Physisical mechanisms at the origin of fluid overpressure-driven earthquakes

Candidate name: Michele
Candidate surname: Mauro
PhD Cycle: XXXIX
Curricuclum: Earth Science
Candidate e-mail: michele.mauro@uniroma1.it
Suggested internal supervisor: Marco M. Scuderi
Supervisor e-mail: marco.scuderi@uniroma1.it
Suggested internal co-supervisor: Carolina Giorgetti
Co-supervisor e-mail: carolina.giorgetti@uniroma1.it

1 State of the art

Earthquakes are amongst the most destructive and unpredictable phenomena on the planet. They can have a dramatic impact in terms of human and economic losses, as reminded us by the most recent catastrophic events, such as the Tōhoku 2011 (Mw 9.1, Japan), Norcia - Amatrice 2016 (Mwmax 6.5, Italy), Turkey and Syria 2023 (Mw 7.9). For this reason, improving our knowledge of this phenomenon is crucial and could bring enormous benefits to our society.

Earthquakes nucleate in the upper crust when an abrupt slip along pre-existing fault planes[1] occurs, releasing a large amount of elastic energy accumulated over the centuries during the slow movement of the tectonic plates. Fluids play a key role in earthquakes nucleation because they lubricate the fault and fluid pressure reduces the effective normal stress that holds the fault in place[2] promoting fault reactivation, as described by the Amontons/Coulomb theory:

$$\tau_f = \mu\,(\sigma_n - P_f) \tag{1}$$

Within this framework, a fault reactivates when it reaches a critical shear stress (τ_f) that depends on the coefficient of friction μ and the effective normal stress ($\sigma_n - P_f$) acting on the fault. In a graphical representation of Mohr Circles (fig.1), an increase in fluid pressure decreases the effective normal stress bringing the fault toward the stress state for reactivation.

Many studies have emphasized the importance of fluid overpressure in the mechanics of seismic faulting and the spectrum of fault slip behaviors. For example, slow earthquakes[3,4] represent transient phenomena between aseismic creep and regular earthquakes [5] and they are often associated with overpressurized fault portions.

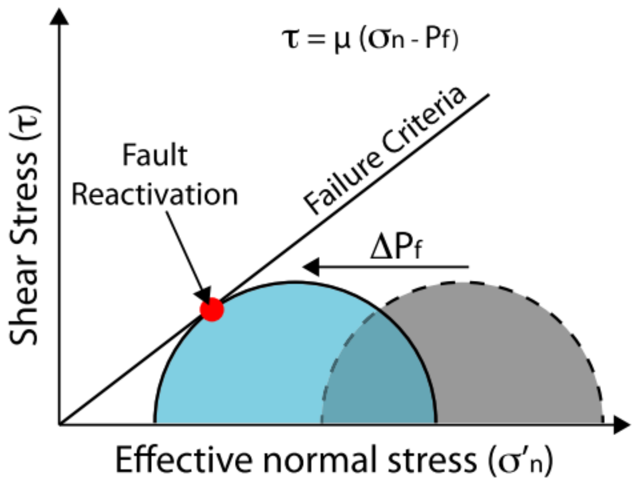

Figure 1: Effect of fluid pressure on fault reactivation visualized with Mohr Circles

In recent years, the phenomenon linked to fluid overpressure that has drawn the most attention has been that of induced seismicity[6]. In this case, earthquakes are triggered by anthropic activities (wastewater injection, geothermal energy, and CO2 storage) that induce fluid pressure increase along critically stressed faults[7,8], which can be reactivated following the mechanism described in equation 1. The sharp increase in seismicity in regions like the USA, (i.e. Oklahoma 2011[9]), highlights the societal and scientific challenges posed by this phenomenon and its impact on local communities (fig.2).

Nonetheless, fluid overpressure is not always closely related to seismicity, because it sometimes may promote aseismic creep[10], causing stress transfer with the potential of triggering earthquakes on nearby fault portions[11].

The constitutive equations of Rate-and State Friction (RSF) describe fault stability based on the velocity dependence of friction[12,13]. In particular, a necessary condition to nucleate an instability is the reduction in friction as the velocity increases (velocity weakening behavior). Combining elastic dislocation theory with RSF constitutive laws, frictional instability occurs if the elastic stiffness of the loading system, k, is smaller than a critical fault rheologic stiffness, k_c, defined by the effective normal stress and the frictional constitutive properties of the fault[14]:

$$k < k_c = \frac{(\sigma_n - P_f)(b-a)}{D_c} \tag{2}$$

where D_c is the critical slip distance and $(b-a)$ is the friction rate parameter. Equation 2 predicts that an increase in fluid pressure reduces k_c, favoring stable sliding rather than seismic behavior[15,16]. Therefore, this raises a paradox because is in contrast with Mohr-Coulomb theory (eq. 1) and with evidence of induced seismicity. This

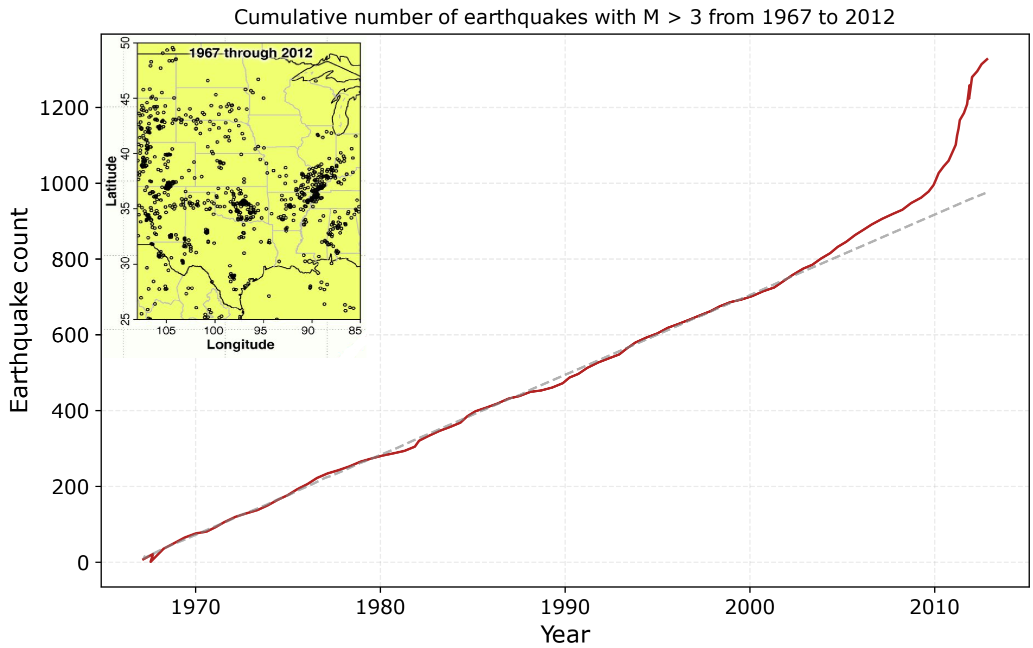

Figure 2: Sudden increase of the $M > 3$ events in the central states of the USA since the early 2000s associated with induced seismicity [7].

enigma arises due to a lack of understanding of the physical processes at the origin of the coupling between fluids and fault stability theory, besides an insufficiency of works in literature that measured frictional stability under overpressurized conditions.

Thus, characterizing the hydro-mechanical coupling between fault zone structure, frictional properties, and fluid flow (i.e., permeability, hydraulic diffusivity) is crucial to understand fluid-induced fault slip. Some works have shown the relevance of recording active waveforms during laboratory experiments because their signal variations can be used as a reliable precursory signal to failure[17] and as a powerful method to characterize the physical processes that govern friction at the microscale [18,19]. However, these processes are still poorly understood, therefore, knowing them can be a great step forward for earthquake mechanics.

2 Research goals

2.1 General objective

Improve our understanding of the physical and microphysical processes at the origin of the dichotomy between aseismic creep and earthquake nucleation.

2.2 Specific objective

- Empirical law to explain the relationship between fault reactivation and slip behavior (stable, unstable) simulating different fluid pressure conditions.
- Real-time tomography models to connect the mechanical properties and microphysical processes (contact mechanics) of fault gouges during the experiments.

3 Implications and applications

The set of experiments carried out will be useful to answer a series of questions to fill the gap of knowledge presented in the introduction:

characterizing RSF parameters for strong and weak minerals under high fluid pressures to understand how lithology can control fault behavior, to mitigate seismic hazard in specific conditions (wastewater injection, induced seismicity). Understanding the physics of these constitutive parameters through active waveform analysis can be useful to clarify the micro-physical processes that govern friction. This approach is essential to upscale the laboratory observations to natural seismicity, given the excellent correspondence between laboratory measurements and those in nature [17,21,22].

4 Work plan

This Ph.D. project aims to conduct rock deformation experiments to investigate the relationship between hydraulic parameters (fluid pressure, permeability, etc.) and Rate-and-State parameters, to provide valuable insights into earthquake physics and fault stability. Additionally, active seismic wave recordings will be integrated during the experiments to shed light on the microphysical processes governing friction under these specific conditions, both in strong and weak minerals[20]. Experiments will be performed using the biaxial machine BRAVA2 in Sapienza. This innovative apparatus will allow the reproduction of specific boundary conditions found in fault zones, thanks to the help of two pistons (vertical and horizontal, respectively shear and normal stress) and the possibility of reaching temperatures and pressures higher than other existing biaxial apparatuses. All the experiments will be performed on natural and synthetic fault gouges in a double-direct shear configuration (DDS).

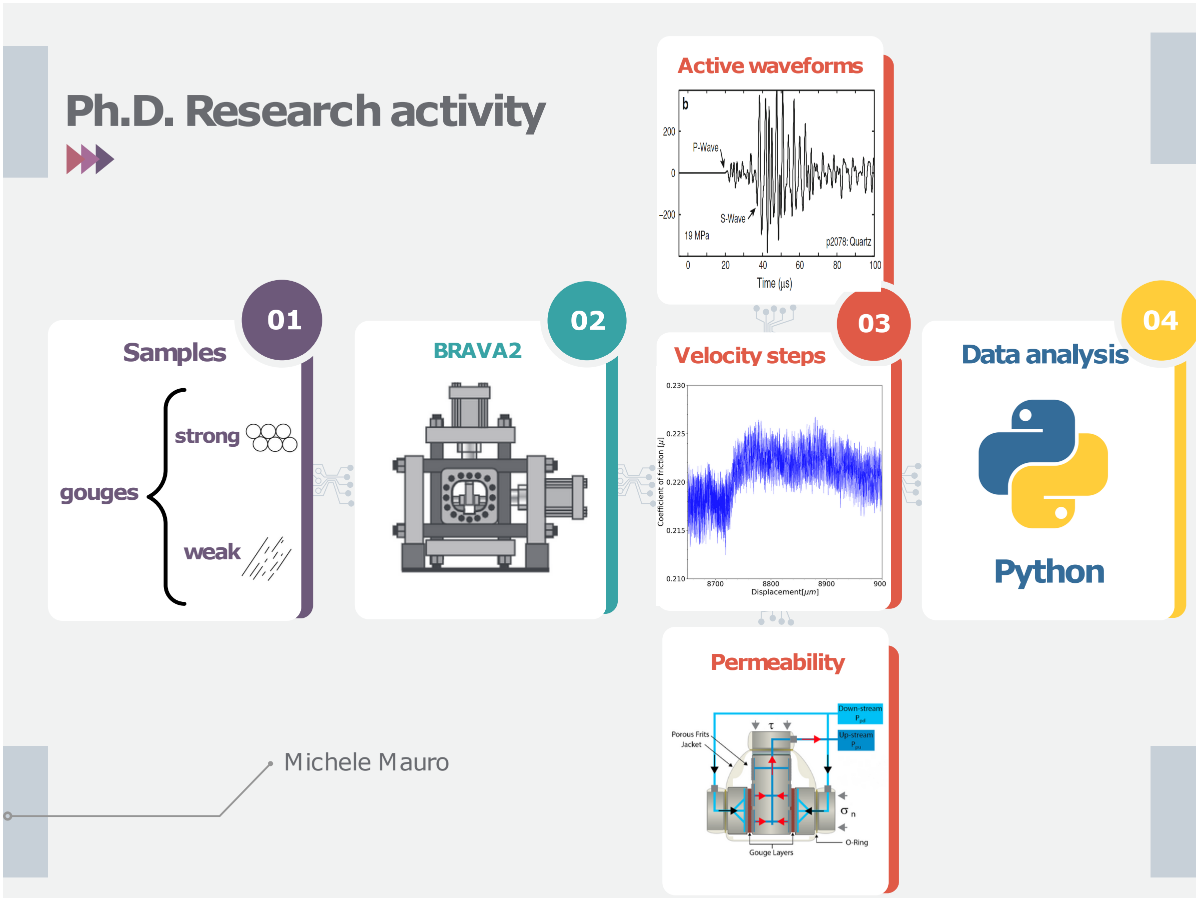

Figure 3: Summary of the main steps of the Ph.D. project: once samples of both strong and weak minerals have been obtained (01), these will be analyzed through experiments conducted with the biaxial apparatus BRAVA2 (02), to characterize the hydro-mechanical coupling between frictional properties of the materials and fluid flow (permeability, hydraulic diffusivity, etc.). Measurements of active waveforms will be integrated to better understand microphysical processes that govern friction during deformation (03). All the obtained data will be analyzed with Python (04).

During the research activity (fig.3), the following steps will be executed:

1. **retrieve** the natural and synthetic fault gouges samples for both strong (granular materials like quartz or calcite) and weak (phyllosilicates) minerals,

2. **sample preparation:** the samples will be cut, powdered, and sieved with grain sizes <150 μm,

3. **preliminary experiments** to evaluate the RSF parameters in dry and wet conditions to have an overview of the faults' stability. To quantify the Rate-and-State parameters the vertical piston speed (shear stress) will be varied to reconstruct the velocity dependence of friction (velocity steps).

4. experiments to retrieve the RSF parameters under different **fluid pressure** conditions. In particular, in these experiments, the change in fault behavior will be evaluated as the pore pressure increases from sub-hydrostatic to near lithostatic conditions. Measurements of permeability both parallel and perpendicular to the layer will be performed.

5. **Integration of active waveforms recording** during velocity steps through piezoelectric transducers (PZT) capable of generating and recording mechanical waves within the sample. In particular, the **peak-to-peak amplitude** and the **velocity** of the transmitted waves will be analyzed to clarify the micro-physical mechanisms that govern friction and stability of faults,

6. **Scanning Electron Microscope (SEM) analysis** to assess microstructural changes of samples to link them to active waveforms measurements.

4.1 Milestones

- Development and implementation of an active waveforms acquisition and synchronization system in laboratory experiments (first year).
- Characterization of fault stability for different lithologies and its relationships with fluid pressure (second year).
- Implementation of the active waveforms recording system in experiments with high fluid pressures to obtain real-time tomography models (second and third year).

4.2 Dissemination plan

During these three years, I will participate in national and international conferences (EGU, AGU, SGI, etc.) to present my work.

This project aims to the publication of at least one scientific paper in an ISI journal for each of the following topics:

1. relationship between lithology (strong vs weak) and fault behavior with increasing fluid pressure and pore fluid factor.
2. characterization of the microphysical processes that govern friction (RSF parameters) through active waveforms recording.

4.3 Training activities and abroad mobility

During the Ph.D., I will deepen and develop multidisciplinary knowledge in the following areas:

- **experimental field** through laboratory experiments with biaxial apparatus, different types of transducers (PZT, load cells, LVDT, etc.), and calibration tools.
- elements of **structural geology** through microstructural analysis of the samples,
- advanced knowledge of data analysis through **Python programming** and elements of Machine learning,
- advanced knowledge of **earthquakes physics**, thanks to a deepening of the works in literature and attending courses provided by the Earth Sciences Ph.D. course of La Sapienza University and ERC Tectonic Seminars,
- **team working**, thanks to the collaboration with other members of the Sapienza DST at the Rock Mechanics and Earthquake Physics lab.

I will spend a period of formation abroad (1 month) at Penn State University (PSU).

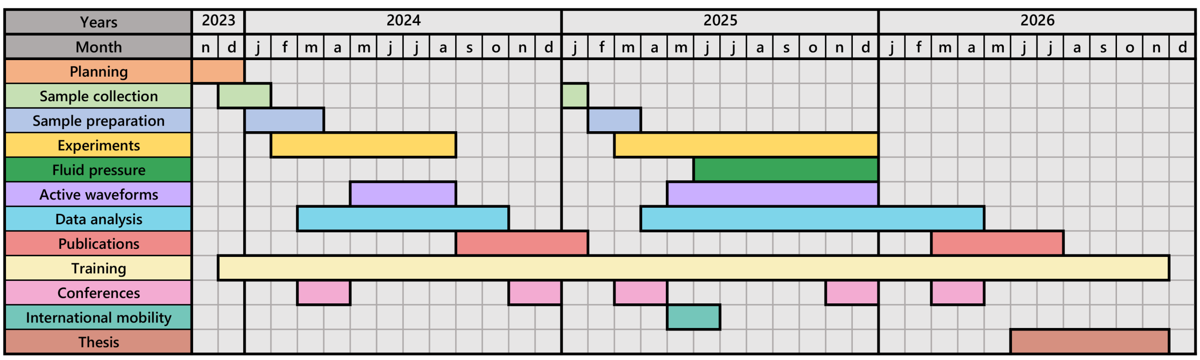

Figure 4: Gantt Chart of the Ph.D. project

5 References

[1] Sibson, Richard H. ”A note on fault reactivation.” Journal of Structural Geology 7.6 (1985): 751-754.

[2] Hubbert, M. & Rubey, W. Role of fluid pressure in mechanics of overthrust faulting. Geol. Soc. Am. 70, 115–166 (1959).

[3] Kato, Aitaro, et al. ”Variations of fluid pressure within the subducting oceanic crust and slow earthquakes.” Geophysical Research Letters 37.14 (2010).

[4] Liu, Yajing, and James R. Rice. ”Slow slip predictions based on granite and gabbro friction data compared to GPS measurements in northern Cascadia.” Journal of Geophysical Research: Solid Earth 114.B9 (2009).

[5] Peng, Zhigang, and Joan Gomberg. ”An integrated perspective of the continuum between earthquakes and slow-slip phenomena.” Nature geoscience 3.9 (2010): 599-607.

[6] Keranen, Katie M., and Matthew Weingarten. ”Induced seismicity.” Annual Review of Earth and Planetary Sciences 46 (2018): 149-174.

[7] Ellsworth, William L. ”Injection-induced earthquakes.” Science 341.6142 (2013): 1225942.

[8] Townend, John, and Mark D. Zoback. ”How faulting keeps the crust strong.” Geology 28.5 (2000): 399-402.

[9] Keranen, Katie M., et al. ”Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 Mw 5.7 earthquake sequence.” Geology 41.6 (2013): 699-702.

[10] Bedford, John D., et al. ”The stabilizing effect of high pore-fluid pressure along subduction megathrust faults: Evidence from friction experiments on accretionary sediments from the Nankai Trough.” Earth and Planetary Science Letters 574 (2021): 117161.

[11] Cappa, Frédéric, et al. ”Stabilization of fault slip by fluid injection in the laboratory and in situ.” Science advances 5.3 (2019): eaau4065.

[12] Dietrich, J. H. ”Modeling of rock friction, 1.” Experimental results and constitutive equa (1979).

[13] Ruina, Andy. ”Slip instability and state variable friction laws.” Journal of Geophysical Research: Solid Earth 88.B12 (1983): 10359-10370.

[14] Scuderi, Marco M., and Cristiano Collettini. ”The role of fluid pressure in induced vs. triggered seismicity: Insights from rock deformation experiments on carbonates.” Scientific reports 6.1 (2016): 1-9.

[15] Scholz, Christopher H. ”Earthquakes and friction laws.” Nature 391.6662 (1998): 37-42.

[16] Leeman, J. R., et al. ”Laboratory observations of slow earthquakes and the spectrum of tectonic fault slip modes.” Nature communications 7.1 (2016): 11104.

[17] Scuderi, M. M., et al. ”Precursory changes in seismic velocity for the spectrum of earthquake failure modes.” Nature geoscience 9.9 (2016): 695-700.

[18] Nagata, Kohei, Masao Nakatani, and Shingo Yoshida. ”Monitoring frictional strength with acoustic wave transmission.” Geophysical Research Letters 35.6 (2008).

[19] Knuth, Matthew W., Harold J. Tobin, and Chris Marone. ”Evolution of ultrasonic velocity and dynamic elastic moduli with shear strain in granular layers.” Granular Matter 15.5 (2013): 499-515.

[20] Byerlee, James. ”Friction of rocks.” Rock friction and earthquake prediction (1978): 615-626.

[21] Chiarabba, C., De Gori, P., Segou, M., & Cattaneo, M. (2020). Seismic velocity precursors to the 2016 Mw 6.5 Norcia (Italy) earthquake. Geology, 48(9), 924-928.

[22] Trippetta, F., Collettini, C., Vinciguerra, S., & Meredith, P. G. (2010). Laboratory measurements of the physical properties of Triassic Evaporites from Central Italy and correlation with geophysical data. Tectonophysics, 492(1-4), 121-132.