PhD project proposal:

Mineralogy, structures and fluid injection role in fault stability: implications for CO_2 storage

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1. Introduction and State of the art

Underground CO_2 or hydrogen storage relies on injection of fluids into an identified subsurface reservoir, commonly bounded by faults. These reservoirs are predominantly hosted within sedimentary rocks such as alternances of shale-sandstones and/or carbonates. Faults bounding them will be then characterized by fault rocks with a varying mineralogical composition, influencing frictional properties [4] and permeability (Fig.1). The integrity of these reservoirs and their structural trap is strongly related to fault frictional properties and to fault permeability evolution when, with the increasing of fluid pressure during CO_2 sequestration, the stress state approaches the Amontons - Coulomb failure envelope [1,2]. In addition, fault frictional properties strongly influence the fault slip behavior upon reactivation favoring or limiting fluid injection-induced seismicity [3].

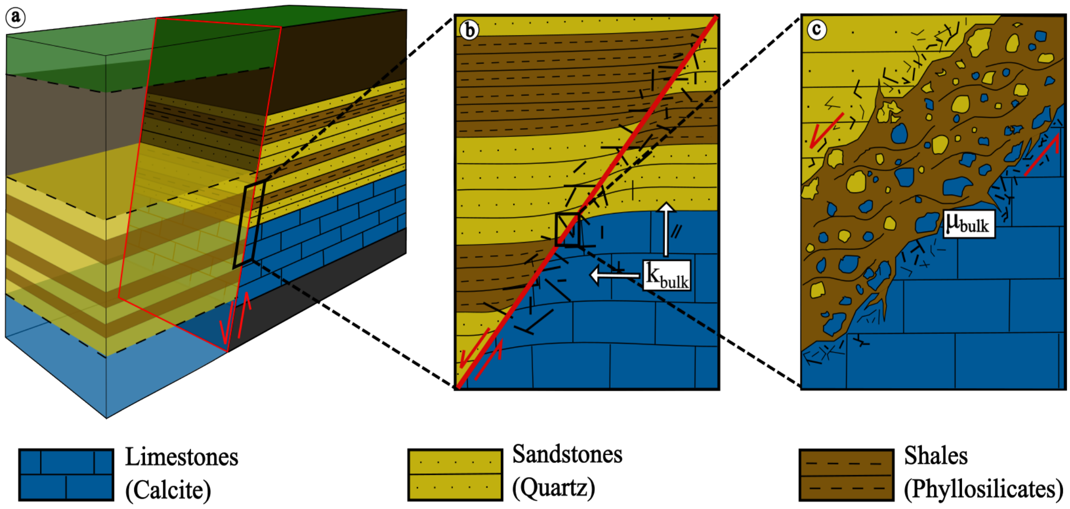

Figure 1: (a): 3D sketch of fault bounding heterogeneous reservoirs; (b) along-dip section of the fault; (c) smearing along the fault plane of phyllosilicates and mixing with quartz and calcite.

Mineralogical composition is one of the most important factors controlling frictional properties [4,5,6,7,8] and permeability [9] in fault zones. Fault gouges rich in granular minerals, either silicates or carbonates, show high frictional strength with a friction (μ) > 0.6, high healing properties and different frictional instability properties that are influenced by normal stress [10], slip velocities [10], temperature [11] and fluids [12]. The increase in platy minerals content such as phyllosilicates in fault rocks results in a reduction in frictional strength with $\mu \approx 0.2 - 0.3$ for a 100% phyllosilicate gouge, healing close to zero and a marked velocity strengthening behavior [7,8,13]. These characteristics are at the base of the Rate and State friction laws (RSF) that are commonly used to determine fault slip behavior [14] and so the susceptibility to instabilities of a fault. Permeability (k), in contrast, shows an increase with quartz percentages and usually a decrease with calcite and in particular clay and phyllosilicates [9].

Previous works indicate that there is a complex interaction between different type of mineral phases and fault hydro-mechanical properties. To improve our understanding on the sealing attitude of faults-bounding reservoirs it is crucial to define how different mineralogical compositions influence frictional and fluid flow properties. To do that it is therefore relevant to perform experiments on a large gamut of gouge mixtures [15]. Fault zones in these reservoirs are in fact characterized by different percentages of minerals, whose frictional properties and permeability have not been comprehensively characterized so far together. In the last years, Keranen and Weingarten (2018) provided a comprehensive overview of the mechanisms responsible for induced seismicity, emphasizing the importance of understanding the interaction between fluid flow, fault composition and mechanical parameters to safely manage injection operations [16]. These studies highlight that, despite significant advances in understanding induced seismicity, considerable uncertainties remain, particularly regarding how mineralogical parameters and the hydraulic characteristics of faults influence their reactivation.

My research aims to address these gaps by investigating how the heterogeneous mineral composition of fault zones affects their hydromechanical behavior under fluid injection, characterizing heterogeneous fault gouges Rate and State frictional properties, together with fault-parallel and perpendicular permeability. This is crucial to better constrain the potential of leakages along permeable faults during CO_2 storage and fluid-assisted induced seismicity [17].

2. Research goals

2.1 Overall objectives

Enhance our understanding on permeability and frictional properties of ternary fault rock mixtures with implications for CO_2 leakages and induced seismicity.

2.2 Specific objectives

Characterization of heterogeneous fault gouge properties by:

- Frictional and permeability (both perpendicular and parallel) measurements for fault gouges represented by ternary mixtures.
- Evaluation of fault slip behavior during reactivation induced by fluid pressure accumulation.

3. Implications and applications

I will perform a comprehensive study on the hydro-mechanical properties of ternary fault mixtures, representing to a first approximation most of the seismogenic faults within the sedimentary cover. This will be essential to develop models aimed at assessing the potential of both fault leakages and induced seismicity during CO_2 storage with application on both scientific studies and industrial activities.

4. Work plan

This PhD project aims to conduct rock deformation experiments to fully characterize fault gouges Rate and State frictional properties and to investigate hydraulic parameters such as permeability, both parallel and perpendicular.

During the first year, I will contribute to the development of the experimental apparatuses to perform pressurized experiments. These experiments will be performed for different gouges composition, ranging from three simple configuration such as 100% quartz, 100% calcite and 100% clay. Mixed compositions will be then represented by different percentages of minerals, from two components mixture such as 50% quartz – 50% clay to three components ones, with 33% of each mineralogical phase, including intermediate cases (Fig.2 uses a ternary diagram to show the ternary mixtures to be tested in this work).

The experiments will be carried using the biaxial machine BRAVA2 at La Sapienza university, an innovative apparatus which will allow the reproduction of specific boundary conditions found in fault zones with forcing blocks designed to measure fault perpendicular and parallel permeability. In particular, the evaluation of fault parallel permeability will be fundamental to characterize the role of shear induced anisotropy in increasing permeability in clay rich faults and better assess the potential of fault leakage and high-permeability preferential zones near the faults.

Sample ID	Composition %		
	Calcite	Clay	Quartz
1	0.0	0.0	100.0
2	50.0	0.0	50.0
3	100.0	0.0	0.0
4	80.0	20.0	0.0
5	66.0	17.0	17.0
6	55.0	20.0	25.0
7	40.0	20.0	40.0
8	25.0	20.0	55.0
9	17.0	17.0	66.0
10	0.0	20.0	80.0
11	22.0	35.0	43.0
12	33.0	34.0	33.0
13	43.0	35.0	22.0
14	50.0	50.0	0.0
15	0.0	50.0	50.0
16	17.0	66.0	17.0
17	0.0	100.0	0.0

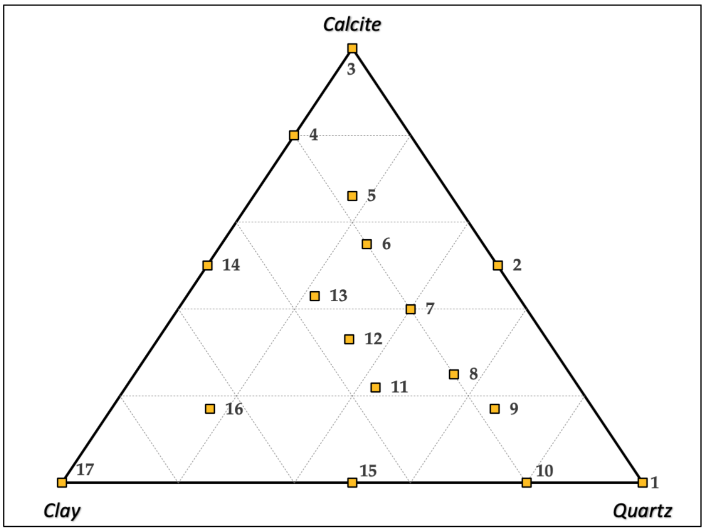

Figure 2: Experimental compositions of fault gouges. Percentages are in nominal volume.

The experimental procedure involves applying a constant normal stress to the fault with a compaction period until steady-state compaction is reached. Following this, a 10 mm displacement run-in phase occurs at a rate of 10 μm/s to develop a specific fabric depending on normal stress and mineralogical composition. After this phase, fault-parallel and perpendicular permeability are measured using both Darcy's method and the oscillatory method. This suite of experiments will be conducted in the first 10 month, alongside training courses. Subsequently, a new suite of experiments will be performed to investigate fault behavior during fluid injection-induced reactivation, which will take 2-3 months.

The second year will focus on data and structural analysis, (5 months) providing a comprehensive overview of the acquired dataset. Since I believe that to understand fault slip behavior it is important to look at faults from different angles and scale, I would like to study fault structure and fault rock development within multicompetent mechanical layers like those forming within carbonates-shales in the Apennines (Giorgetti et al., 2016) and in sandstone-shales in the Lodeve Basin in southern France (Wibberley et al., 2007). This will be essential for the abroad mobility period (2 months), facilitating discussions with TotalEnergies researchers regarding the data and to develop fluid-flow models. Moreover, in the second year I will participate to international conferences showing my research. Once these steps will be done, new suites of experiments could be performed using real fault samples in a triaxial configuration, together with the study of seismic data in fluid-injection activities-related zones (6 months). In the meanwhile, I will cooperate with people working in the Rock Mechanics and Earthquake Physics Laboratory to develop the experimental apparatuses.

5. Milestones

1. Frictional properties and permeability characterization for ternary mixtures.
2. Characterization of mixtures behavior upon reactivation with different injection rates and/or compaction degree.
3. SEM analysis to determine microstructure and to match the mechanical, hydrological and structural data.

6. Dissemination plan

During my PhD I will participate at National and International conferences such as SGI and EGU-AGU to present my study. The project aims to publish at least two scientific papers in ISI journals in the following topic:

1. Permeability anisotropy in different fault gouge mixtures and its structural dependence.
2. Mechanical properties of heterogeneous fault gouges and the role of fluid injection in fault stability of heterogeneous fault gouges.

7. Training activities

I intend to attend institutional courses and seminars planned by the Department of Earth Sciences of La Sapienza University of Rome (for the first and second year). I also plan to follow ERC Tectonics seminars, together with of CO_2 storage courses. Furthermore, I will interact with researchers from ENI and Total Energies to discuss the applicability of my study on CO_2 sequestration activities and fluid flow in fault zone studies.

8. Abroad mobility

I plan to spend a period of at least a month at Total Energies in Pau, France, to have a direct contact with a potential case study of CO_2 storage and discuss the implications of my research for Geo-Energy.

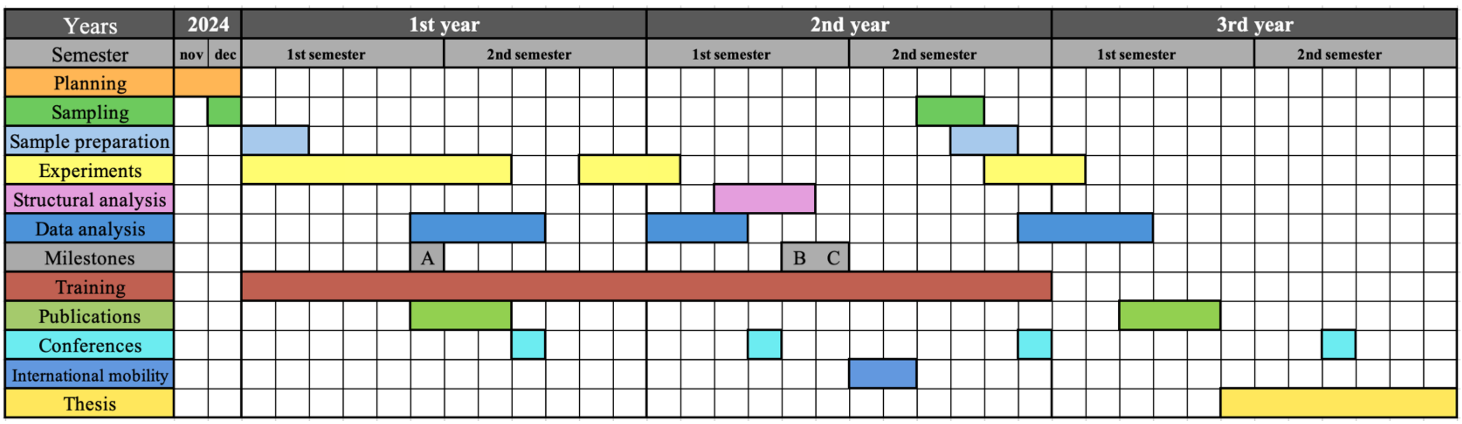

Figure 4: GANTT chart with activities planned during my PhD.

9. References

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