Session 4

TALKS:

Dynamic source parameters inferred from moment rate functions using the empirical Green's function approach for northern California earthquakes

T. Taira, and D. Dreger

A better understanding of the earthquake rupture process is central to studies of earthquake source physics. A point-source approximation has been used widely to identify the underlying faulting mechanics with high accuracy (Dreger et al., 2008). However, this approximation will not allow us to assess rupture directivity and to identify if multiple sub-events are involved. We compile moment rate functions (MRFs) of small to moderate earthquakes ($3 <= M <= 6$) for northern California through an empirical Green's function approach with the aim to systematically evaluate rupture complexities. Also our interest is to characterize rupture dynamics through evaluating seismological radiated energy, radiation efficiency, and fracture energy by using MRFs with an assumption of slip weakening model (Abercrombie and Rice, 2005; Malagnini et al., 2014). Our results with a dataset of over 300 earthquakes suggest a weak non-self-similarity behavior, which appears to be consistent with results from Kanamori and Rivera (2004) that analyzed southern California earthquakes. We performed a finite-fault modeling for subsets of earthquakes by inverting MRFs (Mori and Hartzell, 1990) including the 2022 Mw 5.1 Alum Rock earthquake. This earthquake exhibits a complex rupture process involving three subevents with a southeast directivity. The peak and median slips are found to be 42 cm and 14 cm respectively, which provides the peak and median stress drop of 28 MPa and 5 MPa.

Observations of laboratory earthquake rupture: implications for earthquake early warning

A. Kiss, E. Spagnuolo, C. Cornelio, S. Aretusini, V. Longobardi, M. Cocco, J. Taddeucci, and S. Colombelli

The onset of an earthquake is associated with a nucleation phase, which is necessary to create the conditions for the subsequent dynamic rupture propagation. Theoretical models and laboratory experiments have been proposed to compensate for the lack of direct observations of earthquake nucleation, remaining poorly understood and described through conceptual models. A central and unresolved question is whether and how the nucleation and breakout phases influence the subsequent dynamic rupture propagation and arrest and ultimately determine the final earthquake size. Recent seismological evidence points towards weak determinism between nucleation and final earthquake size. Here we present the Mechanics of Earthquakes and Extended Ruptures Apparatus (MEERA) - a horizontal multiaxial apparatus designed to nucleate dynamic instabilities on an experimental fault. The extended size of the fault (30 x 5 cm) enables the simulation of rupture propagation under a controlled environment. This provides an opportunity to study physical controls on final rupture size. Surface and along-fault deformation before and during dynamic instabilities are monitored with the help of digital image correlation and fiber optic sensing. In addition, an array of 12 high frequency (10 MHz) acoustic emission sensors record elastic waves radiated from dynamic instabilities. The aim of experiments on MEERA, part of the wider ERC-FORESEEING project, will be to bring observations on natural earthquake data to the scale of laboratory fractures and to understand whether the onset of acoustic emissions signals follows a similar trend with magnitude as observed for small natural earthquakes. We will present preliminary results of experiments showing the emergence of a critical nucleation length for dynamic rupture propagation during experiments and will discuss the implications of these findings for larger scale natural earthquakes, in the context of Earthquake Early Warning applications.

The deterministic behaviour of earthquake rupture beginning

V. Longobardi, S. Colombelli, and A. Zollo

Earthquakes are among the most destructive natural hazards whose released energy can be quantified by their magnitude. Predicting how much energy will be released before the end of the rupture process represents a challenging question. The way earthquake ruptures grow, propagate and arrest determines the final size: small-to-moderate ruptures evolve in few seconds within few kilometers, while large-to-huge events develop in tens of seconds and several hundred kilometers. If the rupture process starts in the same way for small and large earthquakes, no deterministic prediction of the final size is feasible, until the process has completed. Instead, if the source mechanism starts differently from its beginning, real-time proxies can be measured on early radiated waves to discriminate the final event size. Here we show that the initial ground displacement grows differently for small and large earthquakes, based on the analysis of an unprecedented catalog of seismic waveforms from worldwide earthquakes. The result supports the hypothesis of early predictable magnitude for a wide range of different earthquakes in diverse geological settings. This study confirms that the initial growth of displacement can be used for a fast magnitude estimation, making it potentially feasible for future implementation in early warning systems.

Rupture dynamics and seismic radiation of fluid-induced micro-earthquakes

F. Mosconi, E. Tinti, A-A. Gabriel, E. Casarotti, P. Dublanchet, and M. Cocco

Understanding the mechanisms controlling the propagation and arrest of fluid-induced microearthquakes is critical for resolving key questions in earthquake mechanics and assessing induced seismic hazard. However, direct near-field observations of earthquake sources remain extremely rare. The FEAR project addresses this gap by inducing a M~1 earthquake through controlled fluid injection in the Bedretto Tunnel (Switzerland), ~1 km below the surface, where a dense multidisciplinary network of sensors enables real-time monitoring of rupture processes at unprecedentedly short distances on a target fault. We perform fully 3D dynamic rupture simulations of fluid-induced earthquakes, nucleating within the pressurized region, considering both planar and rough fault geometries. The planar fault case, characterized by homogeneous prestress, allows us to isolate the effect of rupture propagation under a spatial gradient of effective normal stress induced by pore pressure. Under these conditions, the ratio of strength excess to dynamic stress drop controls rupture behavior, leading to two end-member regimes: (i) self-arresting ruptures that stop within the fault boundaries at high ratios, and (ii) continuously accelerating ruptures (run away) that release the full fault potential at low ratios. Analysis within the canonical Linear Elastic Fracture Mechanics framework (LEFM) reveals that, for self-arresting ruptures, the normal stress gradient controls the spatial decrease in the dynamic stress drop, smoothly driving the rupture front out of energy, whereas run-away ruptures show a growing crack driving force at the rupture tip that sustain their propagation. Real geological faults systematically exhibit geometric and rheological complexity across all scales. In particular, for immature faults or fracture networks characterized by thin principal slipping zone or bare fracture surfaces, the geometrical roughness of the slipping plane induces heterogeneous normal and shear stress distributions at short spatial wavelengths. Fluid-injection therefore acts on an already heterogeneous stress field, superimposing an additional normal stress gradient associated with pore pressure variations. This complexity challenges a simple crack-like description of fluid-induced earthquakes. We have included fault roughness in our 3D dynamic rupture simulations of fluid-induced earthquakes. Our results reveal that even Mw~1 ruptures exhibit highly complex kinematics, with rupture propagation governed by local stress variations. Rupture arrest may be controlled either by the pore-pressure gradient or by geometric barriers, depending on the characteristics of the fault roughness. Analysis of the synthetic radiated wavefield using a spectral inversion approach reveals systematic differences between self-arresting and runaway ruptures in terms of high-frequency content, corner frequency, and moment-rate functions. These differences are directly linked to on-fault rupture behavior and are primarily controlled by the mechanisms governing rupture arrest. Combining dynamic modeling with near-fault observations in experimental settings such as the Bedretto Underground Laboratory offers a promising pathway to identify arrest signatures in real data and to improve our understanding of rupture arrest in both natural and fluid-induced earthquakes.

Scaling of rupture initiation from P-wave onset: insights from earthquakes and laboratory experiment

S. Colombelli, V. Longobardi, S. Aretusini, C. Cornelio, A. Kiss, E. Spagnuolo, and A. Zollo

Despite recent advances from real observations, laboratory experiments and numerical modelling, the mechanisms governing earthquake generation and wave propagation are still not fully understood. Theoretical analyses and laboratory experiments have shown that seismic ruptures begin with a process of quasi-static slip accumulation over a limited region of the fault (referred to as the preparatory phase). Here, when a critical threshold is reached, the fracture becomes unstable, accelerates for a short time (referred to as the break-out phase) and finally triggers the dynamic propagation. While the breakout phase is observed at laboratory scale, no direct evidences are available at the scale of real-earthquake data. The unresolved question is whether the breakout phase has an influence on the final size of the forthcoming event. In other words, it remains unclear whether all earthquakes begin through a similar process—characterized by the exceedance of a yield stress and influenced by local frictional properties or geometric complexities of the fault surface—with the rupture extent determined during propagation, or whether fundamentally different initiation mechanisms govern the generation of small and large events. Within the framework of the ERC funded FORESEEING project, here we focus on the analyses of the P-wave onset of real earthquakes to shed light on the mechanism of generation of seismic ruptures and to understand the role of the parameters involved in the process. We investigate the behaviour of seismic signal across multiple datasets, focusing on earthquakes with magnitudes Mw 1–4 from four well-instrumented regions: the Campi Flegrei region (Southern Italy), the Irpinia Near Fault Observatory (Southern Italy), the

TABOO network (Central Italy), and The Geysers geothermal field (USA), for a total of thousands of events and available waveforms. Following the approach of Longobardi et al. (2025), we analyze the behavior of the low-pass displacement vs. time curve (LPDT). We found that LPDT curves grows differently for micro (Mw 1-2) to small earthquakes (Mw 2-4), following a similar trend as observed for worldwide moderate-to-large events (Longobardi et al. 2025). The scaling is consistent across datasets despite differences in magnitude range and geological setting and suggests that the observed behaviour reflects an intrinsic property of the seismic source rather than and wave propagation or region-specific effects. For a limited number of events, we extended the analysis to laboratory-scale acoustic emission experiments, allowing a direct comparison between seismic and acoustic signals over a wide range of spatial and temporal scales. Such a multi-scale approach will provide new insights into the universality of LPDT scaling and its relation to fracture processes and source dynamics. These results demonstrate the consistency of LPDT scaling across diverse seismic environments and support its potential use as a powerful tool for rapid source characterization, with strong implications for Earthquake Early Warning applications.

Dynamic rupture propagation with laboratory derived slip-weakening constitutive laws

Cornelio C., Murphy S., Spagnuolo E., Nielsen S., Cocco M.

Accurately modelling earthquake rupture requires constitutive laws that capture how faults weaken during rapid slip. While dynamic simulations commonly employ the Linear Slip-Weakening (LSW) law, laboratory experiments on real fault-hosting rocks show non-linear weakening and exhibit an initial slip-hardening phase. We incorporate the laboratory-derived Ohnaka Slip-Weakening (OSW) law based on high-velocity friction data from Carrara marble and gabbro into 2D dynamic rupture simulations and compare rupture behavior with LSW. We compare the results under equivalent conditions of critical slip distance, breakdown work, or fracture energy. Experiments show that the energy dissipated when stress evolves from the yield to the peak value is not negligible and the decay from peak to residual stress is not linear. Our simulations demonstrate how the initial hardening phase affects the energy flux at the crack tip and how the shape affects rupture propagation. There is no equivalent condition that allows LSW rupture behavior similar to OSW. Indeed, OSW ruptures display broader stress fronts, smoother slip-rate evolution, larger cohesive zones and systematically lower rupture and peak slip velocities than LSW. Our results also suggest that using LSW with seismologically inferred breakdown work may overestimate fracture energy, rupture speed and high-frequency ground motions.

POSTERS:

Fluid-modulated rupture efficiency and nucleation in a structurally partitioned fault system: the 2010–2014 Mt. Pollino swarm (Southern Apennines, Italy)

G. Calderoni, R. Di Giovambattista, M. Ponte, and M. La Rocca

How pore-fluid pressure modulates dynamic rupture efficiency and nucleation conditions across a structurally heterogeneous fault system remains an open question, particularly for the transition from microearthquakes to moderate events within fluid-active sequences. We address this through the 2010–2014 Mt. Pollino swarm (Southern Apennines, Italy), which provides an unusually complete observational dataset spanning two orders of magnitude in seismic moment and involving clearly distinct structural and rheological domains. Full moment tensor solutions and Savage–Wood radiation efficiency reveal strong mechanical partitioning. Events with positive isotropic components (up to ~40%) cluster within a west-dipping, high-attenuation volume at ~6 km depth, consistent with fluid-saturated hybrid failure and systematically low radiation efficiency. In contrast, earthquakes on a more competent east-dipping fault exhibit high radiation efficiency ($\eta SW \geq 0.3$) and predominantly double-couple mechanisms, indicating efficient shear-dominated dynamic rupture. This spatial segregation of rupture styles is not random but reflects the underlying rheological and permeability structure: elevated pore pressure within the high-attenuation reservoir promotes inelastic volumetric deformation at the expense of radiated energy, while the fluid-driven stress front, upon reaching stronger lower-attenuation crust, triggers energetically efficient brittle ruptures. The coexistence of these two rupture modes within the same sequence provides a field-scale analogue to laboratory observations of pressure-dependent failure modes under varying pore-pressure conditions. The largest events show stress drops of ~1 MPa and self-similar scaling ($M_0 \propto L^3$), comparable to tectonic earthquakes, confirming that elevated pore pressure does not fundamentally alter fault strength or stress release per event but acts as a kinetic modulator of nucleation timing and spatial pattern. Migration follows $V \propto T^{-0.76}$, steeper than the diffusive expectation ($V \propto T^{-0.5}$), and the dimensionless parameter $\varphi=\log10\ (VT^{\alpha}) \approx 1.8$ indicates a rapid migration regime, inconsistent with simple diffusion and suggesting a mechanism beyond pure pore-pressure diffusion. The Mw 4.3 (May 2012) and Mw 5.2 (October 2012) events, separated by ~150 days and ~7 km, are consistent with progressive nucleation within a months-long fluid-driven transient rather than a classical foreshock–mainshock pair, with hydraulic diffusivity $D = 0.174 \pm 0.044\ m^2/s$ indicating that a pore-pressure front could bridge the two clusters over this timescale. The Mt. Pollino dataset thus offers observational benchmarks, isotropic component fraction, radiation efficiency contrasts, and V–T–M_0 scaling exponents, that directly constrain the role of fluids in modulating nucleation conditions and rupture efficiency from microearthquakes to moderate events, with implications for dynamic rupture models in heterogeneous fluid-active crust.

Inferring Fault Stress and Aseismic Slip During Earthquake Sequences: Insights From Modeling of a Hydromechanical Experiments

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Earthquake sequences are commonly interpreted as the reactivation of critically stressed faults driven by stress redistribution at depth. Recent observations, spanning scales from meters to kilometers, suggest that the triggering of such sequences may involve complex hydromechanical processes, including fluid overpressure, slow aseismic slip fronts, and cascading stress transfers. However, making quantitative inferences about the hydromechanical processes governing fault reactivation from earthquake catalogs remains challenging, although this may be partially addressed using earthquake cycle models. Here, we present hydromechanical earthquake cycle simulations designed to reproduce fault slip reactivation and the development of earthquake clusters observed during a three-week stimulation experiment in a granitic rock volume through controlled fluid injection. The experiment was conducted at the Bedretto Underground Laboratory (Switzerland) in the framework of the ERC-Synergy FEAR project. We model the fault system as two planar rate-and-state frictional interfaces embedded in a homogeneous elastic medium. One of the two fault segment is intersected by the injection borehole, where fluid was injected under alternating pressure and flow rate-controlled protocols. The model incorporates all available mechanical constraints derived from in-situ and laboratory observations, including the in-situ stress state, frictional properties, and elastic parameters, and imposes the measured fluid overpressure history at the injection site. We explore a range of initial fault conditions, characterized by their proximity to steady-state frictional stress, as well as different scenarios of frictional heterogeneity and hydraulic behavior. Our results show that fluid injection triggers both migrating aseismic slip fronts and repeated failure of seismogenic asperities, consistent with the repeating earthquake activity observed on the second fault segment. We further demonstrate

that the initial stress state and the permeability law exert strong control on the spatial and temporal patterns of seismicity and aseismic slip in response to fluid injection. These findings provide new insights into the potential for using earthquake catalogs to infer fault stress conditions and aseismic slip on natural faults.

Focal Mechanisms and Fracture Network Activation Patterns from the M0A and M0B Hydraulic Stimulation Experiments at the Bedretto Underground Laboratory (Switzerland)

G. Poggiali, E. Tinti, M-A. Meier, and M. Cocco

Understanding the physical processes governing induced earthquakes requires observations at scales bridging rock physics laboratory and field-scale seismology. The Bedretto Underground Laboratory for Geo-Energy and Geo-Resources (BULGG, Switzerland) provides a unique and densely instrumented hectometer-scale testbed. Among the laboratory's various activities, the FEAR project aims to activate a natural geological fault zone. To this task, the Mzero (M0) experiments were designed to induce seismicity and a target magnitude mainshock within a fractured rock volume in the geo-thermal test bed. The experiments allow the collection of near-source observations of fluid-driven seismicity as well as the rupture processes of the target ~Mw 0 earthquake. The M0 experiments comprised two distinct main stimulation episodes adopting different injection protocols that exhibited markedly different seismogenic responses: M0A, which included a multi-day fluid preconditioning phase, produced a highly localized seismic sequence and the target main shock, whereas M0B initiated directly at high injection pressure and generated a higher seismicity rate within a larger, migrating cloud of seismicity. To understand the mechanics of induced earthquakes and the different seismicity patterns caused by distinct injection protocols, we computed the focal mechanisms of the induced microseismicity across 6,612 events (2,257 from M0A and 4,355 from M0B) selected based on a (amplitude based) magnitude threshold. Phase picking and first-motion polarities were derived using machine learning, validated against theoretical traveltimes. For acoustic data, polarities were further corrected for incidence angles. Applying the SKHASH algorithm to this automatic polarity dataset, we computed 3,694 focal mechanisms, retaining only high-quality solutions for robust interpretation. To accurately quantify energy release, moment magnitudes (Mw) were estimated for approximately 900 events using spectral inversion. Initial analysis reveals that these focal mechanism solutions generally align well with the expected strike and dip of the observed seismicity clouds and known geological structures. To systematically unpack the rupture kinematics within these spatiotemporal clouds, we implemented a DBSCAN clustering algorithm using a hybrid distance metric that combines spatial distance with the Kagan angle. This approach successfully highlights distinct spatio-temporal groups of highly similar source mechanisms. By integrating these high-resolution, clustered focal mechanisms with local slip tendency analysis, and tracking their temporal evolution, we provide new insights into the local stress field and the specific fracture orientations activated under varying stimulation strategies. Ultimately, the temporal evolution of seismicity and fault plane solutions reveal how fluid preconditioning versus direct injection accommodates deformation in a complex fracture network, providing a critical mechanical baseline for future natural fault activation experiments.