

Session 3

TALKS:

Geosystemic Insights into Pre-Seismic Buildup: Evidence from Two Major Recent Earthquakes

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Two powerful recent earthquakes—the Mw 7.1 Wushi event (January 22, 2024) and Mw 7.7 Myanmar event (March 28, 2025)—serve as testbeds for a geosystemic framework examining the earthquake preparation stage. We integrate observations from lithosphere, atmosphere, and ionosphere within the Dobrovolsky preparation zone, combining multi-year lithospheric trends with days-to-months atmospheric and ionospheric perturbations ahead of the ruptures. For Wushi, roughly 60 signals emerge, featuring year-long lithospheric shifts alongside three-month atmospheric/ionospheric effects, including outgoing longwave radiation spikes from four days before to four days after the mainshock. The Myanmar case employs eleven precursor categories revealing a signature S-shaped temporal progression indicative of critical failure, reinforced by their spatial clustering consistent with lithosphere-atmosphere-ionosphere coupling (LAIC). Swarm satellite observations highlight Y-component magnetic perturbations across 22 of 85 half-orbits up to eight days prior; duration-derived magnitude proxies estimate $M \approx 7.2$ (near the actual 7.7), while anomaly intensities show tight clustering hinting at a distinct seismic fingerprint. Overall, findings reveal (i) multi-parameter, multi-scale perturbations intensify via exponential or S-curve acceleration toward rupture, (ii) joint terrestrial-satellite data aids epicenter pinpointing, and (iii) magnetic and atmospheric satellite signals hold promise for short-term prediction models—pending wider validation for reliable deployment. This study is carried out within two projects: the Space It Up project funded by the Italian Space Agency, ASI, and the Ministry of University and Research, MUR, under contract n. 2024-5-E.0 - CUP n. I53D24000060005 and Limadou EXPO funded by the Italian Space Agency.

Physics-based simulations of seismicity along the San Andreas fault

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Seismicity along the San Andreas Fault is simulated using physics-based models and compared with observations from southern California. Using a simplified fault representation and a previously validated simulation algorithm, we generated a 100,000-year synthetic catalog containing approximately 2.9 million earthquakes with $M_w \geq 4.5$. The statistical and dynamical properties of the catalog, evaluated against the SCEDC catalog for the period 1960–2026, show good agreement in terms of magnitude distribution and spatiotemporal seismicity patterns. Remaining discrepancies are mainly attributed to the simplified fault representation and the neglect of minor seismogenic sources. We then applied a stacking technique to both real and simulated datasets to investigate temporal variations of seismic parameters before and after earthquakes exceeding selected magnitude thresholds (“pivot” events). In the long-term behavior of the simulated catalog, the average stress on the fault plane increases while its variability decreases prior to pivot events, accompanied by an increase in clustered seismicity. A notable feature observed in both datasets is a significant decrease in the b-value in the days preceding pivot events. These results highlight the potential of long-term physics-based simulations for interpreting natural seismicity patterns and exploring spatiotemporal variations associated with the preparation phase of large earthquakes along the San Andreas Fault.

Scaling of seismic and aseismic moments of natural and induced earthquakes

L. Passarelli

An increasing amount of in-situ experimental evidence indicates that fluid injection under pressure can activate faults, producing not only conventional earthquakes but also aseismic slip. The coexistence of seismic and aseismic slip can be interpreted through a fault pressurization process that promotes the initiation of aseismic rupture. As these aseismic ruptures propagate, they generate stress concentrations at their tips, which in turn can induce seismic slip on brittle asperities. This conceptual framework has also been invoked to explain the behavior of shallow faults (depths < 10 km) observed during well-characterized slow slip events (SSEs). In particular, studies of SSEs in extensional and transform tectonic environments show a consistent power-law relationship between seismic and aseismic moment spanning multiple orders of magnitude. In this study, we extend the scaling relationships observed for crustal SSEs to include induced seismicity, in-situ experiments, and

laboratory-scale earthquakes. Our results demonstrate that this power-law scaling persists even for low-magnitude slow slip events, including those documented in laboratory settings. Nevertheless, a notable observational gap exists for SSEs within the magnitude range M_w 0–4. To investigate this, we performed numerical simulations of SSEs and their associated seismic activity by coupling a poroelastic framework with a stochastic earthquake model. The resulting distributions of seismic and aseismic moments are consistent with both natural and induced observations and follow the same scaling behavior. These findings reinforce the idea that stress perturbations generated by aseismic slip act as the main driver of seismic activity, while fluid pressurization along faults plays a key role in initiating aseismic slip. Additionally, variations in confining pressure provide an explanation for the depth-dependent differences in the relative contributions of aseismic and seismic slip. Overall, our results indicate that the mechanisms governing the transition from aseismic to seismic deformation under fluid pressurization are robust and consistent across scales, from laboratory experiments to natural fault systems.

Spontaneous complexity in the dynamics of slow laboratory earthquakes

G. Pozzi, G. Volpe, J. Taddeucci, M. Cocco, C. Marone, C. Collettini

Rock deformation experiments play a key role in our understanding of earthquake physics and friction constitutive laws. These laws commonly describe the response of analogue laboratory faults as a simple and homogeneous system, without accounting for the spatial-temporal evolution of structures in the sample. However, increasing experimental evidence suggests that slip instability is closely tied to heterogeneity, complex rheologies, and inhomogeneous boundary conditions. To address this, we designed a transparent setup to observe real-time deformation, track the spatial-temporal evolution of shear fabric, and document unstable slip in experimental faults. Our video documentation reveals that the progressive development of fault fabrics results in heterogeneous but not random stress redistribution. We show that stress and structural heterogeneities play a key role in the nucleation, propagation, and arrest of slip instabilities, raising questions about the robustness of scaling laboratory frictional laws to nature.

Laboratory fluid injections reveal fault structure controls on slip behavior

S. Aretusini, C. Cornelio, E. Spagnuolo, and M. Cocco

The growing demand for low-emission energy has intensified underground fluid injection activities, which can alter rock stress states and induce fault slip. The slip style - seismic or aseismic - critically influences associated hazards. We conducted laboratory fluid injection experiments on natural fault materials from the Bedretto Underground Laboratory, comparing gouge-filled faults and bare-rock fractures under realistic stress conditions. Our results reveal that fault structure governs slip behavior: fractures exhibit sudden slip at lower stresses, while gouge-filled faults undergo creep followed by slip at higher stresses. Fault dilation modulates these differences by delaying slip onset in gouge-filled faults and promoting progressive slip acceleration. Numerical modeling informed by experiments suggests that bare-rock contacts are prone to dynamic slip nucleation, whereas gouges favor stable slip. These findings highlight the need to consider fault heterogeneity and hydraulic properties when assessing seismic risks from fluid injections.

Time delay neural networks reveal pressure-independent fault rupture processes in laboratory acoustic emission

T. King, and S. Vinciguerra

Fault nucleation and growth are central to earthquake hazard. Here we analyse fault development in Alzo granite under triaxial confining pressures of 5–40 MPa using a time-delay neural network applied to multi-parameter acoustic-emission data. The model integrates waveform attributes (peak delay, scattering) with occurrence metrics (event rates, Gutenberg–Richter b-value, spatial fractal dimension) to track the transition from distributed microcracking to localised faulting. Genetic algorithms optimise the network, which dynamically weights parameters to characterise fault growth. We find three phases consistent across pressures: microcrack nucleation marked by scattering changes; fault growth captured by evolving spatial and magnitude distributions; and coalescence with rapid peak delay increases and b-value change. The model predicts stress-drop timing and size across pressures and failure mechanisms, from axial splitting to shear localisation, linking waveform features to physically interpretable phases of deformation.

POSTERS:

Mineralogical control on fluid induced fault slip behavior: frictional healing vs velocity dependence of friction

Coppola L., Volpe G., Giorgetti C., Pozzi G., Wibberley C., Bourgeois F., Collettini C.

Fluid-induced fault reactivation and associated seismicity is a critical process in reservoir exploitation and emerging geo-energy activities such as Enhanced Geothermal Systems (EGS), wastewater disposal and Carbon Capture and Storage (CCS). During fluid injection, the fault stress state progressively approaches the failure criterion $\tau = (\sigma_n - Pf)\mu + C$, where τ is shear stress, σ_n normal stress, Pf fluid pressure, μ friction, and C cohesion. Once the stress state reaches the failure envelope, faults may reactivate either seismically or aseismically. However, the mechanisms governing aseismic versus seismic fault reactivation during fluid injection remain debated. Previous laboratory studies suggest that this seismic vs. aseismic deformation may be influenced by fault frictional properties influenced by mineralogy, fault zone structure, stress state, and injection rate, yet the relative contribution of these factors remains unclear. To address this issue, we present an experimental study on binary and ternary fault gouges with variable fractions of quartz, calcite, and illite. These are minerals commonly found along fault zones including foredeep deposits often exploited for geo-energy applications. For each mineralogical composition, two experimental datasets were acquired in a double direct shear configuration. In the first dataset, we used slide–hold–slide and velocity-step tests to measure friction, frictional healing and the velocity dependence of friction. In the second dataset, we investigated fault slip behavior during fluid-pressure-induced reactivation at three different stress states. The frictional properties reveal a pronounced contrast between granular and platy phyllosilicate-rich gouges. Granular materials exhibit high friction ($\mu \approx 0.6$), positive frictional healing, and low a – b values that tend to become negative at higher sliding velocities, indicating velocity-weakening and potentially seismogenic behavior. In contrast, illite-rich gouges (illite > 40%) display low friction ($0.28 < \mu < 0.4$), low to negative healing, and strongly positive a – b values, indicative of velocity-strengthening and aseismic behavior. During fluid injection induced-reattivation, granular-rich gouges reactivate through an exponential increase in slip velocity, mimicking seismic-like instability. Conversely, illite-rich gouges reactivate through aseismic but accelerated creep that does not evolve into dynamic failure. Notably, reactivation in granular gouges is abrupt and occurs at stress states well above the predicted failure envelope, whereas in illite-rich gouges reactivation is gradual and occurs at or before the predicted failure envelope. In addition, at

constant illite content, quartz-rich gouges reactivate faster than calcite-rich fault gouges. The integration of these results suggests a conceptual framework in which fluid-induced fault reactivation is governed by the interplay between frictional healing and rate dependence, with mineralogy exerting a first-order control. In granular gouges, strong healing dominates the fluid induced reactivation process, leading to delayed but abrupt fault reactivation that can overcome the stabilizing slight rate-strengthening effect, promoting an exponential acceleration under fluid pressurization. In contrast, in phyllosilicate-rich gouges, weak or negative healing combined with a marked rate strengthening behavior stabilizes slip, favoring continuous aseismic creep. This framework demonstrates that the balance between healing and rate dependence, strongly linked to fault mineralogy, governs whether fluid-induced fault reactivation produces seismic slip or aseismic creep.

Frictional properties and fluid-induced reactivation of fault rocks from a granitic EGS reservoir

S. Woo, G. Volpe, L. Coppola, C. Collettini, M. Son

In 2017, an MW 5.5 earthquake struck the Pohang region, representing the most damaging seismic event in South Korea, and has been linked in previous studies to hydraulic stimulation at the Pohang Enhanced Geothermal System (EGS) site. However, the relative roles of fluid injection, imposed stress state and fault-zone structure in nucleating this event remain a matter of debate, and the laboratory results presented here are intended to illuminate one mechanically plausible scenario rather than provide a unique causal explanation. Despite the scientific and societal importance of this earthquake, the frictional properties of rocks from the Pohang system are still poorly constrained. Here we experimentally characterize the frictional properties and slip behavior during fluid-induced reactivation of granodiorite wall rock powder and fault gouge recovered from the Pohang PX-2 borehole (~3.8 km depth). We first assessed the mineralogical assemblages of the two fault materials, which consist of mixtures of quartz, K-feldspar, plagioclase and phyllosilicates (mostly chlorite), with phyllosilicate contents varying between 15% and 23% for the wall rock and the fault gouge, respectively. We then measured friction, healing rate and the velocity dependence of friction for both materials under water-saturated conditions at normal stresses of 20–100 MPa using the BRAVA apparatus hosted at the National Institute of Geophysics and Volcanology (INGV). We performed frictional experiments in a double-direct-shear configuration, using a protocol consisting of a run-in at 10 $\mu\text{m/s}$, slide-hold-slide tests (SHS; hold times ranging between 3 and 3000 s), velocity-stepping

tests (VS; velocities ranging between 0.3 and 300 $\mu\text{m/s}$), and fluid-injection tests (pore-pressure increases of 0.25 MPa every 5 min). Steady-state friction coefficients for both materials fall within the Byerlee range ($\mu \approx 0.55\text{--}0.62$). SHS tests reveal that both fault gouge and wall rock exhibit relatively high healing, with β in the range $\approx 0.0046\text{--}0.0092$. Conversely, velocity-stepping tests reveal that, over the tested stress and velocity range, the wall rock has a slightly velocity-weakening to neutral behavior ($a-b = -0.0007$ to 0.0020), while fault gouge is predominantly velocity-neutral to strengthening ($a-b = 0.0005$ to 0.0028). Additional fluid-injection experiments indicate that, despite these slight differences in frictional properties, both the fault gouge and the wall rock can be reactivated under elevated pore pressure, with slip accelerating from creep to millimetre-per-second rates. Accompanying microstructural observations will examine whether differences in grain-size reduction, shear localization, or porosity evolution account for the similar reactivation behavior despite the slightly contrasting frictional properties. Overall, these measurements will help quantify how lithological heterogeneity, rate-and-state parameters, and pore-pressure evolution govern slip stability and the nucleation potential of injection-induced earthquakes in geothermal settings, with important implications for induced-seismicity hazard assessment in granitic EGS reservoirs.

Understanding temporal changes in crustal dv/v : Isolating episodic hydrological signatures in California's Central Valley

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While relative seismic velocity changes (dv/v) have been used as indicators of crustal strain and post-seismic recovery, deciphering and accurately associating precursory signals remains a challenge in active tectonics. To better understand how transient phenomena impact seismic velocities, we adopt a hydrological framework to explore how aquifers respond to intense and sudden hydrological loading as a proxy for broader crustal mechanics. The 2022-2023 atmospheric rivers (ARs) resulted in intense precipitation across California. Over a 3-month period, 332mm poured over Central California, acting as a transient hydrologic perturbation offering a new opportunity to study the crustal response to rapid hydrological loading. Recent developments in coda wave interferometry using ambient seismic noise have demonstrated their ability to capture seasonal variations in aquifers with high temporal resolution. We use continuous waveform data from the Northern California Earthquake Data Center (NCEDC), focusing on 12 three-component broadband seismometers across the Southern Central Valley of California. We compute daily ambient noise cross-correlation functions to monitor relative seismic velocity changes reflecting changes in elastic properties from

2021 to early 2026. Using the moving-window cross-spectral (MWCS) method on coda waves band-passed between 0.1 Hz and 0.9 Hz, our preliminary results suggest a distinct dv/v signature associated with the early 2023 events. We observe a maximum relative velocity decrease of approximately 0.1% following the onset of the ARs. This transient drop is consistent with increased pore pressure and episodic surface loading. To investigate the underlying mechanisms, we invert for seasonal parameters characterizing the pre-Tulare flood period, post-Tulare flood period and the Tulare flood period. Our work represents a first step towards separating elastic versus poroelastic effects in the shallow crust in the Central Valley using seismic data.