Session 2

Studying the Viability of Kinematic Rupture Models and Source Time Functions with Dynamic Constraints

M.E.Locchi[1], F.Mosconi[1], M.Supino[2], E.Casarotti[2], E.Tinti[1,2]

[1] *La Sapienza University of Rome, Italy;*

[2] *Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy;*

Earthquake is one of the greatest natural hazards and, a better understanding of the physical processes causing earthquake ruptures is required for appropriate seismic hazard assessment. Kinematic modelling is a standard tool to provide important information on the complexity of the earthquake rupture process and for making inferences on earthquake mechanics. Despite recent advances, it has been documented that, for the same earthquake, source models obtained with different methodologies can exhibit significant discrepancies in terms of slip distribution, fault planes geometry and rupture time evolution.

Prescribing the slip velocity on extended faults is one of the crucial components in the models because it contains key information about the dynamics. However, in kinematic inversions this function is assumed a-priori using different shapes, although functions compatible with rupture dynamics should be preferred. To investigate the effect of the slip velocity function on the ground motion and the inverted slip history, we run a series of forward and inverse models. We generate spontaneous dynamic models and use their ground motion as real events and we invert the data with kinematic models. Kinematic inversions have been conducted utilizing both single-time and multi-time windowing and to investigate the uncertainties we adopt four different source time functions.

In this way we examine how the slip velocity function influences the slip distribution on the fault plane and if the inferred kinematic parameters are consistent with the dynamic models. We also examine the variability of PGV from synthetic seismograms up to 1 Hz, obtained with forward models assuming the same slip distribution, rise time and rupture velocity, but changing the source time functions (i.e. box, triangular, regularized-yoffe and exponential). Those results provide a glimpse of the variability that kinematic slip velocity functions might have when used as a constraint to model the earthquake dynamics.

Fault reactivation by fluid injection: insights from laboratory friction experiments with multiple reactivation sequences

Stefano Aretusini, Chiara Cornelio, Giuseppe Volpe, Giacomo Pozzi, Elena Spagnuolo, Giulio Di Toro, Cristiano Collettini, Men-Andrin Meier, and Massimo Cocco

Faults can be reactivated by fluid injection and pore pressure increase in the rock volumes surrounding the fault zone. Induced earthquakes represent only one of the possible responses of active faults to pore pressure perturbations, since other strain transients characterize the spectrum of fault-slip behavior. A series of fluid injection experiments, designed and undertaken in the framework of the ERC Fault Activation and Earthquake Ruptures (FEAR) project, will be conducted in the Bedretto Underground Laboratory for Geosciences and Geoenergies (BULGG, Switzerland) to understand fault reactivation processes on a target well-identified fault zone. Small and accessible faults are to be instrumented to monitor deformation and seismicity during both fluid injection and fault reactivation.

The mineralogical, microstructural, and hydraulic properties of the target fault zone are investigated to characterize the fault-slip behavior. Characterization of the frictional response is achieved through a suite of laboratory rock-deformation experiments using both double-direct and rotary experimental apparatuses. Fault stimulation by fluid pressurization was also simulated in the laboratory by using an injection protocol reliable for the in-situ hydraulic stimulation and consisting of stepwise pore fluid pressure increase. Experiments undertaken at low velocity with the double-direct apparatus (BRAVA) suggest that the selected fault, composed of mixed phyllosilicate-granular materials, is frictionally stable but yet can be dynamically reactivated by hydraulic stimulation.

Experiments were also performed on the fault gouge from the target fault with the rotary experimental apparatus (SHIVA). First, we apply half of the stresses measured at depth in the underground laboratory to accomplish the operating capability of the apparatus: 12 MPa normal stress, 7.5 MPa confining pressure and 1.5 MPa pore fluid pressure. Second, we imposed a slip rate of 10^{-5} m/s for 0.01 m to have an equally compacted and textured layer. Third, we applied a shear stress so that an equivalent slip tendency of 0.35 is achieved (ca. 2.7 MPa), and kept it constant. We then increased stepwise the pore fluid pressure by 0.1 MPa every 150 s. This allows the spontaneous nucleation of slip events. After fault reactivation, the maximum slip velocity was set to 0.1 m/s. The fluid injection sequence results in a first reactivation (R1). Thanks to the nominally infinite slip available in SHIVA we run a second injection sequence up to a reactivation (R2).

Our experiments show two different styles of reactivation between R1 and R2. R1 reactivation is abrupt, with slip rate accelerating up to 0.1 m/s. Instead, R2 has a stage in which slip rate oscillates

(0.5-3 mm/s) just before the last step of pore pressure increase leads to acceleration to 0.1 m/s. This would suggest a role for the shear fabric developed during the first reactivation, in which extensive grain size reduction might have led to stiffening of the fault, responsible for the oscillatory slip. This frictional behavior suggests the importance of considering the effect of texture development during multiple cycles of seismic slip. The generalization of our data and observations will contribute to shed light on the mechanics of faults and induced earthquakes by fluid pressure increase.

Stress drop estimates for Italian earthquake sequences

G. Calderoni

Istituto Nazionale di Geofisica e Vulcanologia, INGV, Sezione di Roma, Roma, Italy.

Stress drop is a source parameter that is fundamental to understanding the mechanics of earthquake sources and rupture dynamics. However, it is subject to large and poorly controllable uncertainties, as it is difficult to remove the propagation effects of waves travelling from the earthquake to the seismometer from the recorded seismograms. Both the random and the systematic deviations between the studies are larger than the standard errors given by individual studies. Calderoni & Abercrombie (2023) observe significant uncertainties in stress drop estimates arising from various factors, such as the selection of magnitude catalog, frequency range, and width, as well as challenges in delineating source and path effects and balancing them against site effects. Additionally, assumptions made in simplified source models contribute to these uncertainties. The observed magnitude dependence of the stress drop varies across studies, with generalized inversions yielding the highest values and approaches based more on individual event yielding the lowest. The positive aspect of this problem is that the relative spectral estimates of stress drop between events are more consistent and the relative values are more reliable because different studies agree that a given earthquake has a relatively high or low stress drop. For these reasons, in this study I compare the stress drop estimates for some Italian earthquake sequences. The aim for this study is to interpret our results by taking into account the known geological structures and analyzing the possible role of fluid in seismogenic regions.

Joint earthquake source inversion method using P-wave spectra and focal mechanism solutions

Yifang Cheng,[1,2] Douglas S. Dreger,[1,2] Richard M. Allen[1,2]

[1] Department of Earth and Planetary Science, University of California, Berkeley, CA, USA

[2] Berkeley Seismological Laboratory, University of California, Berkeley, Berkeley, California, U.S.A.

Improving characterizations of small earthquake sources advances our understanding of fault structures and seismic mechanics. Traditional methods for determining focal mechanisms, stress drops, and rupture directivities are limited by ambiguities in nodal plane identification and the neglect of rupture directivity, which impedes in-depth analyses and comparisons between earthquakes of varying magnitudes. To address these challenges, we introduce an innovative adjoint source inversion method that integrates focal mechanism solutions with P-wave spectra. Initially, we determine the apparent P-wave corner frequencies for the target event by analyzing the source spectral ratio between the target event and its surrounding Empirical Green's Function (EGF) events. We then synthesize corner frequencies with all potential fault plane orientations derived from the focal mechanism solutions and select the optimal fault plane orientation and 3D rupture directivity that best correspond with the observed azimuthal variations of P-wave corner frequencies.

Validated using a synthetic dataset and 2634 M≥1.5 events around the Parkfield locked patch, our findings indicate significant unilateral rupture directivity in 88% of the earthquakes. Of these, 53% occur along the main fault with various dipping angles, and 47% exhibit high angle to the main fault with near-vertical dips. Events above the locked patch predominantly show NE dipping planes with SE directivity, while those below exhibit SW dipping with NW directivity, suggesting consistent earthquake rupture direction with the hanging wall's slip direction. Incorporating directivity effects, 84% of events exhibit larger corner frequency, indicating higher stress drops than those previously estimated without directivity corrections. The proposed method can help to solve unprecedented detailed spatiotemporal variation of small earthquake properties, including fault orientation, 3D rupture directivity, and stress drop, which offers new perspectives on fault geometry, kinematics, and dynamics.

Modeling 3D dynamic rupture and arrest of spontaneous fluid- induced microearthquake

Francesco Mosconi[1], Elisa Tinti[1,2], Emanuele Casarotti[2], Alice-Agnes Gabriel[3], Luca Dal Zilio[4], Antonio Pio Rinaldi[5] and Massimo Cocco[2]

[1]Università La Sapienza, Rome, Italy

[2]Istituto Nazionale Geofisica e Vulcanologia, Rome, Italy

[3]Scripps Institution of Oceanography, UC San Diego, La Jolla, CA 92093, USA

[4]Technical University of Munich, Germany

[4]ETH Zurich, Institute of Geophysics, Department of Earth Sciences, Switzerland

[5]Seismology and Geodynamics, Institute of Geophysics, Department of Earth Sciences, Swiss Federal Institute of Technology (ETH Zürich), Zürich, Switzerland

Understanding the dynamics of microearthquakes is a timely challenge to solve current paradoxes in earthquake mechanics, such as the stress drop and fracture energy scaling with seismic moment. Dynamic modelling of microearthquakes induced by fluid injection is also relevant for studying rupture propagation following a stimulated nucleation. The ERC-Synergy project FEAR (Fault Activation and Earthquake Ruptures) in the Bedretto Underground Laboratory (Swiss Alps) at approximately 1500m depth offers a unique opportunity to investigate fluid-induced micro- events on broadband seismic arrays. In this study, we leverage this opportunity to perform dynamic ruptures caused by fluid injection on a target pre-existing fault (50m x 50m), generating a Mw ≤ 1 seismic event. We conduct fully dynamic rupture simulations coupled with seismic wave propagation in 3D using a linear slip-weakening constitutive law, implemented on the supercomputer Leonardo (CINECA) with a multi-GPU distributed system.

Stress field and fault geometry are constrained by in-situ characterization, allowing us to minimize the a priori imposed parameters. We investigate the dynamics of rupture propagation and its arrest for a target $M_W < 1$ induced earthquake with spatially heterogeneous stress drops caused by pore pressure changes and different constitutive parameters (i.e., critical slip-weakening distance, D_C, dynamic friction). We explore different homogenous conditions of frictional parameters, and we show that the spontaneous arrest of a propagating rupture following a dynamic instability is possible in the modeled stress regime by assuming a high fault strength parameter S, that is high ratio between strength excess and dynamic stress drop characterizing the fault before injection. The arrest of rupture propagation in our modeled induced earthquakes depends on the heterogeneity of dynamic parameters caused by the spatially variable effective normal stress, which controls the on-fault spatial increment of fracture energy G_C. Furthermore, in faults with high S values (i.e., low rupturing potential), we find that even minor variations in D_C (from0.45 to

0.6 mm) have a substantial effect on the rupture propagation and on the ultimate size of the earthquakes. Our results show that modest variations of dynamic stress drop determine the rupture mode, distinguishing self-arresting from run-away ruptures. Studying dynamic interactions (stress transfer) among slipping points on the rupturing fault provides insights on the dynamic load and shear stress evolution at the crack tip. The inferred spatial dimension of the cohesive zone in our crack models is roughly ~0.3-0.4m, with a maximum slip of ~0.6cm. Finally, analyzing the radiated synthetic waveforms, we examine the differences in the high-frequency content of simulated waveforms between self-arresting and run-away earthquakes and provide an estimation of the source parameters obtained through the spectral inversion. This estimation is then compared with source parameters of the dynamic forward models.

Our results suggest that inferred for accelerating dynamic ruptures differ from those observed during rupture deceleration in a self-arresting earthquake caused by the spatial gradients of normal stress and pore-pressure. These results related to rupture arrest integrate those obtained with spatial variations of the initial stress, highlighting the role of the heterogeneities of stress drop and G_C.

Friction, Mineralogy, and Microstructures: how Complex is the Brittle Deformation of Faults?

G. Pozzi, G. Volpe, R. Ruggieri, M. Scuderi, T. Tesei, C. Marone, C. Collettini, M. Cocco

Faults accommodate most of the brittle deformation that occurs in the lithosphere. They are also the loci that generate and propagate seismic to aseismic slip. The rocks deforming inside the core of the faults are the main actors that control the modality of slip and thus their mechanical properties are a key subject of study that is carried out through experimental investigation. The most relevant mechanical property is friction, a parameter that commensurates the resistance to shear motion of the rocks. Nevertheless, friction is not an intrinsic, constant feature of the investigated materials. It is instead modulated by several attributes and external factors. For instance, the rate and state framework describes the sensitivity of friction to the sliding velocity, proving a successful theory to quantify the potential of the onset of seismic slip in natural faults. Several works have also demonstrated that the frictional properties of the same material can dramatically change as function of the fabric (the textural, geometrical attributes of the deforming rock).

It is therefore evident that brittle deformation of rocks cannot be assessed in isolation of the conditions at which the phenomenon is measured. To fully understand the complex bulk behaviour of a deforming rock we must investigate the interaction of several mechanisms that are active from the grain-scale up to the entire fault zone.

In this work we present the collection > 60 friction experiments performed on BRAVA biaxial apparatus (INGV, Italy), presented here by associating the analysis of mechanical data with the analysis of rock microstructures. This joined investigation highlights the mechanisms that control rock friction: cataclasis, crystal plasticity, pressure-solution, grain-boundary sliding, cementation, and indentation. We also show the emergence of complex slip behaviours (experimental fault stability) as function of the coexistence of processes with different timescales and explained by the spatial arrangement of the mineral phases in the fault core.

Our results shed light on the origin of the macroscopic frictional properties of fault rocks, stressing the fact that they are not a characterising property but rather the observable of a complex, dynamic, and highly non-linear system.

Source and spectral characteristics of ordinary and low-frequency earthquakes inferred from the probabilistic analysis of 10-year large data sets.

Mariano Supino

Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy.

We analyze two large data sets of 10 years (2009-2018) of ordinary earthquakes (OEs) detected in Italy by INGV and low-frequency earthquakes (LFEs) detected in Japan by JMA. We estimate the joint probability density function of seismic moment (M0) and corner frequency (fc) from S-wave displacement spectra. We use unfiltered signals and manually revised S-wave arrival times.

We estimate a wide range of moment magnitudes (Mw = 0-6 for OEs, 0.5-2.5 for LFEs) and observe a self-similar scaling between M0 and fc for both OEs and LFEs with a constant stress-drop of ~MPa and ~kPa, respectively. However, OE spectra show a constant corner frequency fc* ~10 Hz for Mw <~ 2.5. We refer fc* to the cut-off frequency of the medium anelastic attenuation, acting as a low-pass filter and producing an apparent corner frequency that does not scale with the earthquake source (M0).

Conversely, for the same Mw <~ 2.5, LFEs exhibit fc between 1 and 8 Hz that scale with M0, showing that their low-frequency content is a real source characteristic and not an apparent consequence of anelastic attenuation.

Finally, both OEs (for Mw <~ 2.5) and LFEs show a systematic underestimation of local magnitude when compared with moment magnitude, that we analytically explain as a consequence of anelastic attenuation (fc*) for OEs and of low stress-drop (~kPa) for LFEs.

Our method allows the use of raw earthquake waveforms to infer robust information both for monitoring purposes and for physical interpretations of the earthquake source in different tectonic settings and at different scales.

Fracture energy and breakdown work scaling with coseismic slip

Elisa Tinti[1,2], Massimo Cocco[2], Stefano Aretusini[1], Chiara Cornelio[1], Stefan B. Nielsen[3], Elena Spagnuolo[2], Paul Selvadurai[4], and Giulio Di Toro[5,2]

1. Dipartimento di Scienze della Terra, Università di Roma La Sapienza, Rome, Italy
2. Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy
3. Department of Earth Sciences, University of Durham, Durham, United Kingdom
4. ETH Zurich, Switzerland
5. Dipartimento di Geoscienze, Università di Padova

Geological observations reveal that earthquakes nucleate, propagate, and arrest in complex fault zones whose structural heterogeneity depends on the tectonic loading, geometry, lithology, rheology, presence of fluids, and strain localization processes. These fault zones can host a wide range of fault slip behaviors (e.g., creep, aseismic- and slow-slip events, afterslip, and earthquakes). This implies that the environment in which earthquakes occur is diverse, and that different physical and chemical processes can be involved during the coseismic dynamic rupture.

Earthquakes are generated by rupture propagation and slip within fault cores and dissipate the stored elastic and gravitational strain energy in fracture and frictional processes in the fault zone (from microscale - less than a millimeter - to macroscale - centimeters to kilometers) and in radiated seismic waves. Understanding this energy partitioning is fundamental in earthquake mechanics to describe dynamic fault weakening and causative rupture processes operating over different spatial and temporal scales.

The energy dissipated in earthquake rupture propagation is commonly called fracture energy (G) or breakdown work (Wb). Here we discuss these two parameters, and we review fracture energy estimates from seismological, modeling, geological, and experimental studies and show that fracture energy scales with fault slip and earthquake size. Our analysis confirms that seismological estimates of fracture energy and breakdown work are comparable and scale with seismic slip. The inferred scaling laws show modest deviations explained in terms of epistemic uncertainties. The original collection of fracture energy estimates from laboratory experiments confirms the scaling with slip over a slip range of more than 10 decades. Fracture energy associated with breaking of intact rocks is larger than for precut specimens and might suggest differences between the role of fracture and friction, or a different size of the rupture front zone. It is important to recall that fault products after deformation in the laboratory correspond to fault products observed in nature, and acoustic emissions recorded in the laboratory can be processed as seismic waves on a natural fault. We conclude that although material-dependent constant fracture energies are important at the microscale for fracturing grains of the fault zone, they are negligible with respect to the macroscale processes governing rupture propagation on natural faults.

In this study we discuss the scaling of fracture energy and breakdown work with slip, and we propose different interpretations relying on different processes characterizing complex fault zones.

Our results suggest that, for earthquake ruptures in natural faults, the estimates of G and Wb are consistent with a macroscale description of the causative processes.

Reconciling observations and results from laboratory experiments and numerical modeling with geological observations can be done, provided that we accept the evidence that earthquakes can occur in a variety of geological settings and fault zone structures governed by different physical and chemical processes.

How to cite: Tinti, E., Cocco, M., Aretusini, S., Cornelio, C., Nielsen, S. B., Spagnuolo, E., Selvadurai, P., and Di Toro, G.: Fracture energy and breakdown work scaling with coseismic slip, EGU General Assembly 2023, Vienna, Austria, 24–28 Apr 2023, EGU23-13506, https://doi.org/10.5194/egusphere-egu23-13506, 2023.