The first is the number of examples (clusters) available in good quality catalogs, which is generally one order of magnitude lower than the one generally needed in machine learning applications. The second is class imbalance, because a subsequent strong earthquake is recorded in a percentage lower than 50% of the observed clusters. In recent years, the algorithm has been improved to increase its generalization capability, despite the small number of clusters available in seismological databases and the presence of some outliers. A renovation of the old version of the software, both in terms of algorithm and usability, was developed as part of the project " Analysis of seismic sequences for strong aftershock forecasting" funded by a grant from the Ministry of Foreign Affairs and International Cooperation as part of the scientific and technological collaboration between Italy and Japan.

The current version of the software, NESTOREv1.0, is now mature enough to be distributed to the scientific community for application and testing in new areas, and will be available on GitHub in the coming months. NESTOREv1.0 is composed of four modules that respectively: (1) identify clusters from a seismic catalog, (2) find appropriate thresholds for features

*Speaker

to distinguish cluster types on a training set, (3) use the result of the previous module to verify the performance of the trained algorithm on an independent test set, and (4) allow near real-time application to clusters as they occur.

As a test of the algorithm, we considered for the Italian territory the seismicity recorded in the last 40 years by ISIDE and OGS catalogs, the latter benefiting from a dense network in Northeast Italy. Several regions with different seismicity characteristics emerge from the analysis. The area of northeastern Italy and western Slovenia shows lower productivity both in terms of number of events and earthquake energy than the rest of the territory. For this reason, a separate training of NESTORE was applied, which showed results in good agreement with those obtained with previous versions of NESTORE (Gentili and Di Giovambattista, 2020). The second area is located in a smaller region between northwestern Tuscany and the southwestern part of Emilia-Romagna, with seismicity characterized by short-duration bursts with high productivity. Since the available training set for this region is almost exclusively populated by B-type clusters, a local training for that area is not possible and we excluded that region from our analysis. The remaining larger area, which includes most of the Italian territory, is characterized by type A clusters mainly in the central Apennines and type B clusters in the remaining territory. We trained NESTOREv1.0 using the ISIDE catalog on the time interval 1980-2009 (corresponding to 22 clusters) and tested the forecasting capability on clusters occurring between 2010 and 2021 (14 cases). The software test provides a correct cluster type forecasting for 86% of the cases, encouraging the application of NESTOREv1.0 in the Italian territory.

Acknowledgements

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Keywords: Largest aftershock, Seismicity, Machine learning, Bath's law, Aftershock sequence, Italian seismicity

The statistical distribution of time intervals between consecutive earthquakes worldwide

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Abstract

Earthquakes cluster in time in a tighter way than in a Poisson process, in which events would be independent from each other and from when each one occurred. This tight clustering must be considered for forecasting the probability of earthquake occurrence in a future time period, or when testing hypothesis of short- or long-range earthquake triggering.
Nevertheless, the standard analysis of temporal earthquake occurrence usually proceeds by "declustering" the earthquake time series, trying to identify aftershocks or other triggered events and then pruning them from the sample, leaving only the supposedly independent events. This procedure attempts to artificially make the process Poissonian-like (so that the probability of occurrence of the next earthquake is forced to be constant in time).

Since there is not a unique way of identifying triggered earthquakes, this removal is subjective to some degree (it involves lack of knowledge about the process, that is, epistemic uncertainty). Such a method also reduces the sample itself, reducing the power of any statistical inference made with it (in other words, with fewer events it is more difficult to distinguish which model best fits the data).

An example of this issue is the debate on whether the recent surge of great earthquakes (magnitude 8 or larger) since 2004 is random or not. If they were Poissonian, the distribution of time intervals between them should be exponential. The answer may depend on whether triggered events are artificially removed from the sample or not.

In this research, we explore in a comprehensive way the statistical distribution of time intervals between consecutive earthquakes occurred worldwide. As a previous step, we analyse in detail the completeness of global earthquake catalogues, considering periods separated by milestones in global seismic monitoring. We use a complete earthquake sample for each analysis, and do not attempt to separate triggered from independent events.
We consider different magnitude thresholds, and for each of them test which statistical distribution (such as Weibull, gamma or exponential) best fits the data. This enables us to quantitatively assess whether there is a universal distribution or, on the contrary, if it depends on the magnitude range considered. Also, we test whether Poissonian occurrence can be rejected for the whole series of the largest earthquakes.

*Speaker

Keywords: interevent times, point processes, renewal processes, earthquake probabilities, earthquake forecasting

Building an Earthquake Forecasting Tool

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Abstract

Operational earthquake forecasting involves the circulation of authoritative information to help communities understand the likely way sequences will evolve and aid recovery, and future resilience planning. Earthquake forecasting informs major decisions aimed at reducing seismic risk and improving earthquake resilience. In New Zealand, GNS Science through the GeoNet programme is the official provider of geological hazard information and has been publishing operational earthquake forecasts since the September 2010 Darfield earthquake. However, the requirement for human input in the production of forecasts has limited the speed at which initial forecasts are produced and the frequency with which they can be updated. Hence, there is a need for an automated tool that can produce forecasts quickly, regularly and systematically for the whole country or a selected region. Here we discuss a software tool (the Hybrid Forecast Tool, HFT) that integrates different forecasting models and has the capability to routinely generate forecasts. The incorporated forecast models cover three different timescales; short-term (from hours to few years, which are constrained by earthquake-clustering statistics and mainly describe aftershock decay), medium-term (from years to decades, which captures the increase of seismicity prior to large earthquakes) and long-term (from decades to centuries, which smooth out the spatial distribution of earthquake occurrence and can include information on faults and strain-rate). The individual models were originally developed in different software programming languages (Fortran, Java, and R) and on different operating systems, and they have been tested and published in various forms. The HFT combines all models in a single platform, using a Docker container, which circumnavigates technical challenges such as the incompatibility of different software libraries. The HFT can be operated through a graphic user interface (GUI) and command line that allow for setting up automatic and regular forecast runs. The HFT enables GNS Science to reliably provide forecasts for future responses to large earthquakes and regular forecast updates.

Keywords: Operational earthquake forecasting, earthquake, clustering statistics

*Speaker

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State of the Art of Time-Dependent Probabilistic Seismic Hazard Assessment

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Abstract

The ability to successfully forecast the future behaviour of a system is a strong indication that the system is well understood. Certainly, many details of the earthquake system remain obscure, but several hypotheses related to earthquake occurrence and seismic hazard have been offered. Probabilistic seismic hazard analysis (PSHA) provides the conceptual framework to quantify the rate (or likelihood) of exceeding various ground-motion levels for a spatial grid within a given time span given all possible earthquakes. For decades, PHSA has been utilised by governments and industry for making official national hazard maps, developing building code requirements, determining earthquake insurance rates and even for deciding safety criteria for large infrastructure such as nuclear power plants and hydroelectric dams. PSHA in its classical formulation adopts the removal of foreshocks and aftershocks from earthquake catalogs to separate independent seismic activity from background seismicity. This treatment has been shown to likely cause an underestimation of the seismic hazard, hence the need for time-dependent PSHA. Time-dependent applications can be classified into two groups; long-term models based on renewal statistics and short- and medium-term models based on clustering statistics. The latter honours the fact that earthquake occurrence is not stationary by including spatiotemporal clustering (e.g., aftershock sequences and precursory seismicity). Combining seismic hazard with different spatiotemporal scales could be a practical way to achieve a reduction in the exposure (e.g., the medium-to-long term planning of land use) or the vulnerability (e.g., short-term structural reinforcement or assessment). Thus, in terms of reducing seismic disaster risk and answering the increasing needs of social sustainability (towards earthquake resilience), integrating a fully time dependent PSHA is warranted. However, the current state of this art is under-reported in the literature. Here we review the concept and recent progress on the study of time-dependent seismic hazard assessment, with emphasis on short- to medium-term time dependence.

Keywords: Time Dependent, Probabilistic Seismic Hazard Assessment, aftershock sequences, precursory seismicity

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Stochastic Chaos and Predictability in Laboratory Earthquakes

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Abstract

Laboratory earthquakes exhibit characteristics of a low-dimensional random attractor with a dimension similar to that of natural slow earthquakes. A model of stochastic differential equations based on rate- and state-dependent friction explains the laboratory observations. We study the transition from stable sliding to stick-slip events and find that aperiodic behavior can be explained by small perturbations ($< 0.1\%$) in the stress state. Friction's nonlinear nature amplifies small scale perturbations, reducing the predictability of the otherwise periodic macroscopic dynamics. Similar to weather forecast, we think that ensemble forecast is the most reasonable way to assess the future state of the system because of the unavoidable stochastic terms that affect the dynamics.

*Speaker

A Coulomb Stress response model for time-dependent earthquake forecasts

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Abstract

Physics-based models allow extrapolating previously unsampled parameter ranges and enable conclusions on underlying tectonic or human-induced processes. Two widely-used physics-based seismicity models are the Coulomb Failure (CF) and Rate-State (RS) models, which assume pre-existing populations of faults that respond to Coulomb stress changes. The CF model depends on the absolute Coulomb stress and assumes instantaneous triggering if stress exceeds a threshold, while the RS model only depends on stress changes. Both models can predict background earthquake rates and time-dependent stress effects, but the RS model, with its three independent parameters, can additionally explain delayed aftershock triggering. This study introduces a modified CF model in which instantaneous triggering is replaced by a mean time-to-failure that depends exponentially on the absolute stress value. For critical initial stresses, we show that the model leads to identical forecasts as the RS model and reproduces the Omori-Utsu relation for aftershock decays and stress-shadowing effects. Thus, both CF and RS forecasts can be seen as special cases of the new model. However, the new stress response model can also account for subcritical initial stress conditions, which is particularly relevant for induced seismicity in intraplate regions.

Keywords: stress triggering, earthquake forecast, seismicity model

*Speaker

Repeating low frequency icequakes at the base of cold glaciers in the Mont-Blanc massif triggered by snowfalls

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Abstract

We have detected clusters of repeating low frequency icequakes located all over the Mont-Blanc massif between 2017 and 2021.These signals show a narrow frequency content with a characteristic frequency of about 5 Hz at all stations, whatever the distance from the source. These events occur as bursts of tens to several thousand events, with typical inter-event times of about 2-3 minutes, and last for days or weeks. Bursts of events usually start as small events with irregular occurrence times and progressively evolve toward more regular recurrence times. Seismic amplitudes and seismic waveforms also progressively evolve with time within each cluster, suggesting changes in either rupture length or rupture velocity. Most events are detected in autumn, winter and spring during and after snowfalls. We used all available temporary and permanent stations within or around the Mont-Blanc massif to locate these events. Most clusters are located above 3000 m above sea level, mainly on steep and North-facing glaciated slopes. Some clusters are clearly associated with cold ice (near Mont-Blanc summit) while others below 2700 m a.s.l. are likely located under temperate glaciers. Other clusters are located near the limit between cold-based and temperate glaciers. Cold-based glacier mainly move by creep, with little or no basal sliding. This suggests that the loading mechanism for these low-frequency icequakes may be viscous deformation within the ice, while high-frequency icequakes under Argentère glacier have been explained by the repeated failure of asperities surrounded by stable sliding (Helmstetter al al. JGR 2015).

Keywords: low, frequency icequakes repeaters glaciers triggering

*Speaker

Informative modes in the nearest-neighbor earthquake diagram

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Abstract

The nearest-neighbor analysis of seismicity in space-time-magnitude domains (e.g., Zaliapin and Ben-Zion, *J. Geophys. Res.*, 2013) can be used for multiple problems of statistical seismology, including detection of clusters, catalog declustering, and characterization of induced seismicity. Most of these problems use a representation of a proximity measure h as a product of rescaled time T and rescaled distance R between events, and are facilitated by the existence of two prominent modes (background and clustered) in the 2-dimensional joint distribution (T, R). The goal of this work is to utilize additional informative modes in the nearest-neighbor diagram. We analyze earthquakes in California and observe several distinguishing modes of seismicity, including induced seismicity, repeating earthquakes, and large vs. small aftershock sequences. In particular, most of the induced seismicity observed in the Geyser and Coso geothermal fields occurs in the diagram's background domain. This induced seismicity mode has similar overall values of h as the tectonic background seismicity, but is characterized by larger rescaled time T and smaller rescaled distances R. The mode of repeating earthquakes observed prominently in the Parkfield area is characterized by very large rescaled time T and small rescaled distances R, with overall h values comparable to those in the cluster mode of tectonic earthquakes. Aftershock sequences of large and small-to-medium magnitude mainshocks occupy different parts of the cluster mode. We also find modes that likely represent artifacts generated during the construction of the analyzed earthquake catalog. Furthermore, we illustrate these features of the (T, R) diagram and discuss how the results provide important information on spatiotemporal distribution features in different types of seismicity.

Keywords: nearest, neighbor analysis of seismicity, earthquake clustering, aftershock sequences, declustering, induced seismicity, repeating earthquakes

*Speaker

Numerical Investigation of Cascading Foreshock and Aftershock in Discrete Fault Network

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Abstract

Earthquakes often show a foreshock-mainshock-aftershock sequence. Analyzing the sequence is crucial to understanding the clustered seismicity nature and eventually improving the predictability of large earthquakes. Cascading has long been considered to play a crucial role in generating both foreshock and aftershock. The widely adopted earthquake forecast models, e.g., CRS and ETAS models, are based on the cascading process. In this work, we numerically investigated the foreshock and aftershock sequence in a discrete fault network with rate and state friction law and compared the result with the ETAS model. We set a fault zone consisting of dense fault segments and an off-fault area consisting of sparsely distributed smaller faults in the simulation domain. The simulations are conducted 100 times with randomly generated fault location, initial velocity, and fault length within the weighted distribution, yielding a Gutenberg-Richter law. The simulation results reproduce the properties of foreshocks and aftershocks in nature. Simulated aftershocks occur in the area of increased Coulomb stress and decay following Omori law as observed in nature. We observe immediate foreshocks that cascade toward mainshock within a day and early foreshocks that do not immediately trigger mainshock but still significantly destabilize the fault zone and subsequently advance the time to mainshock rupture. Individual foreshock sequences do not show a clear trend. However, once stacked, it shows apparent inverse-Omori law acceleration. In general, our model similarly behaves to the ETAS model since it incorporates the two statistical frameworks of the ETAS model (Omori law and Gutenberg-Richter law), and all seismic events have magnitude-dependent productivity to trigger another event. Comparison to the ETAS model shows that the triggering productivity is lower in the aftershock sequence than in the foreshocks due to the depletion of critically stressed faults in our simulations. Our model considers physics at an individual fault level and allows us to incorporate the actual geometry of the fault zone, enhancing the predictability of earthquake behavior.

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Accounting for earthquake rates' temporal and spatial uncertainties through least-information forecasts. Applications to the New Zealand Seismic Hazard Model.

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Abstract

Earthquake rates are seldom stationary, precluding the elaboration of seismicity forecasts for low-seismicity regions, where the scarcity of data limits a significant statistical analysis. We investigate the spatial and temporal performance limits of stationary Poisson seismicity forecasts, with applications to Probabilistic Seismic Hazard Assessment (PSHA). We design a bootstrapping experiment using fast-forward catalogues, i.e. catalogues from high-seismicity regions as proxy of long-term low-seismicity region catalogues. First, we propose a temporal process that relaxes the condition of stationarity, but rather assumes local-stationarity between intervals and power-law self-similarity in earthquake number distributions. Results show variability of earthquake rates to be up to 10 times higher/lower as predicted by Poisson models, where also least-information forecasts in low-seismicity areas, such as uniform area models (UA), are preferred to smoothed-seismicity-models (SSM). Second, we devise a data-driven method based on strain rates to constrain uniform areas that encompasses the spatial uncertainty, from which a rate distribution can be inferred from the earthquake counts within. We provide a set of forecasts for the update of the New Zealand National Seismic Hazard model, which have an increased mean rate values up to 10 times in low-seismicity regions compared to SSM, whereas also presenting a decrease close to 20% in regions exhibiting high seismicity. Rate variability is represented as Mixed-Poisson processes, such as the Negative Binomial or Lognormal-Poisson distributions. We further analyse the impact of the forecasts in the seismic hazard space. For 10% probabilities of exceedance in 50 years in low-seismicity regions, using UA provides an increase of _˜0.1 g of the expected peak ground acceleration (PGA) compared to SSM. Including both temporal and spatial uncertainties increases the expected PGA to 0.2 g, whereas the effect on high-seismicity regions is minimal (_˜0.01–0.05 g). These results suggest the need to address the non-stationarity found in training data, which would provide a more realistic forecast than any Poisson-based method. It also encourages the use of non-Poisson analytical closed forms in forecasts to solve the seismic hazard integral in PSHA, which can retain the non-stationary features of the training data.

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A size distribution of deep low-frequency tremors in the Nankai Trough zone: Modeling with a mixture distribution

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Abstract

As a size distribution of slow earthquakes, a power-law distribution (e.g. Bostock et al., 2015, JGR, doi:10.1002/2015JB012195) and an exponential distribution (e.g., Chestler & Creager, 2017, JGR, doi:10.1002/2016JB012717) have been proposed. Nakano (2019, GRL, doi:10.1029/2019GL083029) suggested that a tapered Gutenberg-Richter (GR) distribution (Vere-Jones et al., 2001, GJI, doi:10.1046/j.1365-246x.2001.01348.x), which contains the characteristics of the above two distributions, fits well the size distribution of slow events. In this study, we propose a mixture distribution of a power-low distribution and an exponential distribution for the size distribution of slow earthquakes. Let π_p and π_e, where $\pi\_p+\pi\_e=1$, be the mixture coefficients (or mixture ratio) of power-low and exponential distributions, respectively. We suppose that these coefficients have a dependency on the size of events. We also suppose that the value of π_e changes from 0 to 1 (and the value of π_p changes from 1 to 0) as the size of events is larger and it is represented by the cumulative distribution of a normal distribution. Consequently, the mixture distribution approaches an exponential distribution if the size of events is sufficiently large, and it does a power-low distribution if the size is sufficiently small.
Then, we consider the product of the mixture distribution and the cumulative distribution of another normal distribution. The second cumulative distribution corresponds to the detection capability of events (e.g., Ogata & Katsura, 1993, GJI, doi:10.1111/j.1365-246X.1993.tb04663.x; Iwata, 2013, GJI, doi:10.1093/gji/ggt208). Thus, this product (or model) can be used to analyze the size distribution of observed events without any cutoff size.
We applied this model to the deep low-frequency (DLF) tremors in the Nankai Trough zone, southwestern Japan. The dataset of the size of DLF tremors is based on Daiku et al. (2018, Tectonophys., doi:10.1016/j.tecno.2017.11.016)(D2018). D2018 constructed five regions along the Nankai Trough (see Figs. 2 and 3 of D2018 for the details.) and calculated the apparent moment A of a few hundreds of DLF tremors in each of the five regions from April 2002 to July 2013. In this study, following Nakamoto et al. (2021, JGR, doi:10.1029/2020JB021138), we used the seismic moment $M\_0=4\pi\rho V\_s\hat{}3\ A/F\_s$ as the size of the DLF tremor, where ρ, V_S, and F_S are the density of material, the S-wave velocity and the average of S-wave radiation pattern coefficients, respectively. These values are taken from Maeda and Obara (2009, JGR, doi:10.1029/ 2008JB006043).

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We attempted to fit the proposed model to the observed size distributions of the tremors in the five regions. We also applied an exponential distribution, a power-low distribution, and a tapered GR distribution to the five size distributions. The parameters of each of the four models (or distributions) are estimated with the maximum likelihood method. Then, the goodness-of-fit of the models is compared through Akaike Information Criterion (AIC) (Akaike, IEEE Trans. Auto. Control, doi: 10.1109/TAC.1974.1100705). As the value of AIC is smaller, the goodness-of-fit is better.
For all of the five regions, out of the examined four models, the model proposed in this study is selected as the best model; the value of AIC is the smallest. The results suggest that the size distribution of DLF tremors changes from a power-law distribution to an exponential distribution and that the proposed model is efficient in representing the property of this change.

Keywords: size distribution, deep low, frequency tremor, slow earthquake, mixture distribution

Testing subduction-zone earthquake models

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Abstract

Several global forecast models are under testing to explore earthquake magnitudes and rates in subduction zones. GEAR1, published in 2015, assumed that all subduction zones had identical dip angle, seismogenic thickness, shear modulus, corner magnitude, coupling, and all other properties except length and convergence rate. Another recent model, SMERF, assumed separate values of dip, coupling, corner magnitude, and other parameter for 37 separate subduction zones, thus depending on 6 x 37 fitted parameters. To protect against over-parameterization, Bayona-Viveros et al. combined the 37 zones into 14 super-zones, assuming uniform parameters in each. That modification allowed estimation of parameters over shorter time periods, and resulted in separate forecast models SMERF2, TEAM, and WHEEL. The aggregation was based on a 2016 paper by Kagan and Jackson, who aggregated earthquake data over Flinn-Engdahl zones. While the aggregation helped stabilize the estimation procedure, the Flinn-Engdahl zones were drawn before plate tectonics was accepted and they were based almost entirely on earthquake data. Here I'll present results with a similar approach, but with aggregation of zones by tectonic features such as dip angle, convergence rate etc.. This allows tests of the influence of those properties, without biasing the tests by selecting earthquake data. I'll start with the popular hypothesis that dip angles best explain the largest magnitudes

Keywords: testing, zones, dip angle, regionalization, corner, magnitude

*Speaker

Coda-Based Estimation of Source Parameters of Laboratory Acoustic-Emission Events

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Abstract

We propose an approach that is aimed to enrich the catalogs of acoustic emission events recorded in laboratory experiments with such parameters as seismic moment and corner frequency. Because of the difficulty of separation of direct waves in experiments performed on small samples, we use the coda waves that are composed of the reverberation of the acoustic field in the tested sample. After multiple reverberations, the resulting wavefield can be approximated as nearly homogeneously distributed over the sample and with signal amplitudes decaying exponentially in time (linearly in a logarithmic scale).
Within the framework of this model, the frequency-dependent coda amplitude at any moment of time is described as combination of a source spectra, of a decay rate combining internal attenuation with reverberation losses, and of a sensor response. One of the main difficulties with the laboratory experiments is that acoustic sensors are very difficult to calibrate and their absolute response function in most of cases remains unknown. With the simple reverberation model, the logarithms of coda amplitudes at different times and sensors and for multiple events are described by a system of linear equations that we solve in a least-square sense to find frequency-dependent coda-decay rates, relative source spectra and sensor responses. In a next step, we compute spectral ratios between different events to eliminate the sensor responses and to estimate main source parameters such as corner frequencies and relative seismic moments.

We provide details of our data analyses technique and present time-dependent corner frequency vs relative moment diagrams for two experiments on granite of the Voronezh massif and Berea sandstone under pseudo-triaxial loading. The main trend of inverse proportionality of corner frequencies and relative moments is maintained throughout both experiments. The dependence close to the cubic that is frequently estimated for tectonic earthquakes observed on the first stages of both experiments when confining pressure steps applied to the intact rock. After applying axial load changes in stress-drop is being observed.
Experiments carried out in the RESC of IPE RAS "Petrophysics, Geomechanics and Paleomagnetism" on a controlled hydraulic press INOVA-1000 of the Geophysical Observatory "Borok", IPE RAS.

*Speaker

Keywords: acoustic emission, rock physics, coda of a signal, spectral ratio, corner frequency, relative seismic moment

Modelling the probabilities of anomalous seismicity rate increases prior to mainshocks

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Abstract

The idea of using foreshocks to forecast larger earthquakes is not new, however this idea has never been realised. Regional micro-seismicity catalogues are relatively new, and research shows you only observe foreshocks if you analyse micro-seismicity catalogues. Exploiting these new catalogues may reveal key insights about foreshocks, and how they relate to the earthquake nucleation phase. Recent work has defined foreshocks as statistically significant increases in the seismicity rate around where the mainshock occurred, compared to the normal rates. Using this definition and searching within 20 days and 10km of mainshocks in Southern California (the Quake Template matching catalogue), around 20% of mainshocks have foreshocks. But once you take into account how often anomalous seismicity rate increases occur and no mainshock follows, only 6% of mainshocks have foreshocks. How the normal seismicity rates are modelled determines how many mainshocks have foreshocks. There is no currently agreed upon best method, and past models have not been tested to see how well they represent these rates. We test the following models from the literature: A Poisson distribution based on the background rate; a Gamma distribution based on the inter-event time distribution; and a Poisson distribution

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based on epidemic type aftershock sequence model conditional intensities. We define a simple model of normal earthquake behaviour by performing Monte-Carlo sampling of the local catalogue around mainshocks. We count how many earthquakes occur in random 20 day windows. This gives a distribution of the numbers of events within 20 days. This simple method retains the clusters of events that are typical for that area. We then use the Kolmogorov-Smirnov test to see if the above models could have produced the distribution. We also propose new models. We fit a negative binomial model to this distribution. We also produce another distribution in the same manner based on seismic moment rather than the seismicity rate. Preliminary results suggest the probability a mainshock has foreshocks strongly depends on the chosen model, and even negative binomial models don't fit the empirical data well. As a result, foreshock probabilities stated in the literature should be treated with caution.

Keywords: Foreshocks, modelling, seismicity rates

Statistical Power of Tests for Evaluation of Earthquake Forecast Models

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Abstract

The Collaboratory for the Study of Earthquake Predictability (CSEP) is an international effort to evaluate earthquake forecasting models independently and provide the cyber-infrastructure together with a suite of testing methods. For testing forecasts, CSEP defines a grid-based format to represent the forecast in terms of the expected number of earthquakes for each cell in the grid. In CSEP, the spatial consistency of a forecast is evaluated using the Spatial test (S-test), based on joint log-likelihood evaluations. The high-resolution grid combined with inhomogeneous earthquake distributions leads to many empty cells that may never experience an earthquake and cause a huge disparity in the number of cells and the number of observed earthquakes. This imbalance can lead to the lack of statistical power of the S-test and forecast testing in general. The power of the S-test defines the ability of the test to correctly identify whether two distributions of data (e.g., earthquake forecast and actual seismicity) are the same or different.

To explore this issue, we take global earthquake forecasts as a case study. We find that for a very fine-meshed single-resolution grid, an unrealistic high number of approximately 32000 earthquakes is required in the test catalog to achieve the highest power of the S-test. The required number of earthquakes in the test catalog decreases for decreasing grid resolution, but uniformly decreasing the resolution leads to the loss of spatial information offered by the forecast model in seismically active regions. Thus, we use data-driven multi-resolution grids to test the forecast models in which the resolution is determined by the availability of data. The data-driven multi-resolution grids offer powerful testing with as low as 16 earthquakes in the test catalog. Therefore, we propose using multi-resolution grids in future CSEP forecast experiments and further studying its application in regional and local experiments.

We further explore multi-resolution grids for spatial forecasts of aftershock activity. For that purpose, we study stress-based forecast models with a binary classification approach using measures, i.e., ROC curve and MCC-F1, based on the contingency matrix. We observe that the choice of grid resolution also affects the binary test results. Currently, we are striving to explore the quantitative effect of the grid resolution on those performance metrics.

Keywords: Earthquake forecasts evaluation, Multi resolution grid

*Speaker

Machine learning DAS signal denoising without clean ground-truth signals

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Abstract

We present a weakly supervised machine learning (ML) method for suppressing strong random noise in distributed acoustic sensing (DAS) recordings. The method aims to map random noise processes to a chosen summary statistic, such as the distribution mean, median or mode, whilst retaining the true underlying signal. The dataset used is a DAS array deployed at the surface of the Rutford Ice Stream in Antarctica. Despite being a very low anthropogenic noise environment, strong random noise processes, such as weather-induced instrument noise, heavily dominate the signal from microseismic icequake events. Here, we demonstrate that the proposed method greatly suppresses incoherent noise and enhances the signal-to-noise ratios (SNR) of microseismic events, enhancing the performance of subsequent processing steps, such as event detection. Our best performing model for this task is extremely lightweight by deep learning standards (three hidden layers, 47,330 model parameters), processing 30 secs data recorded at a sample rate of 1000 Hz over 985 channels (_˜ 1 km of fibre) in < 0.3 secs. Furthermore, it is trained in a 'weakly supervised' manner, such that it requires no manually-produced labels (i.e., pre-determined examples of clean event signals or sections of noise) for training. Lastly, our GPU-optimised Tensorflow implementation is considerably faster than standard Python filtering routines, such as bandpass filtering using the open-source obspy framework, and doesn't require any prior assumptions on the distribution of the noise or event signals, unlike traditional spectral methods. We argue that efficient data-driven denoising methods, such as the one presented, will prove essential to time-critical DAS detection and early warning processing workflows, particularly in the case of microseismic monitoring.

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Source characterization with 3 seconds of records on a single station

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Abstract

How fast can we produce an estimation of the magnitude and source location of an earthquake? Present early-warning systems require at least 4 stations to provide a first estimation. This introduces inherent delays which depend on the instrumentation density. We present here a Machine Learning (ML) approach for earthquake detection and source characterization running on a single station. We developed two separate algorithms for detection and source characterization. Our detector is trained on noise and earthquake waveforms from the STEAD global database, plus a regional dataset from Peru. It achieves over 99.9 % accuracy. The second algorithm is trained on a database including STEAD, Peruvian, Chilean and Japanese waveforms. We extract 164 attributes (in the time, spectral and cepstral domains) from seismic traces including only 3 seconds of records after the arrival of the P wave. We then train the ML algorithm to predict the magnitude, epicentral distance, back-azimuth and depth of the earthquake from these 164 attributes. We repeat the process with 4 sec of data, then 5, up until 50 seconds, allowing us to provide updated estimates every second. The algorithm is currently running in beta version in the early-warning system of Peru and will go online in July 2022.

Keywords: Machine Learning, early warning, single, station

*Speaker

Instantaneous Tracking of Earthquake Growth With Elasto-Gravity Signals

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Abstract

Rapid and reliable magnitude (M w) estimation for large earthquakes (M w > = 8) is key to
mitigate the risk associated with strong shaking and tsunamis. Standard early warning systems based on seismic waves fail to rapidly estimate the size of such large earthquakes. GNSS-based approaches provide better estimations but are also subjected to large uncertainties and latency associated with the slowness of seismic waves. The recently discovered speed-of-light Prompt Elasto-Gravity Signals (PEGS) has raised hopes to overcome these limitations, but has never been tested for operational early warning. Here, we show that PEGS can be used in real-time to track earthquake growth instantaneously after
the event reached a certain magnitude. We develop a deep learning model that leverages the information carried by PEGS recorded by regional broadband seismometers in Japan before P-waves. After training on a database of synthetic waveforms augmented with empirical noise, we present the first example of instantaneous tracking of an earthquake source time function on real data. Our model unlocks "true real-time" access to the rupture evolution of large earthquakes using a portion of seismograms that is routinely treated as noise, and can immediately be transformative for tsunami early warning.

*Speaker

Comparing multiple deep learning models to detect hydraulic-fracturing induced seismicity

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Abstract

The monitoring of hydraulic fracturing-induced seismicity (HFIS) is crucial to assess and mitigate risks to protect infrastructure and livelihood. Deep learning phase picking models have been proposed as a solution for efficiently processing large volumes of data typically produced during microseismic monitoring. These models have detected regional earthquakes not catalogued by existing traditional methods (e.g., STA/LTA, autocorrelation), which can lead to changes in the statistical characteristics (e.g., Gutenberg-Richter b-value) of the catalogue which can be used to predict the maximum magnitude that can occur at a site as well as to predict the rate of earthquake in relation to injection rate. It also presents the opportunity to observe new changes in spatiotemporal evolution of induced seismicity and discern the relative importance of different driving mechanisms of HFIS.
We chose four existing phase picking models (GPD, U-GPD, PhaseNet and EQTransformer) trained on large volumes of regional earthquakes recorded on surface station datasets (100 Hz) and investigated how well they generalise and pick microseismic phases in higher frequency (2000 Hz) borehole data.The PNR-1z dataset comprises continuously recorded injection operations on the PNR-1z well at a hydraulic fracturing site in Preston New Road, England where the operators catalogued > 38,000 events using the Coalescence Microseismic Mapping (CMM) method. We examined phase classification abilities of each model and subsequently generated earthquake origin time catalogues for the PNR-1z dataset to compare against the initial catalogue.
Results show that some of the models (particularly PhaseNet) recognise seismic phases well within our data: they recover up to 94.6% of the initial catalogue and also found a large proportion of undetected events (> 32,800, an 80% increase in events). PhaseNet's successful application on our dataset might be attributed to its exposure to different instrument data during training, as well as its comparatively small model size which likely reduces overfitting to its initial training set. In addition, because PhaseNet's architecture is fully convolutional, the model produces a phase probability for each sample in a continuous seismic trace, thus resulting in precise phase picks. We conclude that in its current state, PhaseNet can be applied off-the-shelf on high frequency borehole data to detect HFIS. The many events that went undetected previously might reveal new insights into the spatio-temporal evolution of seismicity during fluid injections.

*Speaker

An extension of the ETAS model to 3-D

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Abstract

The Epidemic Type Aftershock Sequence (ETAS) model is a widely used stochastic point process model for describing the distribution and clustering of earthquakes in space and time. For historical reasons, the ETAS model is two-dimensional and uses only epicentral information because of the large depth uncertainties in the past. Nowadays, however, earthquake catalogs also provide high-precision depth values that contain valuable information. Therefore, 3-D versions of the ETAS model are desirable, exploiting the full hypocentral information of earthquake catalogs. We develop a new 3-D ETAS model that incorporates a depth kernel into the trigger function. To explore its most appropriate parametric form, we first examine the empirical depth distribution of aftershocks as a function of the depth and magnitude of the mainshock. To this end, we apply the nearest-neighbor distance (NND) method to select direct aftershocks observed in California and other regions and fit truncated power-law kernels that account for the free surface and finite depth of the seismogenic zone. Finally, we show initial applications of the developed 3D ETAS model for several case studies.

Keywords: 3D ETAS model, Nearest Neighbor Distance (NND), statistical seismology, point process modeling.

*Speaker

Lab Earthquake Prediction, Precursors, and the Evolution of Size-Frequency Distributions During the Lab Seismic Cycle

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Abstract

Recent work shows that frictional stick-slip failure events, the lab equivalent of earthquakes, can be produced under controlled conditions for the full range of slip behaviors observed on tectonic faults. The spectrum of lab fault slip modes includes a continuous range from aseismic slip and creep events to aperiodic slow slip and fast, elastodynamic failure events. These data show that labquakes are routinely preceded by foreshocks in the form of acoustic emissions. They also reveal systematic changes in fault zone elastic properties that represent robust precursors to failure for the full spectrum of slip modes. Foreshocks include a cascade of microfailure events that show systematic evolution of the frequency magnitude (FM) relations, with an increase in event rate and a greater proportion of larger events as time to failure approaches. Machine learning (ML) techniques based on these changes are capable of predicting the failure time of labquakes and also the fault zone shear stress and other aspects of labquakes.. These works provide an opportunity to use ML to interrogate the physics of impending failure. I summarize the physical processes of ML-based failure predictions, precursors, and changes in FM relations during the lab seismic cycle.

*Speaker

Earthquake swarms along the Chilean subduction zone

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Abstract

We search for earthquake swarms along the Chilean subduction, from $-18ˆo$ to $-38ˆo$ of latitude, 2003-2020, as a way to provide better insights on where and when slow slip episodes occur. We develop an objective, statistical, model-based method that detect swarms as anomalous changes in earthquake rate. A set of 16 swarms is obtained after careful inspection of the candidate swarms; this assessment allows to reject cases for which model errors, rather than 'true' anomalous rate changes, are likely the cause of the detection. Averaging the activity over these 16 episodes, we find indirect evidence for a mostly aseismic driving mechanism, and a mean aseismic to seismic ratio estimated to 89 when using the seismicity rate as a proxy for slip. All the swarms are found in the 20-50 km depth range with the notable exception of one 60-100 km-deep swarm that occurs several days after the 2010 Maule earthquake and downdip of it. The dominant depth range (20-50 km) is in agreement with previous studies that suggest this range to be a transition zone from the shallower, locked part of the subduction, to the freely slipping interface at greater depth and intraslab earthquake activity. The swarms can be separated into three spatial groups, that are all related to a subducting oceanic ridge. This structural control by fluid-rich geological features is modulated by stress control, i.e., swarms cluster in time with intermediate to large ruptures, both prior and following them, pointing to a close interplay between seismic and aseismic slip in relatively well segmented parts of the Chilean subduction.

*Speaker

Influence of sea level changes on seismicity rates from a hydrothermal system in the Marmara region, Turkey

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Abstract

For decades, periodic Earth phenomena, such as tidal loading have been studied to investigate whether their associated stress changes are enough to bring a fault to slip. Triggering of tectonic tremor by solid earth tides has been observed almost everywhere that tremor occurs, in regions typically displaying lithostatic pore pressures and low effective normal stress. Observations of tidal triggering of earthquakes are far less common, and are mostly related to regions where the Earth's crust is close to failure, such as geothermal and magmatic systems, where small stress changes can induce fault slip. As the stress changes are small, typically seismicity of small magnitude displays a larger response to tidal loading. Therefore, high resolution seismicity catalogs with low detection thresholds are needed to capture it. In the Sea of Marmara region of the North Anatolian Fault Zone, Turkey, a fault segment of about 150 km is late in its seismic cycle. The Armutlu Peninsula, directly south of Istanbul, is a hydrothermal region rich in crustal fluids and with abundant hot springs. We document a strong effect of sea level changes in the Sea of Marmara on the seismicity of the Armutlu Peninsula. During a 90-day time period corresponding to the winter months, changes in the sea level up to 1 m were recorded. The sea level fluctuations display an overall period of 13.6 days, corresponding to the fortnightly tides, but are also strongly affected by storms. We generated new high-resolution seismicity catalogs for this region using both AI-based and template matching techniques, and compared the results with those obtained from catalogs employing traditional techniques for earthquake detection and association. Both template matching and AI-based catalog show that local seismicity rates are significantly larger during time periods when the sea level is rising. Available data from local strainmeters suggested that the associated strain changes on the order of 100-400 nstrain are sufficient to bring the local faults to failure.

Keywords: earthquake triggering, tidal loading, hydrothermal

*Speaker

Beyond cascade and pre-slip: complexities involved in the generation of earthquake sequences

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Abstract

Detection and analysis of earthquake precursory processes is a challenging topic that have concerned geoscientist from different disciplines over almost a century. The classical view on how earthquakes nucleate evolved for decades around two widely accepted models where the mainshock is promoted by either the stress change from previous earthquakes or the occurrence of an aseismic transient. The improvements in earthquake monitoring, integration of geodetic techniques to capture slow deformation, and the incorporation of artificial intelligence for seismic data processing recently allowed a more complete picture on how earthquake sequences evolve before the occurrence of the mainshock. Here, we review and compare the available analyses describing observations on precursory processes of 32 earthquake sequences covering a magnitude range MW (3.2, 9.1). We combine and present both seismological and geodetic analysis and discuss the patterns that emerge collectively, with a special emphasis on relating the observations with the physical processes driving the evolution of earthquake sequences. Our analysis highlights various structural, tectonic and boundary conditions that play a role in the dynamics of the earthquake sequences, as well as various physical processes that may be acting superimposed. From it, we propose the idea of earthquake nucleation as a complex imbricated process, involving several temporal and spatial scales.

Keywords: earthquake initiation, precursory processes, review

*Speaker

The space-time variability of the Magnitude-Frequency distribution

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Abstract

The Magnitude-Frequency Distribution (MFD) is one of the most prominent aspects of earthquake occurrence and, as commonly used, it represents a major limitation in improving earthquake predictability.
According to the first round of experiments carried out by the Collaboratory for the study of earthquake predictability (CSEP), the best earthquake forecasting models use a common space-time invariant Gutenberg-Richter (GR) law, performing significantly better than models with space varying b-values (the parameter of the GR law). However, despite a GR-like law is found to describe well magnitude distribution on large space-time windows, many independent pieces of evidence – stemming from the analysis of seismicity, model requirements (e.g., UCERF3), and physical constraints – raise doubts on its reliability when zooming on much smaller space-time windows.

Here, we show the space-time complexity of MFD in some recent seismic sequences, where high-resolution earthquake catalogs are available. The results of these analyses highlight some important new scientific results and new challenges. First, the importance of defining carefully a priori the space-time window in which the MFD is calculated, for example using geological constraints and/or machine learning techniques. Second, a signature of the elastic rebound in faults that have just slipped, which we have modeled using an energy (time) dependent corner magnitude of the tapered GR distribution. Third, some important drawbacks in calculating the MFD in high-resolution catalogs, which derives from a still common inhomogeneity of the magnitudes; this represents a major problem in modeling unbiased MFDs and comparing them when they come from different earthquake catalogs.

Finally, we discuss the implications of these results in terms of the statistical and physical behavior of seismic sequences, and of the improvement of earthquake predictability and forecasting.

Keywords: magnitude, frequency distribution, earthquake predictability, high, resolution earthquake catalogs

*Speaker

A deep catalogue of focal mechanisms for the 2016 Amatrice, Italy earthquake sequence

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Abstract

The 2016 Amatrice, Italy earthquake sequence occurred on a normal fault system in the Central Apennines. With _˜140 permanent or temporary seismic stations directly above the seismic activity, the sequence has been exceptionally well recorded. Tan et al., 2021, The Seismic Record, have used PhaseNet (Zhu and Beroza, 2019, GJI) to detect _˜15 million seismic phases, and compiled a high-precision hypocentre catalogue with _˜900'000 events with the HypoDD method of Waldhauser and Ellsworth, 2000, BSSA. Starting with this catalogue, we use a convolutional neural network classifier to predict P-wave first motion polarities, and the HASH algorithm of Hardebeck and Shearer, 2002, BSSA to compute a deep focal mechanism catalogue. The catalogue consists of $>$ 56'000 focal mechanisms, about 8'000 of which have nodal plane uncertainties below 25 degrees. In contrast to existing, conventional focal mechanism catalogues, the deep catalogue samples almost the entire study region, and almost the entire magnitude range (_˜M0-M5), although nodal plane uncertainties generally tend to increase with decreasing magnitude. We use the focal mechanism catalogue to study the kinematics of the Amatrice earthquake sequence, to test the hypothesis of a coseismic rotation of the static stress field by large and small events, and to analyse the complexity of the stress field before, during and after the earthquake sequence.

*Speaker

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Updates to the Fault-System Inversion Approach for use in the 2023 U.S. National Seismic Hazard Model

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Abstract

A 50-state update to the U.S. National Seismic Hazard Model will be released in 2023 (NSHM23). NSHM23 will utilize an inversion-based methodology for active fault systems in the Western U.S., building upon the approach used in the 3rd Uniform California Earthquake Rupture Forecast (UCERF3). The fault-system inversion approach enables relaxation of fault segmentation assumptions, inclusion of multi-fault ruptures, and mediation between and better fitting of competing data constraints (e.g., slip rates, paleoseismic recurrence intervals, and regional seismicity). We will describe a number of model improvements, including: a variable segmentation constraint to dial the propensity of multi-fault ruptures up and down; a decoupling from the gridded seismicity model; a simpler methodology for determining the regional target magnitude frequency distribution (MFD); a wider range of fault section MFD nucleation constraint options; better constraint weighting to more evenly fit all available data relative to their uncertainties; and several improvements to the simulated annealing algorithm that solves the inversion. In aggregate, these changes lead to a suite of models that better fit the available data constraints, encompass a broader range of uncertainties, and are more computationally efficient than UCERF3. We will then present preliminary NSHM23 fault system inversion solutions and compare them with prior models.

Keywords: NSHM23, UCERF3, inversion, simulated annealing, ERF, hazard

*Speaker

Evolution of the seismicity rate during and after hydraulic fracturing operations in Preston New Road, UK

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Abstract

In August 2019 an hydraulic fracturing operation was carried out at the PNR-2 well in Preston New Road, UK. Hydraulic fracturing caused abundant seismic activity that culminated with a ML2.9 event. The seismic activity was recorded by a downhole array of 12 sensors located in a nearby monitoring well. 55555 events were detected and located in real time during the operations. After improving the number of detections with template matching, distinct seismicity patterns can be identified by separately analysing the periods during the injections and the periods after the injections. More specifically, peaks of seismicity can be observed during the injections. These peaks gradually occur at later times, while their intensity gradually decreases. After the injections, the seismicity decay can be described by the Omori-Utsu law. The decay does not remain constant, but tends to slow down with each injection. The observed variations in seismicity rate can be explained in terms of rate- and state- theory (RTS) and critical pressure theory (CPT).

*Speaker

Towards an Operational Earthquake Forecasting Model for Europe

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Abstract

The go-to models for developing time-dependent earthquake forecasts are Epidemic-Type Aftershock Sequence (ETAS) models. They model earthquake occurrence as a spatio-temporal self-exciting point process, using basic empirical laws such as the Omori-Utsu law for the temporal evolution of aftershock rate, the Gutenberg-Richter law to describe the size distribution of earthquakes, the exponential productivity law and so on. The main focus and core strength of ETAS lie in modelling aftershock occurrence. An important aspect which holds great potential for improvement is the modelling of background seismicity. In most formulations of ETAS, background seismicity is either treated to be constant in time and space during parameter inversion or only considered spatially varying. The spatial variation of the background seismicity is generally inferred by smoothing the location of past declustered earthquakes. Here, we develop an algorithm based on expectation maximization, which allows the inversion of a covariate-dependent background seismicity rate and the remaining ETAS parameters to be self-consistent. We test a wide range of covariates ranging from strain-rate maps, fault slip rates, and relative seismic intensity in expert defined zonations. We develop these ETAS models for continental Europe leveraging the rich data sets and expert solicitations acquired for building the European Seismic Hazard Model (ESHM) 2020. We rigorously test these suites of covariates pseudo-prospectively to identify the ones that lead to the best operational forecasting model for Europe.

*Speaker

Component-driven ensemble modelling with semi-parametric ETAS models

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Abstract

Epidemic-Type Aftershock Sequence (ETAS) models represent the state-of-the-art benchmark against which to test any newly developed earthquake forecasting models. These new models can come in all shapes and flavours, and the idea of ensemble modelling has received attention in recent years within the statistical seismological community. Ensemble modelling aims to produce more informative forecasts by capturing the beneficial properties of different individual models within an overarching model ensemble. Traditionally, such an ensemble is a linear (or multiplicative) combination of ingredient models, and the challenge is to optimize the weights given to each ingredient model. We here propose a novel approach for component-driven ensemble modelling, where a forecast is created by marrying components that are derived from different models.

The components are driven by the following questions: *How many background events do we expect? Where do we expect them? When do we expect them? How many aftershocks do we expect? Where do we expect them? When do we expect them?*

By answering each of these questions with different ingredient models, we can easily create a suite of ensembles. Using pseudo-prospective forecasting experiments, we then compare the performance of these ensembles to those of the ingredient models, and that of a standard ETAS as a benchmark. Preliminary results combining semi-parametric ETAS variants suggest that component-driven ensembles can outperform all ingredient models, with similar trends observed in Southern California and Italy. The novel model combination technique enables these results to reveal the strengths and weaknesses of the ingredient models, which accelerates the development of better and more robust earthquake forecasts and aids the understanding of earthquake dynamics.

Keywords: ensemble modeling, forecasting, ETAS

*Speaker

Bayesian time-dependent earthquake forecasting

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Abstract

The spatio-temporal Epidemic Type Aftershock Sequence (ETAS) model is one of the most successful models for time-dependent statistical modeling of earthquake occurrence. Bayesian inference of the ETAS model allows a natural way to include prior knowledge and to quantify the uncertainty of the model estimates. However, using a Bayesian approach in the context of the ETAS model is more complicated than using powerful standard maximum likelihood methods for the model inference, and can be limited to small or intermediate data sets. We show that a recently introduced Bayesian semiparametric ETAS version using Gaussian process modeling can produce improved forecasts including uncertainty quantification compared with results obtained by the standard ETAS model. Examples of test sites in California illustrate the advantages of the suggested Bayesian approach. In addition, we present how the Bayesian inference can be accelerated which makes the approach suitable also for larger data sets.

*Speaker

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Seismic evidence of an aseismic slip event preceding and following the 2017, Valparaiso, Mw 6.9 earthquake

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Abstract

Understanding the processes that lead to large earthquakes remains one of the key goals in seismology. This is central to our understanding of seismic hazard, including the long controversial issue of earthquake predictability. Recently, Slow Slip Events (SSEs) have been identified before a few large earthquakes, which might reveal the nucleation process of the main rupture. However, the current space and time resolution of geodetic measurement makes detection and monitoring of SSEs difficult. SSEs are believed to drive their own seismicity. A fine monitoring of such seismicity may help monitor SSEs and understand their link with the rupture process. Here, we study the case of the 2017 Valparaiso earthquake that was preceded both by an SSE and an intense seismicity. We build a high-resolution catalog (Mc=2) of the region using a deep-learning phase picking model and by locating detected earthquakes in a local 3D Earth model. The resulting catalog consists of more than 100 000 events from 2015 to 2021 (compared with the _˜8000 events reported by the Centro Sismológico Nacional over the same time-period). The temporal evolution of the seismicity is tested against a modified Epidemic Type Aftershock Sequences model that accounts for short-term incompleteness (Hainzl 2021). We show that an over-productive earthquake rate emerges within the foreshock sequences, continuing at least for several days after the mainshock. This transient background activity seems unaffected by large magnitudes observed during the sequence. In addition, we identify several repeater events between 2016 and 2021 using waveform cross-correlation and double difference relocation. The strongest repeater activity is observed within the foreshock seismicity and seems to decelerate over a few months. These observations support the idea that a part of the seismicity surrounding the mainshock differs from the usual earthquake triggering processes. The joint observation of an SSE, a transient background seismicity and a strong repeater activity initiating during foreshock times suggest a close connection between the SSE and the seismicity. Such connection seems to persist momentarily after the sequence, enhancing the aftershock activities. Therefore, we believe that analyzing high resolution seismicity helps to monitor the activity of the rupture process preceding and following large earthquakes, and can provide new insight for real-time seismic hazard assessments.

*Speaker
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Keywords: Foreshock, Slow Slip, Repeaters, Nuclation, ETAS, I, Short term Incompletness, High resolution catalog, Rupture process

SeisBench: Benchmarking and applying deep learning based phase pickers

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Abstract

Seismic event detection and phase picking are the base of many seismological workflows. In recent years, several publications demonstrated that deep learning approaches significantly outperform classical approaches, even achieving human-like performance under certain circumstances. However, there are two shortcomings. First, given the differences in datasets and evaluation metrics, it is not possible to compare the performance of different picking models to each other. In particular, it is unclear how models perform when applied to data outside the training region. Second, the models do not offer a standardised API and are therefore difficult to apply in production. Here, we present SeisBench - A toolbox for machine learning in seismology. SeisBench is an open-source toolbox written in Python, providing unified access to benchmark datasets, machine learning models, and training pipelines. Using SeisBench, we conducted a large scale benchmark of deep learning based phase pickers. We evaluated six picking and detection algorithms on eight datasets. We'll present selected results of this benchmark here. In addition to the benchmark, we'll show spotlights how SeisBench can be applied for seismological analysis. This includes the application to ocean bottom data, the creation of highly complete regional earthquake catalogs, and the usage in routing teleseismic monitoring at GEOFON.

*Speaker

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A Deep Gaussian Process Model for Seismicity Background Rates

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Abstract

The spatiotemporal properties of seismicity give us incisive insight into the stress state evolution and fault structures of the crust. Empirical models based on self-exciting point-processes continue to provide an important tool for analysing seismicity, given the epistimic uncertainty associated with physical models. In particular, the epidemic-type aftershock sequence (ETAS) model acts as a reference model for studying seimicity catalogs. The traditional ETAS model uses simple parametric definitions for the background rate of triggering-independent seismicity, which limits its applicability to the temporally complex seimicity of seismic swarms that are not dominated by triggering. In order to robustly capture time-varying seismicity rates, we introduce a deep Gaussian process formulation for the background rate as an extension to ETAS. Gaussian processes (GPs) are a robust non-parametric model for function spaces with covariance structure. By conditioning the lengthscale structure of a GP with another GP, we have a deep-GP: a probabilistic, hierarchical model that automatically tunes its structure to match data constraints. We illustrate our method using synthetic examples and real data from the Cahuilla swarm and Ridgecrest aftershock sequence.

*Speaker

Understanding the seismic behavior of a complex fault structure through the use of a novel 3D stochastic declustering algorithm

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Abstract

The Alto Tiberina Fault (ATF) system in Central Italy (Northern Apennine) is a complex fault structure composed of a principal low-angle fault and other minor synthetic/antithetic faults located in the hanging wall of the principal fault. In this work, we developed a novel 3D stochastic declustering algorithm based on the ETAS model, in order to study the clustering properties of the seismicity by considering the earthquakes' depth. This algorithm was applied to a new high-quality instrumental catalog (TABOO catalog) spanning from 2010 to 2015. We found two distinct behavior for the seismicity in the principal fault and the synthetic/antithetic faults, both in terms of clustering properties and magnitude frequency distribution. The principal ATF shows a high b-value and low clustering (i.e. a majority of spontaneous events), while the synthetic/antithetic faults show a low b-value and high clustering (i.e. a majority of triggered events). These results also imply a different magnitude frequency distribution for spontaneous and triggered events, despite a similar rake of the focal mechanisms (normal events). Such a complex fault structure, therefore, shows peculiar and unusual seismic properties.

Keywords: Alto Tiberina Fault (ATF) system, Central Italy, Stochastic declustering, ETAS model

*Speaker

A new Bayesian approach to modelling of short and long term earthquake forecasting using inlabru

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Abstract

Earthquake hazard maps in space and/or time provide a rational basis for long-term hazard mitigation and shorter term operational forecasting respectively. Both require the determination of optimal combinations of model input parameters, and a realistic estimate of the uncertainties involved. While Bayesian methods are well suited to the problem, the construction of posteriors using random sampling (e.g. MCMC) is prohibitively slow for fitting the complex spatio-temporal point process models required, particularly if the parameters are strongly correlated and we wish to include many relevant spatial covariates, such as maps fault maps, or satellite-based deformation rates. The Integrated Nested Laplace Approximation (INLA) offers a potential solution to this problem, because it was designed exactly to handle large spatial models with a range of spatially varying covariates and strongly correlated parameters. It is based on a deterministic method which is also very fast (compared to MCMC methods), and has been applied successfully to analyse complex ecological models involving point process modelling.

Here, we present examples of how this approach can be used for time-independent and time-dependent seismicity forecasting. We show how diverse spatial covariates can be incorporated into forecasts, and how forecasts can be generated from synthetic catalogues based on different posterior samples of the parameters to capture the full range of uncertainty. For example, we show how the approach can be used to test the utility of maps of the Coulomb stress redistribution after an earthquake for potential application in real time seismicity forecasting. We also show how surface geology maps can be used to distinguish between regions where we have an 'evidence of absence' of faults from regions where there is an 'absence of evidence' – and consequently treat these differently.

In a related abstract, Serafini builds on this work through the implementation of a Hawkes process within inlabru that allows us to better model the self-exciting clustering of earthquakes in space and time.

Keywords: seismicity forecasting Bayesian patio, temporal

*Speaker

Imaging a Complex Earthquake Sequence in Sparta, North Carolina, Eastern United States

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Abstract

On August 9, 2020, a Mw5.1 earthquake ruptured the uppermost Crust near the town of Sparta, North Carolina. The earthquake ruptured a 2-km-long surface and it is likely the first surface-rupturing event in the Eastern United States since the New Madrid earthquake sequence (Figueiredo et al., 2022). Following the mainshock, 5 temporary seismic stations were also deployed by scientists from CERI@Univ. Memphis (Horton et al., 2021) in the area. Together with state-of-the-art earthquake detection and relocation techniques, this sequence provides an opportunity to better understand the local fault structures and the source processes of intraplate earthquakes.
Here we combine a deep learning earthquake phase picker (EQTransformer, Mousavi et al., 2020) and a matched filter technique to compile a more complete earthquake catalog for the sequence. We perform detections for the period of August 1 to November 18, 2020. We first detect P and S waves and associate them using EQTransformer. Then we perform a matched filter detection to search for additional events using the combined USGS and EQTransformer catalog as templates (498 templates). Using cross-correlation derived differential-travel times, we relocate all the detected events to obtain a final catalog of 1339 earthquakes with high-resolution locations and a magnitude of completeness of about -1.5.

Our relocated catalog shows two major lineaments that appear to illuminate two fault branches with a slight kink. These two lineaments are consistent with our focal mechanism solution using the generalized cut-and-paste (gCAP) method that shows a thrust event with some strike-slip component and a moment magnitude of 5.13. In addition, the non-DC components of about 12%, implying the mainshock may have ruptured along complex fault geometries. The two double-couple nodal planes are 349○/69○/116○ and 115○/32○/41○ for an optimal centroid depth of 1.3 km. One of our identified lineaments is consistent with surface observations of thrust faulting by Figueiredo et al. (2022) and the dip of our preferred nodal plane. Analysis of first motion polarities of all events M> 1.5 shows variable focal mechanisms, consistent with weak and near-surface structures, but with mostly strike-slip/oblique strike-slip mechanisms in our second lineament. Our results suggest that the mainshock rupture occurred primarily along a thrust fault and a secondary blind strike-slip fault. These observations have potential implications on seismic hazard estimation in intraplate settings.

*Speaker

Keywords: Earthquake detection and location, Intraplate earthquake sequence, Complex rupture

Second-order smoothing method over the Delaunay Tessellation

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Abstract

Smoothness prior is usually used in seismicity analysis and geophysical or geodetic Bayesian inversion. Calculating smoothness over regular grids greatly simplifies the numerical calculation. When observed data are irregularly distributed, interpolation over the regular grids increases the uncertainty of the inversion results, whereas smoothing over the Delaunay Tessellation (DT) avoids the additional interpolation. However, the implementation of the numerical calculation of the second-order derivate (smoothness) of a function, give its values on the DT nodes, is much difficult than implementing the calculation of the first-order derivative (flatness). We proposed a Bayesian smoothing method over the DT, in which not only the flatness prior but also smoothness prior is implemented. For calculating the smoothness over the DT, we provide two methods: 1-layer method and 2-layers method. Numerical experiments and an application on gravity inversion problem show the effectivity of our method.

Keywords: Delaunay Tessellation, smoothness prior, Bayesian analysis.

*Speaker

Aftershocks Preferentially Occur in Previously Active Areas

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Abstract

The clearest statistical signal in aftershock locations is that most aftershocks occur close to their mainshocks. More precisely, aftershocks are triggered at distances following a power-law decay in distance (Felzer & Brodsky, 2006). This distance decay kernel is used in Epidemic-type Aftershock Sequence (ETAS) modeling and is typically assumed to be isotropic, even though individual sequences show more clustered aftershock occurrence. The assumption of spatially isotropic triggering kernels can impact the estimation of ETAS parameters themselves, such as biasing the magnitude-productivity term, alpha, and assigning too much weight to secondary rather than primary (direct) triggering. Here we show that aftershock locations in Southern California, at all mainshock-aftershock distances, preferentially occur in areas of previous seismicity. For a given sequence, the scaling between aftershock rates and the previous seismicity rate is approximately linear. However, the total number of aftershocks observed for a given sequence is independent of background rate. We explain both of these observations within the framework of rate-and-state friction (Dieterich, 1994).

*Speaker

A unified scaling law of seismic to aseismic moment release from laboratory to nature.

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Abstract

Aseismic and slow slip transients are known mechanisms by which faults release the accumulated strain. They occur in all tectonic settings but are abundantly detected and investigated at subduction zones. However, a growing number of new observations give the opportunity to study the slow slip transients at shallow crustal depth in extensional and transform settings. Swarm-like earthquakes and non-volcanic tremor very often accompany aseismic/slow slip transients. The investigation of the release of seismic and aseismic energy has been successful to improve our understanding of the physical mechanics at play during aseismic slip ruptures. Global dataset of slow slip events (SSEs) accompanied by tremor or earthquake swarms indicate a power-law scaling between the seismic and aseismic moment over several order of magnitude. The proposed power-law scaling depends on the tectonic setting and characteristics depth of the events. In particular, shallow (< 10km) SSEs triggering swarm-like seismicity and outside subduction zones form a separating power-law scaling. A physical interpretation invokes a fault pressurization mechanism that creates the condition of nucleating both aseismic and seismic slip where the seismicity is driven by the stressing rate imparted at the leading edges of the aseismic rupture front. A similar mechanism is invoked to explain aseismic and seismic slip during injection operation on fault for induced seismicity during *in-situ* experiments. We here extended the scaling of crustal SSEs to the scale of induced seismicity, *in-situ*, and laboratory earthquake. We find that the power-law scaling remarkably extends to lower magnitude slow slip transients up to the laboratory scale, although an observational gap remains for SSEs between Mw 0-4. In order, to fill in the gap we use numerical simulations of SSEs and associated seismicity coupling a poro-elastic model with a stochastic earthquake simulator. The simulated distributions of aseismic and seismic moments fit well with the natural and induced cases preserving the scaling. Our findings indicates that the scaling is compatible with the hypothesis that stress changes due to the aseismic slip itself is the main driving mechanism, while fluid fault pressurization remains the required condition for nucleation of aseismic slip.

*Speaker

Temporal variations of seismicity rates and Gutenberg-Richter b-values: an example from a high-definition Italian catalog

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Abstract

The high-resolution earthquake catalog related to the seismic activity of the Alto Tiberina fault system (Northern Apennine, Central Italy), constructed from the seismic network of the Alto Tiberina Near Fault Observatory (TABOO), were analysed by statistical methods from a seismological perspective.
With the aim to bring new information on the study of earthquakes preparatory phases and in order to identify possible tectonic stress indicators, we focused on the reliable time series computation of the seismicity rates and of the Gutenberg-Richter b-value.

In this work, the time series were evaluated starting from the generation of the stochastic declustered catalog (Console, Jackson & Kagan, Pageoph 2010) obtained using the 2D ETAS Model.

The capability of the algorithm based on ETAS model to recognize and distinguish the triggered seismicity from the background (e.g. Console & Murru 2001; Console, Murru & Lombardi 2003), allowed to evaluate the daily seismicity rates and b-value variations for both the spontaneous and triggered earthquakes.

Moreover, in order to overcome the problems due to build b-value time series for a non-uniform temporal distribution of seismicity, we considered the weighted likelihood approach for a more robust b-value estimation (Taroni, Vocalelli & De Polis 2021).
The obtained time series, in particular the b-value time series, are different with respect to the ones obtained using the classical rolling window approach for the b-value computation, indicating that some of the b-value fluctuations are related to the natural statistical variability of the parameter.

Keywords: time, series analysis, b, value, statistical seismology, Alto Tiberina fault system.

*Speaker

An automatic polarity determining method of the seismic recordings based on Information theory

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Abstract

Arrival detection and polarity determination are crucial and fundamental problems in seismic data analysis. We develop a new method that calculates probability distribution funtion (pdf) of arrival times based on Information theory. The initial arrival time t of the seismic wave is decided by independent parameter $\epsilon that represents amplitude threshold in waveform segment. After appling threshold selection criterion, we build am$
$motion polarity of the seismic waveform. We test this method with synthetic waveforms as well as recordings from verifiedd$

Keywords: Focal mechanism inversion, Polarities determination, Automatic Picking, Markov chain, Information theory

*Speaker

Earthquake productivity within general ETAS models

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Abstract

Earthquake clustering is a prominent feature of seismic catalogs. Several models have been proposed to describe the triggering mechanism of earthquakes; nonetheless, some theoretical aspects have not yet been thoroughly explored. In this study we investigate the distribution of the number of triggered events as described by a branching process, which might provide useful practical constraints for empirical analysis of seismic catalogs.
According to recent literature (e.g. Shebalin *et al.*, 2020, and references therein), the productivity of a magnitude m event can be defined as the number of triggered events of magnitude above *m-D*, where D is a positive default value. In particular we distinguish between the number of direct descendants and the number of all descendants, denoted respectively by the random variables *v(D)* and *V(D)*.

In the standard Epidemic Type Aftershock Sequence (ETAS) model, the distribution of *v(D)* is Poissonian. However, evidence has recently emerged in favor of the discrete exponential distribution for *v(D)* and for *V(D)* with a dominant initial magnitude m (the case of a simple aftershock cluster). Therefore we consider the general ETAS model adapted to any distribution of *v(D)* and prove that the branching structure of the model excludes the possibility of having a common distribution type for both v*(D)* and V*(D)* at once (Molchan *et al.*, 2022).

We then investigate the features of the V*(D)* distribution within a wide class of ETAS models. We show that there is a fundamental difference in tail behavior of the V*(D)*-distributions for general-type clusters and for clusters with a dominant initial magnitude: the tail is heavy in the former case and light in the latter. The real data display similar behavior. Theoretical conclusions are also illustrated through the analysis of a synthetic earthquake catalog.

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Defining and testing the predictive efficacy of a realistic spring block model

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Abstract

The occurrence of earthquakes is a singular characteristic of every part of the globe, but is characterized by statistical laws that are universal, regardless of the geographical location. The temporal and spatial correlations are a striking example.
Here we propose a spring block-like model coupling an elastic layer, subject to a velocity weakening heterogeneous friction, to a second layer where friction is velocity strengthening. We show that these ingredients allow us to recover all the most relevant earthquake statistical features, such as the Gutenberg-Richter law, the Omori law, the productivity law and the spatial clustering of aftershocks. The extensive simulations that can be obtained with this model, allow us to test the seismic gap hypothesis. Indeed, the estimate of the occurrence probability of the next big shock on the basis of the time delay from the last earthquake still represents a big challenge. The problem is that this issue cannot be addressed only on the basis of historical catalogs which contain too few well documented big shocks, and decades of future observations appear necessary. Our results support recent findings which have shown that important insights can be obtained from the spatial organization of aftershocks and its relationship to the mainshock slip profile. In particular, we show that large earthquakes do not regularly repeat in time, but it is possible to achieve insights on the time until the next big shock from the percentage of aftershocks occurring inside the mainshock slip contour.

*Speaker

Integrated monitoring of fault systems

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Abstract

Faults, or more in general fault systems, are complex geological objects. This complexity controls the style of seismicity, and is often convoluted with external stress perturbations (e.g. static and dynamic stress, variation of pore pressure, tidal stress perturbation). Taken together, this stress and rheological complexity make it hard to untangle the physical processes controlling the seismicity evolution in time and space style, and limits our understanding of how large earthquakes or seismic swarms generate.
In this work we integrate different geophysical observables to get insights about the different physical processes occurring in the Alto Tiberian fault (ATF) system in the central Apennines (ITALY). We first present a catalog containing up to half-millions microearthquakes over a period of _˜3yrs. The analysis (statistics interaction, repeating earthquakes, stress drop) of this seismicity reveals the existence of various style of deformation in the ATF. Combining the seismicity evolution with geodetic observations, we infer the rheological parameters of the shallow fault system, which hosts aseismic deformation and large swarms. We further use observations of velocity variations estimated from ambient noise correlation, to reveal a significant stress sensitivity of the shallow crust. We finally put some thresholds on the stress perturbation required to initiate seismicity in the ATF, by analysis of dynamic triggering.
This integrated analysis, permits to derive significant new insights about the physical state of the ATF, and highlight the importance of integrated analysis of geophysical data.

*Speaker

An Overview of medium-term earthquake forecasting using the EEPAS model: Where are we at?

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Abstract

EEPAS stands for "Every Earthquake a Precursor According to Scale" and is a New Zealand born earthquake forecasting model. It works based on the precursory scale increase phenomenon (Ψ) to forecast the future earthquake occurrence rates. Ψ refers to the observed increase in the rate of occurrence and magnitude of minor earthquakes before most major earthquakes. Each example of Ψ provides a value of mainshock magnitude Mm, precursor time TP, and precursory area AP. Accumulated data of Ψ from many earthquakes shows these quantities to be correlated. Predictive regressions of Mm, log TP, and log AP on MP are what EEPAS uses to forecast the contribution of any earthquake to the expectation of future larger earthquakes. EEPAS is a medium-term forecasting model which can provide forecasts with time horizons ranging from months to decades. Since its introduction in 2004, EEPAS has been successfully applied to well-catalogued regions including New Zealand, California, Mexico, Japan and Greece. It has also been applied in studies of physics-based earthquake simulators. EEPAS has been one of the core elements of NZ hybrid forecasting tool, and continues to be developed. A milestone in EEPAS improvement was compensation of the forecasts for missing precursory earthquakes in the time-lag between the end of the catalogue and the forecasting time-horizon. This enables the forecasting horizon to be extended from a few months to a decade or more without much loss of forecasting quality (information gain). We have also learned how to compensate EEPAS forecasts for the limited record of precursory information before any target earthquake. Overall, EEPAS is better able to adjust for limitations of any earthquake catalogue than previously. However, there are still significant challenges to move toward a global EEPAS model. One challenge is the existence of a space-time trade-off in Ψ. This trade-off gets reflected in a corresponding trade-off of the EEPAS scaling parameters for area and time. We have not yet mastered exploiting this trade-off to optimise forecasting performance. There is also work to be done to address surprises in low-seismicity regions, where recorded precursory seismicity can be sparse or seem to be insignificant. Studies on synthetic catalogues, in which strain rates were systematically varied, suggest much longer precursor times for such regions. Incorporating strain rate into EEPAS would be another step forward towards a global EEPAS model.

Keywords: earthquake forecasting, precursory seismicity, New Zealand

*Speaker

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The rates of hazardous earthquakes in the New Zealand region, and their uncertainties and variabilities

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Abstract

The 2022 New Zealand National Seismic Hazard Model (NSHM) consists of a Seismicity Rate Model (SRM), a Ground Motion Characterization Model, and an uncertainty model. The SRM itself has several components. For earthquakes on known active crustal faults, the SRM is a "grand inversion" (Field et al., 2014) that solves for the rates of earthquake ruptures subject to several constraints, including a prescribed total magnitude-frequency distribution (MFD) and its uncertainty. This is blended with a spatially continuous distributed seismicity model, which is also normalized to sum to a prescribed MFD at each magnitude. The Hikurangi-Kermadec and Puysegur subduction zones are described by separate grand inversions, each constrained by its own total MFD among other inputs. To compute reliable MFDs for these uses, we make several modifications and additions to the New Zealand earthquake catalogue. We start from the Christophersen et al. (2022) catalogue, which homogenized the magnitudes of the GeoNet catalogue into an Mw-like magnitude. We perform event-matching between this catalogue and several relocated and global catalogues, from which we import improved earthquake depths, focal mechanisms, and improved magnitudes and locations and missing events in the offshore subduction regions. We then use the improved earthquake depths, focal mechanisms, subduction interface geometries, and relative plate-motion directions to classify earthquakes as upper-plate, interface or intraslab. Then, we compute magnitude-frequency distributions in the 3D volumes covering the crustal grand inversions, the distributed seismicity models, and the Hikurangi-Kermadec and Puysegur interfaces. While we use the more recent part of the catalogue (generally 1965-present) to compute b-values, our estimate of earthquake rates includes events back to 1840 and incorporates magnitude uncertainties and rounding errors, depth uncertainties, and changing completeness thresholds through time. Perhaps more importantly, it also includes a treatment of the ambiguity in earthquake rates over decadal to centenary timescales that arises due to alternating periods of activity and quiescence in the instrumental and historic catalogue.

Keywords: catalogue, magnitude, frequency distribution, earthquake rate

*Speaker

Geometrical Properties of Seismicity in California

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Abstract

The spatial geometry of seismicity encodes information about loading and failure processes, as well as properties of the underlying fault structure. Traditional approaches to characterizing geometrical attributes of seismicity rely on assumed locations and geometry of fault surfaces, particularly at depth, where resolution is overall quite poor. In this study, we develop an alternative approach to quantifying geometrical properties of seismicity using techniques from anisotropic point process theory. Our approach does not require prior knowledge about the underlying fault properties. We characterize the geometrical attributes of 32 distinct seismicity regions in California and introduce a simple four class classification scheme that covers the range of geometrical properties observed. Most of the regions classified as having localized seismicity are within northern California, while nearly all of the regions classified as having distributed seismicity are within southern California. In addition, we find that roughly 1 out of 4 regions exhibit orthogonal seismicity structures. The results of this study provide a foundation for future analyses of geometrical properties of seismicity and new observables to compare with numerical modeling studies.

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Bayesian ETAS for Improved Earthquake Rate Models for the Pacific Northwest

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Abstract

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

Keywords: ETAS, Bayesian statistics, aftershock forecasting, Pacific Northwest

*Speaker

Periodic modulation of seismicity - a laboratory and modeling perspective

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Abstract

Small transient stress perturbations are prone to trigger earthquakes and a better understanding of the dynamic of earthquake triggering by transient stress perturbations is essential in order to improve our understanding of earthquake physics and our consideration of seismic hazard. In the Earth's crust, these transient stress changes can be caused by various sources (passing of seismic waves, forcing by tides, hydrological load, and other seasonal climatic loads). Recent observations suggest that at first order, seismicity increases with the rate of tectonic loading while the modulation of the seismicity, increases both with the period and the amplitude of the disturbances. Slow earthquakes and micro-seismicity also appear to be more sensitive to tides, so the modulation seems to depend on an effective normal stress disturbance rather than on the absolute value of the disturbance itself.

Here, we first study an experimental fault system, which mimics the natural seismic cycle, that is to say periodic perturbations of the stresses (of variable amplitude and frequency) superimposed to a far field loading, at crustal pressure conditions. The experimental system is instrumented so that micro-seismicity (acoustic emissions), deformations and stresses, are continuously recorded during the experiments, in order to study the response of a system producing micro-seismicity as a function of loading rate, amplitude and frequency of a periodic stress perturbation. The susceptibility of the system to mechanical parameters (e.g. shear stress oscillations, friction oscillations, ...) is derived from the amplitude of the distribution of acoustic emissions normalized by the amplitudes of the parameters in question. Susceptibility to the confinement pressure oscillations, to the shear stress oscillations, and to the friction oscillations all exhibit trends that suggest more complex mechanical behaviours than a simple Mohr-Coulomb-based criterion.

Second, we investigate theoretically the effects of periodic-in-time modulations on the properties of earthquakes by considering successively the one dimensional Burridge–Knopoff (BK) model and the two dimensional Olami–Feder–Christensen (OFC) model. Each model is modified to take into account either a modulation of normal stress or of shear stress acting on

*Speaker

a fault. Despite the differences between the BK and the OFC model, several results are observed in both models. In particular, we observe that earthquake occurrences correlate with stress modulation. The correlation is strongly dependent on parameters such as the type of modulation, its frequency and amplitude, and in some cases on the magnitude of the considered earthquakes.

The physics of earthquake forecasting: challenges and recent advances

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Abstract

The development of short-term earthquake forecasts is critical for the design of risk mitigation actions and raising social awareness during evolving earthquake sequences. In the last decade statistical and physics-based models, or their combination, were proven successful in tracking the spatio-temporal evolution of different sequences around the world. The enhancement of earthquake catalogs and the on-the-fly availability of otherwise time-intensive data products, such as seismic source models, provide the necessary input for the improvement of physics-based models using continuum mechanic principles. Although the golden standard for short-term earthquake forecasting remains the statistical ETAS (Epidemic-Type Aftershock Sequence) model, physics-based, Coulomb Rate-and-State (CRS) forecasts have now reached, and sometimes even exceed, the performance of their statistical counterparts.
The ETAS and CRS forecast models face different challenges: all-positive statistical forecasts predict seismicity at no-occurrence locations while physics-based models underpredict observed seismicity at the near-source area around the onset of earthquake sequences. Interestingly, both models improve their performance when high-resolution datasets are incorporated and enhanced implementations are pursued. Recent forecasting experiments in Italy and California bring us closer to the limits of our predictability but they also challenge us to evaluate our long-standing assumptions. The static stress transfer theory has known different implementations driven by varying assumptions but remains puzzling how stress redistribution works at a granular, sub-km, spatial level with combined static and dynamic interactions. Additionally, well-standing empirical relationships can be now tested more extensively, e.g. is event magnitude the controlling factor of its productivity and, what is the nature of frequency-magnitude distributions at small-magnitude ranges? Outside of the governing principles and assumptions behind our forecasts, our experimental design strategy has also changed these last few years. The initial, 5-year-long forecast experiments over statewide testing regions have provided scientists with the critical infrastructure required and motivated the implementation of sequence-specific experiments. It remains open whether more specific performance metrics should be developed to investigate specific aspects behind the performance of our current parametric models.

From the above, it is clear that the earthquake forecasting discipline of seismology has gone a long way in the last decade. Recent advances in machine-learning-based earthquake catalog development suggest that the capability of short-term earthquake forecasting moves now closer to operational time-frames worldwide, but at the same time the underlying mechanisms of localized earthquake triggering for large-magnitude occurrences remain a mystery. We can anticipate that machine learning will revolutionize earthquake forecasting by both

*Speaker

providing very rich ML-based datasets that spark the scientific curiosity toward discovery, and by enabling the spontaneous discovery itself through the development of non-parametric machine-learning-based forecast expressions.

Unsupervised Artificial Intelligence and Seismicity Declustering : Application to the Corinth Rift area (central Greece)

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Abstract

The intracontinental Corinth Rift is one of the fastest extending and most seismically active regions worldwide (Bernard et al., 2006). It represents an outstanding land-accessible natural laboratory to better understand normal fault mechanics and continental tectonics. The western Gulf of Corinth is the most active part, hosting an extensive microseismic activity with intense seismic swarming. In this context, high-quality catalogues of earthquake clusters are critical to further study the tectonic complexity of such swarm-prone regions. Here, we introduce a new declustering technique using a self-organising map (SOM), an unsupervised machine learning clustering approach based on an artificial neural network (Vettigliet et al, 2018). The SOM neural network performs a non-linear mapping of large input spaces into a two-dimensional grid, which hopefully preserves the topological and metric relationships of the data and gives a better representation of the resulting clusters. It therefore provides easier visualisation and interpretation of the results. The clusters identified by this method can then be studied to allow a probabilistic classification of the seismic events as background event, aftershock or swarm element, based on the features we previously used to train the SOM network (inter-event space-time distances and waveform similarity). To estimate the classification confidence level, we use the neighbourhood structure of the SOM grid to train a second SOM network that clusters data points according to their topological location. Preliminary results show classification confidence of about 80% for the ten-year seismic catalogue of the National Hellenic Seismological Network. This method has the potential to be applied in different tectonic settings and in large geographical areas with complex spatio-temporal earthquake distributions and behaviours.

*Speaker

Bayesian time-independent and time-dependent modelling of seismicity with Inlabru

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Abstract

Earthquake hazard maps in space and/or time provide a rational basis for long-term hazard mitigation and shorter-term operational forecasting respectively. Both require the determination of optimal combinations of model input parameters, and a realistic estimate of the uncertainties involved. While Bayesian methods are well suited to the problem, the construction of posteriors using random sampling (e.g. MCMC) is prohibitively slow for fitting the complex Spatio-temporal point process models required, particularly if the parameters are strongly correlated and we wish to include many relevant spatial covariates, such as fault maps, or satellite-based deformation rates. The Integrated Nested Laplace Approximation (INLA) offers a potential solution to this problem because it was designed to handle large spatial models with a range of spatially varying covariates and strongly correlated parameters. It is based on a deterministic method which is also very fast (compared to MCMC methods) and has been applied successfully to analyse complex ecological models involving point process modelling. Here, using the R-package Inlabru, we present examples of how this approach can be used for time-independent and time-dependent seismicity forecasting. We show how diverse spatial covariates can be incorporated into forecasts, and how forecasts can be generated from synthetic catalogues based on different posterior samples of the parameters to capture the full range of uncertainty. In particular, we show how the approach can be used to test the utility of maps of the Coulomb stress redistribution after an earthquake for potential application in real-time seismicity forecasting. We also show how surface geology maps can be used to distinguish between regions where we have an 'evidence of absence' of faults from regions where there is an 'absence of evidence – and consequently, treat these differently. In a related abstract, Serafini builds on this work through the implementation of a Hawkes process within the R-package Inlabru that allows us to better model the self-exciting clustering of earthquakes in space and time.

Keywords: Bayesian computing, Hawkes process, INLA, time, dependent seismicity forecasts, time, independent seismicity forecasts

*Speaker

Ranking earthquake forecasts using proper scoring rules: binary events in a low probability environment

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Abstract

Operational earthquake forecasting for risk management and communication during seismic sequences depends on our ability to select an optimal forecasting model. To do this, we need to compare the performance of competing models in prospective experiments, and to rank their performance according to the outcome using a fair, reproducible and reliable method, usually in a low-probability environment. The Collaboratory for the Study of Earthquake Predictability conducts prospective earthquake forecasting experiments around the globe. In this framework, it is crucial that the metrics used to rank the competing forecasts are 'proper', meaning that, on average, they prefer the data generating model. We prove that the Parimutuel Gambling score, proposed, and in some cases applied, as a metric for comparing probabilistic seismicity forecasts, is in general 'improper'. In the special case where it is proper, we show it can still be used improperly. We demonstrate the conclusions both analytically and graphically providing a set of simulation based techniques that can be used to assess if a score is proper or not. They only require a data generating model and, at least two forecasts to be compared. We compare the Parimutuel Gambling score's performance with two commonly used proper scores (the Brier and logarithmic scores) using confidence intervals to account for the uncertainty around the observed score difference. We suggest that using confidence intervals enables a rigorous approach to distinguish between the predictive skills of candidate forecasts, in addition to their rankings. Our analysis shows that the Parimutuel Gambling score is biased, and the direction of the bias depends on the forecasts taking part in the experiment. Our findings suggest the Parimutuel Gambling score should not be used to distinguishing between multiple competing forecasts, and for care to be taken in the case where only two are being compared.

Keywords: Probabilistic forecasting, Proper scores, Forecasts ranking

*Speaker

Deep-learning-based single-station-array tremors detection

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Abstract

Relative to a single seismic station, seismic arrays (or networks of seismic stations) drastically improve our ability to detect and locate seismic sources in space. Traditional location methods use the relative arrival times across the array to locate the seismic source. Waveform-based methods can simultaneously detect and locate seismic events by projecting the coherent waveforms back towards the suspected source location. The seismic array's detection and location capacity depend mainly on the array density and the waveforms coherency across the array, which depends on the subsurface structure. The signature of seismic sources consists of the convolution of the source time function and the impulse response of the Earth's structure between the source and the receivers. This implies that the source location is encoded in the waveforms even if we are not yet able to explicitly disentangle the signature of the source-receiver path from the seismic record. We implement an AI-based framework to learn how to detect and locate seismic sources from the records of a single seismic station based on the knowledge previously inferred from a dense seismic array. We detect and locate tectonic tremors within the continuous seismic record of a single station in the northern Cascadia subduction area. This proof-of-concept work shows how and under which assumptions the information from a seismic array of multiple stations can be decoded from the continuous seismic record of a single station. Our approach allows us to extend the temporal coverage backward and forward of existing tremor catalogs without relying on the seismic arrays used to build the catalogs.

Keywords: Tectonic tremors, Cascadia, detection and location, deep learning

*Speaker

Magnitude and Slip Scaling Relations for Fault-Based Seismic Hazard

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Abstract

Scaling relations play an important role in fault-based seismic haard, where slip rates on faults are balanced by cumulative slip in an earthquake rupture forecast. Here we discuss a series of issues which arise in constructing sets of logic tree branches for use in fault-based hazard estimates. These issues include:
1) depth of rupture; 2) transient deepening following large earthquakes; 3) uncertainty in mean; 4) difficulties in using classical continuum exponent fits; 5) multifault compatability; 6) and minimal models.
Recommendations for minimal branch models are discussed.

*Speaker

Stochastic models for induced seismicity

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Abstract

Induced seismicity has become a significant factor in evaluating earthquake hazard associated with the recent development of unconventional energy resources. It is typically driven by anthropogenic activities such as hydraulic fracturing, mining excavation, subsurface water injection, and others. Therefore, it is crucial for earthquake hazard mitigation and risk assessment to develop stochastic models that can describe the observed induced seismicity rate and forecast its evolution. In this work, I consider three such stochastic models to quantify the rate of the occurrence of induced earthquakes. For this, I generalize the Epidemic Type Aftershock Sequence (ETAS) model, where the background rate is driven by the anthropogenic activities, for example, by the subsurface fluid injection. In the first model, the background rate is proportional to the fluid injection rate and also accounts for the time lag associated with the fluid diffusion. The second model uses a convolution operation, where the injection rate is convolved with a specific kernel to describe the influence of the fluid propagation on the seismicity rate. Finally, the last model assumes that the effects of the fluid injection operations can be described by the rate-and-state mechanism. For all three models, the maximum likelihood method is developed to estimate the model parameters. Subsequently, the models are incorporated into a Bayesian predictive framework, where the probabilities for the occurrence of the largest expected earthquakes are computed during specified forecasting time intervals. To compute the Bayesian predictive distribution the Markov Chain Monte Carlo sampling of the posterior distribution is performed. This allows the quantification of the uncertainties of the model parameters within the Bayesian framework. The three stochastic models are applied to several instances of induced seismicity in Alberta, Canada, and Oklahoma, USA. The main result of this work is the development of a Bayesian approach for the estimation of the probabilities for the largest expected induced earthquakes governed by the modified ETAS process. The proposed methodology can be used in the probabilistic assessment of the earthquake hazard associated with fluid injection operations.

Keywords: ETAS, induced seismicity, Bayesian analysis

*Speaker

A Bayesian Framework for Earthquake/Aftershock Forecasting and Testing

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Abstract

Earthquakes are driven by tectonic loading and typically trigger subsequent events. They form clusters and swarms in space and in time. This is a direct manifestation of the non-Poisson behavior in the occurrence of earthquakes, where earthquake magnitudes and time intervals between successive events are not independent and are influenced by past seismicity. As a result, the distribution of the number of earthquakes is no longer strictly Poisson and the statistics of the largest events deviate from the GEV distribution. In statistical seismology, the occurrence of earthquakes is typically approximated by a stochastic marked point process. Among different models, the ETAS model is the most successful in reproducing several key aspects of seismicity. Recent analysis suggests that the ETAS model generates sequences of events which are not Poisson. This becomes important when the ETAS based models are used for earthquake forecasting (Shcherbakov et al., 2019). In this work, I consider the Bayesian framework combined with the spatio-temporal ETAS model to constrain the magnitudes of the largest expected earthquakes/aftershocks during a future forecasting time interval. The formulated approach includes the MCMC sampling of the posterior distribution of the ETAS parameters and computation of the Bayesian predictive distribution for the magnitudes of the largest expected events. It also allows full incorporation of the parameter uncertainties in computation of the relevant probabilities. To validate the forecasts, the statistical tests developed by the CSEP are reformulated for the Bayesian framework. In addition, I define and compute the Bayesian p-value to evaluate the consistency of the forecasted extreme earthquakes during each forecasting time interval. The Bayesian p-value gives the probability that the largest forecasted earthquake can be more extreme than the observed one. The suggested approach is applied to the recent 2019 Ridgecrest earthquake sequence to forecast retrospectively the occurrence of the largest aftershocks (Shcherbakov, 2021). The results indicate that the Bayesian approach combined with the ETAS model outperformed the approach based on the Poisson assumption, which uses the extreme value distribution and the Omori law.

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*Speaker

Keywords: ETAS model, Bayesian predictive distribution, extreme earthquakes

The 2020 Westmorland, California earthquake swarm as aftershocks of a slow slip event sustained by fluid flow

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Abstract

Swarms are bursts of small magnitude earthquakes without an obvious mainshock. Some have been observed to be associated with aseismic transients, while others are thought to be related to fluids. However, the association is rarely quantitative due to the difficulty measuring small geodetic signals related to swarms. We use high-quality GPS/GNSS, radar interferometry (InSAR), relocated seismicity, and novel data processing techniques to study a swarm of $>$ 2,000 earthquakes that occurred between September 30 and October 6, 2020, near Westmorland, California. Using 5-min sampled GPS supplemented with InSAR, we document a spontaneous shallow Mw 5.19 aseismic transient that preceded the swarm by 0.5 days. Seismicity in the early phase can be modeled as an inhomogeneous Poisson process suggesting that they were non-interacting and driven primarily by the aseismic transient rather than a product of cascade triggering. A stress-driven model based on rate-and-state friction successfully explains the overall spatial and temporal evolution of seismicity, including the time lag between the aseismic transient and the swarm and the non-linear expansion of seismicity. Later in the sequence, a distinct back front and a square root of time expansion of clustered seismicity on the en-echelon structures suggest that fluids helped sustain the swarm. Coulomb stress changes and statistics of interevent times suggest that 45 – 65% of seismicity was driven by the aseismic transient, 20 – 35% by inter-earthquake static stress triggering, and 10 – 30% by fluids. Our model also provides constraints on the friction parameter and the pore pressure and suggests that this swarm behaved like an aftershock sequence but with the mainshock replaced by the aseismic transient. With geodetic data available in real-time, the model could allow for forecasting the seismicity rate evolution of swarms before they start and as they evolve.

Keywords: swarm, aftershocks, aseismic, fluid

*Speaker

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Statistical analysis to assess the skill of the Operational Earthquake Forecasting system in Italy

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Abstract

Statistical seismology represents a very active and productive research field, which integrates modelling, data analysis and forecasting in the study of the earthquake process. A relevant application in this field is the Operational Earthquake Forecasting (OEF, Jordan et al. (2011)), an experiment started by several Countries worldwide (Field et al. (2017), Gerstenberger et al. (2014), Falcone et al. (2021)) to collect authoritative information about the spatiotemporal dependence of seismic hazard. On the basis of stochastic models, this experiment provides the probabilistic forecast for the occurrence of a seismic event in a specific space-time-magnitude domain. Such information can both help stakeholders to establish seismic risk reduction strategies, and enhance communities' resilience to potentially destructive earthquakes.
The idea of the OEF experiment in Italy was carried out after the Mw 6.2 event that struck on April 6th, 2009, beneath L'Aquila (central Italy), on proposal of the International Commission for Earthquake Forecasting (ICEF) for Civil Protection. In particular, the report emphasized some important features not yet considered at that time, such as the need to provide continuous information and the importance of testing the forecasts. According to the standards proposed by the Collaboratory for the Study of Earthquake Predictability (CSEP, Schorlemmer et al. (2018)), the OEF-Italy experiment is set on a specific 0.1◦ x 0.1◦ grid lattice covering the whole Italian territory, and is based on a stochastic ensemble model which consists in a combination of ETAS, ETES and STEP models (Lombardi & Marzocchi (2010), Falcone et al. (2010), Gerstenberger et al. (2005)), opportunely weighted according to the relative past performances. Since 2013, the OEF-Italy system is operative in real-time, and produces time-dependent seismic maps of the weekly number of earthquakes, expected by the ensemble model, occurring in each cell of the spatial grid above a fixed threshold magnitude or macroseismic intensity.

As highlighted by the ICEF report in 2009, proper stochastic modeling and testing are indeed essential to deliver reliable seismic rates for societal purposes and, we add, to quantify our real level of knowledge about earthquake predictability. From this perspective, in this work we perform some statistical analyses and tests to assess the forecasting skill of the OEF-Italy system, by means of both classical methodologies (e.g., Zechar et al. (2010), Taroni et al. (2018)) and new performance measures borrowed from other research fields,

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like meteorology, specific to validate alarm-based systems by a binary criterion (forecast = yes or no, occurrence = yes or no; Casati et al. (2008), Roberts & Lean (2008)). Our final aim is to: i) investigate possible weaknesses and room for improvements in the OEF-Italy stochastic modelling, ii) get insights on potential proper probability thresholds to activate state of alert procedures, iii) highlight possible features in the Italian tectonic seismic activity.

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Keywords: Operational earthquake forecasting, statistical analysis, performance skill

Targeting Temporal Seismicity with a Neural Point Process

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Abstract

Point processes have been the dominant way of describing the evolution of seismicity for a while, with the Epidemic Type Aftershock Sequence (ETAS) model being the most widely used. Recent advances in the field of machine learning have constructed highly flexible point process models using neural networks to seek improvements on existing parametric models. We conduct an investigation into the whether these flexible point process models can be applied to short term seismicity forecasting by extending an existing temporal neural model to the magnitude domain. We first find that the neural model can learn to capture synthetic ETAS data, however, requiring less computational time due to the fact that it is not dependent on the full history of the sequence. On data from a new high-resolution earthquake sequence in the Central Apennines we investigate the sensitivity of both ETAS and the neural model with respect to the lowest magnitude passed into each. We find that as the magnitude is lowered the performance of ETAS reduces unlike that of the neural model. We argue that some of the gains made by the neural model are due to its ability to handle incomplete data. Since neither model has an overall forecasting advantage over the other, our work suggests that there is not enough signal in 2-dimensional data to give a neural model an advantage over ETAS, but does offer a more efficient way to model data incompleteness. Our work also stresses the need for considering temporal incompleteness when using new machine learning generated earthquake catalogs.

*Speaker

Using Hidden Earthquakes to Forecast Future Events in Southern California

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Abstract

The spatial distribution of the past seismicity is often used to feed earthquake models, in order to forecast the zones that can be affected by earthquakes in the future. A prospective earthquake forecasting experiment in California showed that in the last 15 years the best-performing model is the one that used epicenters of small earthquakes (M≥2) to define the earthquakes' spatial distribution. In this work we performed a pseudo-prospective experiment, focused on the seismicity of the southern California region from 2008 to 2021, comparing the performance of two spatial seismicity models, based on a classical instrumental catalog and a modern template matching catalog. The results of such an experiment clearly demonstrate that by using "hidden earthquakes", i.e. very small events (M≥0.3) from the modern catalog, it is possible to increase the forecasting performance of the spatial models. These results also suggest a profound similarity between the spatial distribution of the earthquakes, from very small events to larger ones.

*Speaker

A Testable Worldwide Earthquake Faulting Mechanism Model

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Abstract

We present a simple model to forecast global focal mechanisms. This model is based on a simple discrete counting distribution of the global centroid moment tensor catalog, and it also includes, using a Bayesian scheme, the a priori information from the Anderson theory of faulting. Our model is tested in hindcasting mode against independent data of global large earthquakes with M s $\geq$ 7. We obtained statistically significant good agreement between model and data using consistency test, demonstrating that this simple model can satisfactorily forecast focal mechanisms at the global scale. The defined testing procedure can be used to test the model in prospective mode against future events. These forecasts may inform short- to long-term hazard quantifications that require a finite source characterization, as well as real-time source inversion algorithms. This model has been recently published in SRL (https://doi.org/10.1785/0220200445).

Keywords: Focal Mechanism, Forecast, CMT

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Resolving Differences in the Rupture Properties of Prominent California Earthquakes Using Bayesian Source Spectral Analysis

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Abstract

The spectra of earthquake waveforms can provide useful insights into rupture processes, yet the analysis and interpretation of earthquake spectra remains a challenging problem. Here we develop a Bayesian framework that embraces the inherent data and modeling uncertainties of spectral analysis to infer key source properties. The method uses a spectral ratio approach to correct the observed S-wave spectra of nearby earthquakes for path and site attenuation. The objective then is to solve for a joint posterior probability distribution of three source parameters – seismic moment, corner frequency, and high-frequency falloff rate – for each earthquake in the sequence (both EGF and target), as well as a measure of rupture directivity for all target events with good azimuthal station coverage. While computationally intensive, this technique provides a quantitative understanding of parameter tradeoffs and uncertainties and allows one to impose physical constraints through prior distributions on all source parameters, which guide the inversion when data is limited. We demonstrate the method by analyzing in detail the source properties of 14 different target events of magnitude M5 in southern California that span a wide range of tectonic regimes and fault systems. These prominent earthquakes, while comparable in size, exhibit marked diversity in their source properties and directivity, with clear spatial patterns, depth-dependent trends, and a preference for unilateral directivity. Coherent spatial variations in source properties suggest that regional differences in tectonic setting, hypocentral depth or fault zone characteristics may drive variability in rupture processes. This finding may have important implications for our understanding of earthquake physics and its relation to hazard.

*Speaker

Spatial correlation of strain rate and crustal seismicity in Japan

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Abstract

Earthquakes are caused by the stress release in the earth's interior due to the relative plate motion. Therefore, it is considered that strain rate estimated from geodetic data may correlate with seismicity, and this relationship has been discussed in several areas (Zeng et al., 2018; Stevens and Avouac, 2021; Xiong et al., 2021; Wu et al., 2021). Zeng et al., (2018) revealed that the maximum shear strain rate along the San Andreas Fault and Eastern California Shear Zone positively correlated with the distribution of the background seismicity rate in the shallow-crustal environment.
In Japan, there is a tendency that the higher strain rate, the more frequent shallow M $>$ 6 earthquakes occur (Nishimura, 2017) and time-independent forecast model for large crustal earthquakes based on geodetic data is suggested (Nishimura, 2022). In this study, we investigate the spatial correlation between background seismicity rate (smaller earthquakes) and strain rate.

I used the JMA hypocenter catalog (the Preliminary Determination of Epicenters) as the earthquake catalog. I applied the HIST-ETAS model (e.g., Ogata, 2004) to the M $>$ 3.0 crustal earthquakes which were located at $<$ 25 km depth from 1980 through 2010 to estimate spatial variations in background seismicity rate. Then, I compare the spatial variations in background seismicity rate estimated via the HIST-ETAS model with the maximum shear strain rate estimated using the GNSS data from 2006 through 2009 by Okazaki et al. (2021). Spatial variations in background seismicity rate positively correlate with that in the maximum shear strain rate. In the region including active volcanoes or whose lower crust has fluid concentrated zone, background seismicity rate is higher at the same maximum shear strain rate compared with other regions, suggesting that fluids weaken the fault strength.

Keywords: Background seismicity rate, Strain rate, HIST, ETAS model

*Speaker

Mapping spatio-temporal changes in the magnitude frequency distribution of aftershocks with b-positive

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Abstract

The earthquake magnitude-frequency distribution is characterized by the b-value. Some observations suggest that the b-value for aftershocks is larger than for spontaneous events (mainshocks), and that exceptions to this rule occur exclusively in foreshock sequences. Unfortunately, measurements of b-value are biased during aftershock sequences by short-term incompleteness of the earthquake catalog. I present an alternative estimator of the b-value, 'b-positive' that is insensitive to transient changes in catalog completeness and that allows for the real-time, unbiased measurement of b-value during an ongoing sequence. The estimator is based on the differences in magnitude between successive earthquakes, which are described by a double-exponential distribution with the same b-value as the magnitude distribution itself. The new estimator mostly confirms the findings of Gulia and others (*Nature, 2019; SRL 2020*), showing a decrease in *b*-value between the foreshock and mainshock in several prominent sequences over the past decade. More generally, sequences may show an evolving magnitude-frequency distribution with time, with relatively low b-values early in the sequence, and a gradual shift to higher b-values as the sequence progresses. Mapping the spatio-temporal evolution of the 2020 SW Puerto Rico sequence reveals an interesting pattern of lower b-values at the margins of the aftershock zone and in the vicinity of bursts of new activity, followed by gradually increasing b-values as activity subsides. The non-stationary distribution of magnitudes within a sequence may hold information about source processes and has important implications for intermediate and long term aftershock forecasting.

*Speaker

Bayesian analysis of temporal variations of seismicity based on non-extensive statistical mechanics

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Abstract

In 1988, Tsallis introduced a non-additive entropy that has found applications in various fields such as physics, chemistry, medicine, informatics, linguistics, and economics. The concept also gained attention in statistical seismology due to the evidence that Earth's crust behaves as a complex, non-linear dynamic system characterized by long-range correlations. By addressing the problem in the context of non-extensive statistical mechanics, the classical methods of analysis are unsuitable: the Boltzmann-Gibbs (BG) entropy is appropriate to study systems with short range interactions, while new entropies that generalize some of the properties of BG entropy are better suited to describe systems with long range interactions. In this respect a new probability distribution of the magnitude was derived by maximizing a non-extensive generalization of the Boltzmann–Gibbs entropy, namely the Tsallis entropy (Tsallis, 2009).

The result is the q-exponential distribution, whose shape parameter q is called the entropic index and is found to characterize the subadditive ($q > 1$) and superadditive ($q < 1$) regimes; the exponential distribution is recovered as q tends to 1.

Two active seismogenic areas in central Italy are analyzed, the former including the L'Aquila sequence that occurred in 2009 and the latter the Amatrice-Norcia sequence that occurred in 2016. Parameter estimation is performed by following the Bayesian approach in order to exploit the prior knowledge on the phenomenon (Vallianatos et al., 2016) and to assess the uncertainties.

A detailed analysis of the variations of both q index and Tsallis entropy is performed by estimating them over time windows of a fixed number of events that shift at each new event. Both the q index and the Tsallis entropy show significant and lasting decreases before the first strong earthquake in the sequences, and sudden increases after them. This indicates that these quantities offer clues on the activation state of the systems (Rotondi et al., 2022).

In the literature the q-exponential distribution has been used to study other seismic parameters like seismic moment, inter-event times, Euclidean distance between successive events. Following the example of Schoenberg et al. (2009), we have thought that the q-exponential distribution could describe, in addition to earthquake magnitude, also the spatial properties of seismicity such as the area of the Voronoi cells generated by the epicentral locations. We

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extend our analysis to the areas of Voronoi cells generated by the recent seismicity recorded in the study regions. Then we compare the performance of the estimated q-distribution with that of some promising probability distributions of the Voronoi cell area, namely the tapered Pareto distribution and the generalized Gamma distribution. Also in this case the analysis of the time variations of the probability model that provides the best fitting to the datasets provides us information on the phases of the seismic cycle.

Future work aims to analyze different seismic areas in order to test and consolidate the results.

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Bayesian Assimilation of Multicycle Earthquake Simulations into Probabilistic Forecasting Models

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Abstract

A general problem in earthquake forecasting is how to assimilate deterministic physical simulations into probabilistic forecasting models. Here we focus on recalibrating the time-independent Uniform California Earthquake Rupture Forecast Version 3 (UCERF3-TI) of Field et al. (2014) against long earthquake catalogs (_˜10ˆ6 years) generated by the multi-cycle Rate-State Quake Simulator (RSQSim) of Dieterich & Richards-Dinger (2010). We map RSQSim ruptures from the Shaw et al. (2018) catalog onto equivalent UCERF3 ruptures by maximizing the mapping efficiency while preserving the seismic moment. We assume the sequence of equivalent UCERF3 ruptures is Poisson distributed, i.e., each rupture occurs at a time-independent rate, our knowledge of which is uncertain. We use the full UCERF3 logic tree to construct a joint prior distribution of rupture rates, which we represent by independent Gamma distributions. Updating the UCERF3 gamma priors with the empirical RSQSim Poissonian rate yields Gamma posterior distributions that can be calculated analytically. Our results show that participation rates are decreased in the northern section of the San Andreas Fault System (SAF) with respect to the UCERF3 model, which we attribute to the slip rate difference between RSQSim and UCERF3. Furthermore, our posterior model results in substantial lower rates in the Coachella, San Gorgonio, and San Bernardino SAF sections, reflecting the fact that RSQSim does not propagate ruptures through the San Gorgonio knot. We also briefly address the more challenging problem of constructing time-dependent forecasts that have been conditioned on knowledge of the previous rupture history over time intervals of the last 100 years or so.

*Speaker

Can we reproduce fault mechanics in the lab?

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Abstract

Faults and earthquakes are generally considered as a paradigm for slowly driven physical systems that release the incoming energy through intermittent bursts spanning a wide range of sizes and energies. Owing to the (so far elusive) search for robust prediction tools, it has been dreamed for a long time to reproduce faults and earthquake physics under controlled conditions and detailed monitoring in the lab, in order to better understand the underlying physics (1).

Earthquakes and faults dynamics are characterized by several scale-free statistics (2), such as the distribution of their seismic moments (Gutenberg-Richter's law) as well as temporal and spatial correlations, e.g. expressed through a decaying rate of aftershocks (Omori's law) (3) and scale-free sub-diffusion (4). In the last decades, it has been also realized that tectonic loading can be released, besides classical earthquakes, through a variety of mechanisms such as aseismic slip, tremors, repeating earthquakes, ect..

Before to be proposed as an experimental model allowing to decipher these empirical observations, a laboratory analog should therefore reproduce this complexity. In other words, a power law distribution of burst energies is a necessary, but not a sufficient condition to claim a formal analogy. As an example, compressive rupture under monotonic loading, characterized by very clear precursory phenomena but scale-free statistics only at failure(5), cannot be considered as a good candidate, as previously claimed (1).
Recently, several experimental set-ups, based on the propagation of a quasi-brittle crack within a disordered landscape (

*Speaker

Analysis of the 2016 Central Italy earthquake sequence by using a refined earthquake catalog

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Abstract

By using an outstanding earthquake catalog obtained by machine learning method (Tan et al., 2021), that contains more than 900 000 relocated earthquakes, we aim at modeling the seismicity of the 2016 Central Italy earthquake sequence, and to find hints of the high-pressurized fluids located under the studied area by identifying small swarms occurring during the sequence.
The magnitude of completeness mC is found to fluctuate significantly over the course of the sequence, and down to sub-daily time scales. Rather than defining one single value for mC, we here propose to keep all earthquakes, and to account for changes in detection with time.

We define an earthquake stochastic model based on the " Epidemic-Type-Aftershock-Sequence " (ETAS) model, by making it an 4-dimensional problem (x, y, z, t — m) and by introducing an earthquake detection probability. We assume that there is no background seismicity, an earthquake is considered as a point source and each large earthquake has its own specific productivity prefactor. The parameters optimization of this model is done by using an "Expectation-Maximization " (EM) algorithm that requires a splitting of triggering earthquakes according to the threshold magnitude mP, i.e. the minimum magnitude that an earthquake need to reach in order to be modeled as potentially triggering other earthquakes. By fixing ETAS parameters and exploring varying mP values, the results show that the accuracy of our models improves with decreasing mP value, as expected, but that this increase in the quality comes with over-fitting the data. We analyze this by assessing the prediction capacity of the models: we separate the sequence in two time intervals (a " training " interval to fit the parameters, and a " validation " interval to measure the predictive value of the model). This approach improves on the classical method that simply fits the model parameters over the whole available dataset without preventing overfitting. We then analyze how the observed seismicity rate locally departs from the best-predictive model so to isolate possible swarm activity during the sequence.

Keywords: Earthquake modelling, aftershock sequence, earthquake nucleation, aseismic deformation, swarms

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The research on the spherical space-time ETAS model

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Abstract

The widely used space-time ETAS (epidemic-type aftershock sequence) model was developed by Ogata (1998). This model successfully explains foreshocks and high order aftershocks in earthquake sequences and provides a very effective tool for seismic activity analysis. However, this space-time ETAS model is only suitable for studying within a small space range. When the study range is wide or in a high latitude, since the earth is a sphere, the simulation results of the model will produce errors. This study reformulates the space-time ETAS model from its planar version to a spherical version by modifying the widely used planar space-time ETAS model (Zhuang et al., 2002; Zhuang, 2012). The new version is applicable to analyze and forecast seismicity in high latitude regions or on a global scale. And the model is verified by applying it to the global CMT catalog. The results show that the new model can well simulate the global seismicity variation. It supports better modeling of seismic activities and seismic interactions in global regions. Moreover, our model has high computational efficiency, even for a large range of global data.

*Speaker

The role of three-dimensional fault interactions in creating complex seismic sequences

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Abstract

A physics-based earthquake simulator should reproduce first-order empirical power-law behaviors of magnitudes and inter-event time clustering. However, sequences exhibiting these laws have only been produced in discrete and low-dimension continuum simulations. We show that the same emergence also occurs in 3-D continuum simulations with fault interactions. Our model approximates a strike-slip fault system slipping under rate-and-state friction. We produce spatio-temporally clustered earthquake sequences exhibiting characteristic Gutenberg-Richter scaling as well as empirical inter-event time distribution. With fault interaction, partial ruptures emerge when seismogenic width W over characteristic nucleation length L_∞islargerthan16.24, butnoneoccurswithoutfaultinteraction.Themainshockrecurrencetimesofindividualfaultsrema
periodicandfitaBrownianpassagetimedistribution.Thesystemmainshockrecurrencetimehasashort−termOmori−
typedecay, indicatinga22%chanceofmainshockclustering.Weextendthesimulationtoa10−faultsystemmimickingthecen
basedmulti−cyclemodelsadequatelyreflectobservedstatisticalsignaturesandhaspotentialforlong−termhazardassessm
termforecasting.

Keywords: earthquake cycle, fault interaction, earthquake rupture

*Speaker

Keywords: modeling seismicity, branching processes, Galton, Watson process

Evaluating earthquake forecasts with likelihood based marginal and conditional scores

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Abstract

Earthquake forecasting consists of the forecasts of the numbers, occurrence times, locations, and magnitudes of seismic events, and even the correlations among them. In order to evaluate each component in the forecasting, CSEP provides varieties of testing criterions but still far from enough. In this study, starting from the essential meanings of the full likelihood of a point process, I will explain how to evaluate the marginal likelihoods for each component in the forecasts and the conditional likelihoods for some components under the condition that some other components are given. These marginal and conditional likelihoods are the bases for the marginal and conditional scores in performance evaluation when multiple models are used in the forecasting. I will also illustrate how to use Monte Carlo simulations to accelerate the computation.

Keywords: scoring forecast, point process, CSEP, Monte Carlo, simulation

*Speaker

Neural-network based models for earthquake prediction

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Abstract

State-of-the-art models in statistical seismology, like ETAS and its variants, combine well-established statistical properties of earthquakes (e.g. Gutenberg-Richter law, and Omori's law) into a simple functional parametric form, whose parameters are learned from the data by likelihood optimization. A natural way to improve on such models is using neural networks, due to their ability to model complicated functional dependence, the relative ease with which different measurement modalities can be included, and the ability to simultaneously model multiple aspects of the prediction problem. In this work we present such a neural architecture, combining recent developments in neural point-process modeling and standard ML techniques. Our models are trained to predict various statistical properties of future seismicity, outperforming or competitive with ETAS models in various common metrics. The architecture makes it easy to incorporate other information sources and modalities, and pose different prediction tasks, and we will discuss preliminary results in this direction.

Keywords: Rate prediction, neural networks, machine learning, earthquake forecasting

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New findings on maximum magnitudes and future seismicity scenarios for the gas field in Groningen, The Netherlands

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Abstract

The Groningen gas field is one of the most frequently considered sites for studying induced seismicity. Zöller and Holschneider (Bull. Seismol. Soc. Am. 106, 2917-2921, 2016) calculated confidence intervals for the maximum possible earthquake magnitude and the maximum expected magnitude in a future time interval. In recent years, gas production has been reduced significantly and is planned to be terminated in about ten more years. During this time interval, earthquakes are still expected to occur. Even later, a petering out of seismicity is likely due to memory effects. We show that the confidence interval of the estimated maximum possible magnitude decreases compared to 2016. This observation may be explained by decreasing uncertainties arising from the growing size of the earthquake catalog. Furthermore, we present seismicity scenarios for the next decades based on various data-driven models. In particular, we employ physical models footing on Coulomb-Failure-Stress (CFS) and Rate-and-State-dependent friction (RS), as well as statistical models based on inhomogeneous Poisson processes. The results indicate that earthquakes with a magnitude higher than 4.0 can be expected in the next 30 years, even if the gas field is shut down in about ten years.

Keywords: induced seismicity, maximum earthquake magnitude, statistics

*Speaker

Stress-Strain Characterization of Complex Earthquakes and Seismic Sequences Using Probabilistic Hierarchical Models

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Abstract

Earthquake ruptures and seismic sequences are the inelastic strain response to tectonic stress fields. We develop a physics-based probabilistic model to characterize stress-strain fields using moment measures of mechanism complexity. Distributions of focal mechanisms in seismic sequences and earthquake ruptures are used to estimate the ratio of the Aki seismic moment to the total moment and the partitioning of the moment tensor field over an orthonormal basis of five deviatoric mechanisms. These moment measures of complexity are then used to estimate the principal-stress directions, a differential stress ratio (R), the complexity factor (F'+), and a stress-strain sensitivity parameter (k). Large values of F'+ indicate high mechanism complexity, and high k indicates high-stress concentration. We quantify the effect of focal mechanism uncertainty on the moment measures using a hierarchical probabilistic model. We apply the model to characterize the complexity of stress-strain fields of seismicity in California. We show that the observed complexity is related to evolutionary geologic variables such as the cumulative slip in the fault. For example, the seismicity along the San Andreas Fault in the Parkfield and Loma Prieta sections, which have over 150 km of cumulative slip, shows significant stress-strain sensitivity (k=12), i.e., low complexity. In contrast, faults in the Mojave Block with less than 5 km of cumulative slip show a low sensitivity (k=4.5). The stress field before the Mw7.2 Ridgecrest earthquake of 2019 shows high complexity (k=7), while the aftershocks show less complexity with k=7.25, indicating that the aftershocks are more aligned with the mainshocks than the background seismicity. These preliminary results suggest that seismic monitoring of mechanism complexity may provide information that is useful in time-dependent earthquake forecasting.

Keywords: Mechanism Complexity, Probabilistic Forecasting, Stress Inversion

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