Session 2

TALKS:

Toward a comprehensive seismotectonic model of the central Apennines (Italy): lessons learned by the last major seismic sequences and implications for seismic hazard assessment

Buttinelli M., Maesano F.E., Maffucci R., Vico G., Anselmi M., Fonzetti R., Chiarabba C., Valoroso L., De Gori P., Villani F., Improta L., Tiberti M.M., Basili R., Mariucci M.T., Montone P., Mazzarini F., Gabrielli S., Akinci A., Artale Harris P.

The central Apennines (Italy) represent one of the highest seismic hazard areas in the central Mediterranean, characterized by large mainshock-aftershock seismic sequences and a marked geological and structural complexity.

In recent decades, the inner portion of the central Apennine chain has been affected by multiple mainshock-aftershock seismic sequences characterized by several magnitude 6+ events with normal-faulting kinematics related to active post-orogenic extension (e.g., the 1997 Umbria-Marche, 2009 L'Aquila-Campotosto, and 2016-2017 Amatrice-Visso-Norcia-Campotosto events).

The dense INGV seismic network carefully monitors those areas' diffuse seismicity and other moderate magnitude seismic sequences.

The geological and geophysical community has gained significant expertise over the past 30 years across these three major sequence areas, thanks to the increased availability of surface and subsurface geological data (e.g., geological maps, seismic profiles, structural maps, deep exploration wells, and gravimetric data), as well as a vast and ever-growing earthquake catalogs. The improvement of dense seismic networks for building high-precision/resolution seismic catalogues (recently also AI based) and high-resolution tomographic and attenuation images of the crust, as well as the enhanced computational power for creating geological models, performing gravimetric inversions, and 2D/3D high-frequency ground motions simulations, pushed the advance in the knowledge of the subsurface setting of those areas.

This contribution presents a synthetic geological and seismotectonic model of the upper crust across an area of about 300 x 100 km2 along the NW-SE direction of the chain down to 15-20 km of depth, affected by those three sequences. The model has been developed to honor as much as possible the large amount of geological and geophysical observations by gathering updated geological and

geophysical data, techniques, and approaches. This unleashes the possibility of making new, robust inferences regarding the relationship between large seismogenic faults and the observed seismicity. The synoptic view of this large portion of the Apennine crust experiencing such a complex seismic behaviour highlights striking similarities among the last three seismic sequences.
The common thread in present-day seismogenesis is the role played by the reactivation and interaction between inherited structures, such as large thrust and normal faults, under the current extensional stress field, which may lie behind the more energetic seismic sequences.
The main thrusts in the chain interior promoted the large-scale segmentation and vertical extent of the currently active faults. Nowadays, the entire complex system responds to post-orogenic extension, and crustal fluids trapped between thrusts, acting as mechanical and rheological barriers, also control the energy and behavior of most large seismic events. Such a comprehensive view denotes the central Apennines' peculiar and broad seismogenic character, with important implications for a deeper reassessment of the region’s seismotectonics and seismic hazard.

Global modulation of stress and seismicity in subduction interfaces by surface loads

Yiting Cai, Roland Bürgmann, Eva Boergens, Maxime Mouyen, Kristel Chanard, Karine Le Bail

Surface mass redistribution from hydrological, oceanic, and atmospheric processes constantly deforms the solid Earth, generating stress perturbations that can influence seismicity. Such surface loads provide a natural probe of fault sensitivity to modest stress perturbations, offering insight into the conditions under which earthquakes may be encouraged or suppressed. In subduction zones, where the largest earthquakes and associated cascading hazards occur, the role of these external loads remains insufficiently understood.
We examine how time-varying surface loads modulate the background tectonic stress field and earthquake occurrence across global subduction margins within the upper 50~km. Using satellite gravimetry–derived mass variations, we compute load-induced stress changes at depth and project these stress changes into the principal tectonic stress orientations inferred from global focal mechanisms. This framework allows us to identify when loading-induced stresses align with or counteract the tectonic stress field, potentially promoting or inhibiting fault failure.
We observe systematic, region-dependent variations in seismic response to surface-loading stress perturbations. Peak-to-peak amplitudes of maximum principal stress changes reach 1–4~kPa, with the largest variations associated with near-vertical components. Normal-faulting-dominated slabs show the strongest seismic modulation, with earthquake rates changing by approximately $-

10$\%/kPa, strike-slip-dominated regions by -3\%/kPa, and thrust-faulting-dominated regions generally less than 2\%/kPa. At the subduction-zone scale, some regions such as Halmahera, Makran, New Guinea, and Izu–Bonin exhibit 3–22\% increases in seismicity per kPa decrease in stress, whereas the Caribbean, Pamir, Philippines, South America, and Vanuatu show 5–17\% increases under increasing stress. These results indicate that modest but persistent periodic stresses from surface mass redistribution can measurably modulate earthquake occurrence, highlighting the role of surface loading in subduction-zone dynamics.

Is the Seismic Cycle of the 2001 Bhuj Earthquake Characteristic?

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Twenty-five years after the devastating Mw 7.6 2001 Bhuj earthquake, the mechanisms of this intraplate earthquake remain elusive. The Characteristic Earthquake (CE) hypothesis1 posits that if geometric, stress, and rheological conditions evolve slowly relative to the seismic cycle, fault segments generate earthquakes of similar size and slip distribution over time. We redefine the CE not as identical deterministic replicas of the same rupture2, but as a conditional probability distribution of scenarios sharing geometric and kinematic characteristics3. Consequently, deviations between coseismic ruptures and long-term geological records may serve as diagnostic tools, signaling incomplete representations of source geometry or rheology, or that the long-term record aggregates, in addition to non-tectonic processes, different rupture modes beyond the one observed. We revisit the Bhuj seismotectonics by integrating newly documented paleo-shorelines with a reprocessing of coseismic InSAR and leveling data. While satellite geodesy captures the short-term snapshot4,5, the geology captures the long-term integral6,7, thus, the core of this research lies in reconciling these two distinct projections of the same mechanical reality.

To bridge the gap between the seconds of a rupture and the hundreds of thousands of years of paleo-geodesy, we employ a joint bayesian inversion to parameterize a seismogenic source that satisfies coseismic observations and cumulative deformation. We assume 1) viscoelastic relaxation operates at longer spatial wavelengths than localized upper-crustal deformation, preserving near-field paleogeodetic signals, and 2) spatially uniform climatic forcing, ensuring differential topography reflects tectonic uplift rather than variable erosion.

We test the end-member scenarios where long-term deformation equals the cumulative effect of multiple CE. Here, a mismatch quantifies processes often overlooked in elastic models: aseismic creep, viscoelastic transients, or structural evolution8. Through a refined characterization of the 2001 Bhuj seismogenic source, we propose a new layer of knowledge to the understanding of the seismic cycle.

Conjugate faulting and rapid seismic deformation of Gorda intraplate faults

B. Rong, W. Zhu, and R. Burgmann

The Gorda plate (GP) in the Mendocino triple junction (MTJ) is critical to understand tectonic deformation and seismic hazard assessment at unstable triple junctions. However, earthquake processes and faulting behavior associated with Gorda intraplate deformation remain poorly understood. Here, we construct a high-resolution earthquake catalog from 2000 to 2024 using machine-learning-based detection. We identify conjugate intraplate faults striking northwest-southeast and northeast-southwest, along with swarm-like earthquake clusters in the Gorda crust. Combined with seismic moment tensor data, these observations constrain Gorda intraplate deformation, indicating an average north-south seismic shortening rate of ~ 8.0 mm/yr. Our results reveal previously unrecognized complexity in intraplate fault systems and highlight the important role of Gorda intraplate faults in accommodating active deformation in the MTJ.

Seismic CO_2 pressurization sustains dynamic slip in carbonate faults

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Earthquake faults in carbonate rocks exhibit a long-standing paradox: they sustain large coseismic slip despite their high frictional strength. Among proposed dynamic weakening mechanisms, shear heating-induced decarbonation has been suggested to generate transient CO_2 overpressure, yet its magnitude and mechanical role remain poorly constrained. Here, we investigate natural carbonate faults from the seismogenic Apennines (Italy) by integrating nano-scale observations of fault surfaces

with mineralogical and stable isotope analyses. These data reveal microdomains of seismic decarbonation along principal slip surfaces, characterized by vesicles, pores, and decarbonation trails consistent with high-temperature shear processes. We combine these observations with a stoichiometric–thermodynamic model to quantify the mass and pressure of CO_2 produced during earthquakes. Our results indicate that Mw 5.9–6.5 events can generate up to ~12 tons of CO_2, producing quasi-lithostatic pressures (~196 MPa) under undrained conditions and supra-hydrostatic pressures (up to ~134 MPa) under drained conditions. We propose that seismic CO_2 pressurization evolves dynamically during slip, from an initial undrained stage promoting near-lithostatic conditions and strong weakening, to a partially drained regime where CO_2 escape maintains a pressurized fault environment. This process provides a physically consistent mechanism for sustained dynamic weakening and may contribute to rupture propagation and earthquake destructiveness in carbonate terrains.

Impacts of hydrothermal alteration and preexisting structures on earthquake hazards

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The nucleation and propagation of earthquake ruptures and seismic waves are influenced by the properties of fault zone rocks and fluids. Hydrothermal alteration impacts both the frictional properties of fault surfaces and the bulk elastic properties of the surrounding damage zone. In this study, we leverage geodetic, field, and laboratory observations to investigate how hydrothermal alteration influences slip and off-fault deformation in distributed fault systems across eastern California. Our study finds that fault zones with propylitic and advanced silicic alteration are stiff and strong, whereas phyllic alteration zones are compliant and weak, and that these properties correlate with patterns of coseismic surface slip. Thus, variations in hydrothermal alteration resulting from past and ongoing fluid–rock interaction may influence earthquake dynamics and seismic hazards today.

POSTERS:

Linking Stress Drop and Slip Heterogeneity to Assess Source Rupture Directivity for Earthquakes in Central Italy

Cirella A., Calderoni G., and Akinci A.

Our study provides new insights into finite-fault rupture processes by quantitatively linking key physical parameters—such as slip heterogeneity, stress-drop distribution, and rupture directivity—to better understand this complex phenomenon. As a case study, we demonstrate how source complexity, characterized by estimated rupture parameters, influences high-frequency radiation and ground shaking through the analysis of the 2009 L'Aquila earthquake and the 2016 Amatrice–Visso–Norcia sequence in Central Italy. The results have important implications for improving ground-motion prediction, seismic hazard assessment, and source modelling methodologies, particularly in complex fault systems.

Specifically, we investigate the relationship between Brune stress drop and fault slip, where stress drop is estimated using the Empirical Green's Function method and slip distribution is derived from joint inversion of seismic and geodetic data. We further explore correlations between stress drop and several rupture parameters, including rupture velocity, asperity distribution and strength, and hypocentral location. We assess how these factors influence both the occurrence of rupture directivity and its spatial variability along the fault. Our results indicate that large-slip patches are associated with significant ground-motion amplification, pronounced rupture directivity, and higher stress drop in near-source regions. These findings contribute to improving ground-motion prediction in areas where complex source effects play a critical role.

Seismicity and Vp and Vp/Vs models around the Mefite d'Ansanto deep-CO2 degassing site (Southern Apennines, Italy)

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Mantle-derived fluids play a primary role in the generation of large upper crustal earthquakes in extensional domains. Here, we focus on the Mefite d'Ansanto degassing site, the largest low-temperature non-volcanic deep-CO2 emission site in the world (about 2000 tons per day), located at the northern tip of the Mw6.9 1980 Irpinia faults in the Southern Apennines (Italy). The area, characterized by high heat flow and pervasive CO2 rich fluids circulation, experienced strong historical earthquakes (M6+), but it is associated with low background seismic rate. To investigate this key-sector of the Southern Apennines, we collected high-quality microseismicity data during a two-year dense passive survey (May 2021 to May 2023), integrating 10 temporary stations with 39 permanent stations of the INGV and ISNet (Irpinia Near Fault observatory) network.
We used 360 manually-picked earthquakes to apply a template-matching algorithm to detect low-magnitude seismicity. We computed 1D earthquake locations with the probabilistic location method NonLinLoc, using an ad-hoc best fit 1D Vp velocity model. The final catalog is composed of 1428 earthquakes ($-0.7 < ML < 3.0$). Most of the seismicity has small magnitude ($ML<1$), confirming the low seismic rate of the area and occurs in small clusters (sometimes along small faults) characterized by either short-lived or sustained seismic activity. We also computed new 3D Vp, Vs and Vp/Vs models using local earthquake tomography (LET). The combined interpretation of Vp and Vp/Vs velocity model, seismicity distribution, full moment tensor solutions (i.e., double-couple vs non-double-couple component) and shear-wave splitting analysis helped us to investigate the relationship between seismicity, crustal velocity structure and fluid pressure in this crucial sector of the Southern Apennines seismic belt.

Normal fault interactions through the seismic cycle of the Italian Apennines

C. Rodriguez Piceda, Z. Mildon, B. J. Andrews, Y. Yin, J-P. Ampuero, C. Sgambato and M. van den Ende

Understanding the mechanisms responsible for variable earthquake recurrence intervals and magnitudes is important for probabilistic and time-dependent seismic hazard assessments. These characteristics of the seismic cycle are influenced by stress interactions between nearby faults, as tectonic stress gradually accumulates and is episodically released during earthquakes, followed by static stress redistribution across the fault network (e.g., Harris & Simpson, 1998). These stress changes can be either static, known as Coulomb stress transfer (CST), or dynamic, associated with seismic wave propagation. As a result, nearby ‘receiver’ faults may experience either an increase or decrease in stress depending on their position relative to the source fault, affecting the recurrence and magnitude of earthquakes on the receiver fault.

Here, we investigate how fault network geometry, specifically whether faults are spatially arranged predominantly along-strike or across-strike, influence earthquake recurrence rates and magnitudes. Based on field observations and modelling simplified geometrical relationships, we expect fault networks with multiple across-strike interactions to exhibit more complex seismic sequences, less periodic recurrence intervals, and larger rupture extents, resulting in greater moment magnitude (Mw) variability, compared to networks with fewer across-strike interactions.

To test this hypothesis, we performed numerical simulations of sequences of earthquakes and aseismic slip (SEAS) on two fault networks in the Italian Apennines, which share similar post-Neogene geological background but differ markedly in fault geometry. The Central Apennines are characterized by a wide fault network with multiple normal faults arranged across-strike, whereas in the Southern Apennines, deformation is accommodated by fewer faults that are predominantly arranged along-strike.

The simulations of isolated faults generate periodic cycles dominated by full-rupture events with characteristic magnitudes. In contrast, faults within a fault network show more complex behaviour, with slip modes including full and partial seismic ruptures, as well as slow-slip events. The seismic cycles vary across the different fault networks as a consequence of the fault network geometry. In the Central Apennines, seismic events from multiple across-strike faults create stress heterogeneities on nearby faults, promoting conditions for the development of partial ruptures, greater magnitude variability and less periodic sequences compared to the Southern Apennines. Conversely, faults in the Southern Apennines features fewer across-strike interactions and thus experience more homogeneous stress loading. This leads to a greater proportion of full ruptures and more periodic recurrence times when compared to the Central Apennines. Furthermore, the effects of fault interactions in both fault networks are amplified by how fast a fault is slipping, with faults with higher tectonic slip-rate being more sensitive to stress perturbations compared to slower-moving faults.

A deep-learning-enhanced earthquake catalog for Italy: implications for earthquake and faulting behavior

B. Rong, J. Song, W. Zhu, C. Giunchi, S. Cianetti, A. Michelini, and R. Allen

Microseismicity provides important insights into fault geometries at seismogenic depths, and its spatiotemporal characteristics can provide constraints on the mechanics of earthquake nucleation and rupture. The detection of small earthquakes, though challenging due to their weak seismic signals, has been greatly advanced by the development of deep-learning (DL) methods, which have been successfully applied in a wide range of tectonic settings. In Italy, the complex network of active faults and dense seismic networks highlight the necessity and opportunity for an enhanced earthquake catalog with temporal continuity. Here, we present a DL-based enhanced earthquake catalog of Italy utilizing continuous seismic data from National Institute of Geophysics and Volcanology (INGV). Our earthquake detection workflow, QuakeFlow, includes phase picking, phase association, absolute location, and cross-correlation-based relative relocation. Compared with the routine catalog, our catalog substantially increases the number of detected earthquakes and lowers the magnitude of completeness. The enhanced view of microseismicity across Italy delineates active fault structures in detail, particularly in the central Apennines. The improved spatial and temporal resolution of seismicity will advance our understanding of fault mechanics, earthquake interactions, and foreshock-aftershock behavior.

Effect of Site Corrections on Source-Parameter Estimation in the Ridgecrest Stress Drop Validation Study

A. Attolico, P. De Gori, M. Anselmi, F. Pio Lucente, and E. Tinti

We present a preliminary benchmark of the spectral-fitting method proposed by De Gori et al. 2023 within the SCEC/USGS Community Stress Drop Validation Study, using the Ridgecrest dataset distributed to enable comparison across methods. The Community Study was designed to compare source-parameter estimates in order to understand methodological variability and improve the reliability of spectral stress-drop measurements. At this stage, source parameters are estimated by fitting uncorrected displacement spectra and compared with estimates obtained after applying site-response corrections. The approach proposed by De Gori et al. (2023) is specifically designed to mitigate the trade-off among attenuation, site effects, and source parameters. This is particularly important for the corner frequency, which strongly controls stress-drop estimates. Our preliminary results show that applying the site correction improves the spectral fit and leads to a more stable and reliable estimate of corner frequency and related source parameters. The comparison between uncorrected and site-corrected spectra highlights the importance of properly accounting for local site effects in spectral analyses, especially for small to moderate earthquakes. These preliminary results represent an initial step toward a full benchmark of the method on the Ridgecrest validation dataset and toward a broader assessment of how correction strategies affect the robustness of source-parameter estimation.