PhD project proposal

Ductile to elasto-frictional behavior in evaporite-bearing rocks

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PhD cycle: XXXIX
Curriculum: Earth Sciences
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1. Introduction

Earthquakes represent one of the major geological risks, occurring as a sudden release of elastic strains along tectonic faults [1] by stick-slip motion [2]. Despite catastrophic crustal earthquakes concentrate primarily at plate boundaries, disastrous events also sporadically occur within intraplate regions, at a depth usually ranging from 5 to 20 km [3]. Understanding the mechanics of the seismogenic crust is of paramount importance to improve our comprehension of earthquake physics and seismic hazard.

Deformation of rocks occurs following two ways: brittle and ductile. The main difference between the two is the mode by which the system accommodates stresses. In a brittle environment fractures (micro -to macro- cracks) dominate, localizing and concentrating deformation and stresses within few millimeters -often micrometers- thick slip zones [4]. In a ductile environment, materials use to flow within a wider shear zone, generally at lower strain rates, producing a spatially distributed deformation [3][5]. Brittleness and ductility are not material properties, the same rock can behave in both ways depending on the pressure and temperature (P-T), strain rate and fluid pressure/chemistry conditions under which it deforms.

The rheology of the uppermost Continental Crust is characterized by a brittle behavior from the surface to $\sim$10-20 km depth. This range is also called elasto-frictional regime [3], and the failure of a rock body under these conditions is described by the Mohr-Coulomb criterion. Below such depth, ductile, pervasive deformation can be described by flow laws of viscous creep (e.g. diffusion and dislocation creep)[6].

However, during a seismic sequence, seismicity can not be attributed only to localized ruptures along major faults within the seismogenic layer [7]. For example, in the San Jacinto fault zone, most of the low magnitude seismicity occurs in a zone that is several kilometres wide at seismogenic depth. In some fluid pressure stimulations, a broad network of distributed fractures has been activated without evidence for alignment along a major fault [8].

The Italian Apennines are one of the most seismically active areas in the Mediterranean, as testified by the Mw 6.0 1997-1998 Northern Apennines sequence [9], the Mw 6.3 2009 L'Aquila earthquake [10] and the Mw 6.5 2016-2017 Central Italy seismic sequence [11]. All the last three seismic sequences highlighted the Triassic Evaporites (TE) Formation as the source region for seismogenic faulting [9][12][11]. Thanks to the improved resolution of the seismological dataset, the 2016-2017 Central Italy seismic sequence exhibited both on-fault and distributed seismicity. While localized events occurred along a fault within the carbonatic layer and only partially in the Triassic Evaporites, the distributed seismicity was primarily recorded within the evaporitic sequence and the underlying phyllitic basement (Fig. 2).

TE Formation (Anidriti di Burano) is a 1.5-2 km thick sequence made of deci-decametric gypsum/anhydrite and dolostone interbedding [13]. During the Upper Triassic burial, at a depth of about 600-700 m (Fig. 1), original gypsum started to be replaced by anhydrite according to the dehydration reaction

$$CaSO_4 \cdot 2H_2O_{(gypsum)} \rightarrow CaSO_4 + 2H_2O_{(anhydrite)}, \tag{1}$$

due to pressure and temperature increase [14].

Evaporitic rocks were known to operate as detachment horizons being characterized by plastic behavior [15] even at low pressures and temperatures, in several areas around the world such as for example the French-Swiss Jura [16] or Pakistan [17].

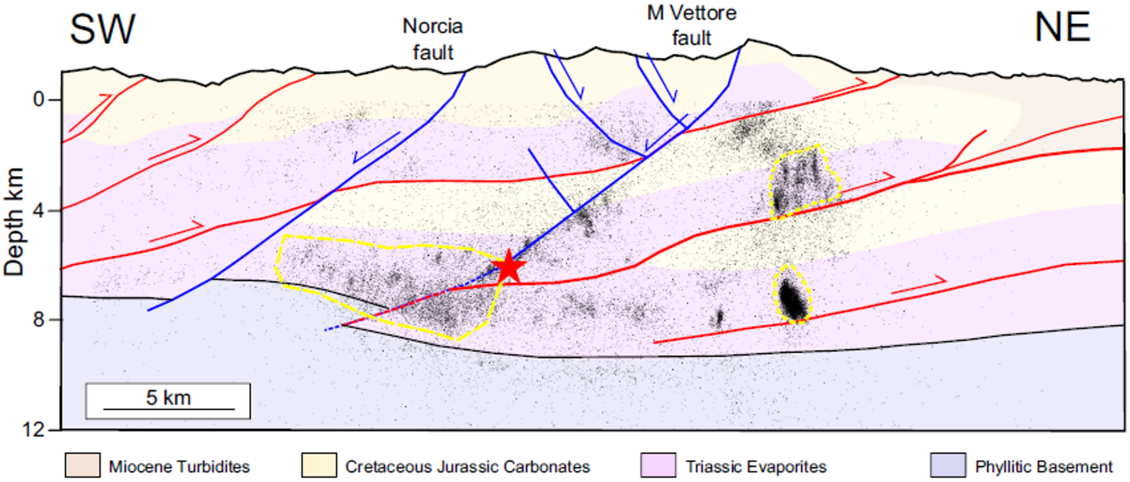


Figure 1. Cross section highlighting both on-fault and distributed seismicity within the Triassic Evaporites. The mainshock occurred along the M. Vettore fault was followed by the microseismicity recorded in the evaporitic layers. From Collettini et al. (2022)

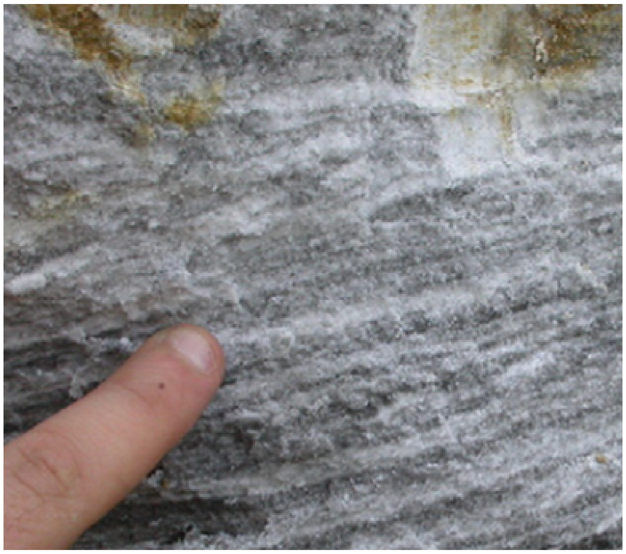


Figure 2. Centimetric dolostone-anhydrite interbedding. From Trippetta et al. (2010).

The rheology of TE has been experimentally analyzed by De Paola et al. (2009) [18] by performing triaxial loading tests on anhydrite cylindrical samples undergoing uniaxial compression at constant strain rate. Results showed that the different effective pressure applied on the samples controlled the deformation style (i.e. brittle or ductile, Fig. 3). In particular, the prevailing deformation is ductile and only for fluid pressures approaching lithostatic values brittle behavior occurs [18].

The coupling of mechanical data with permeability measurements shows that for brittle behavior, an initial quasi-elastic compaction and hardening stage, accompanied by permeability reduction, is followed by an exponential increase of permeability ($> 10^{-17}$ m^2) during failure. On the contrary, for the ductile behavior, distributed cataclastic flow enhances fluid path tortuosity promoting low values of permeability ($\sim 10^{-19}$ m^2) even when the samples were failing in a ductile mode. This suggests a critical role played by fluid pressure in promoting the switch to brittle processes. High fluid pressures within TE is witnessed by deep boreholes measurements which showed fluid overpressures at $\sim$ 85 % the lithostatic load [19]. Probably, both strain rate increase after a mainshock (on-fault earthquake) and efficient sealing by the low permeability ($10^{-19} - 10^{-21}$) anhydrite layers promote brittle and ductile failure within interbedded TE, producing distributed microseismicity [11].

Moreover, a characterization of the frictional properties of TE (performed by Scuderi et al., 2020) [20] highlighted how TE gouge samples occasionally showed velocity weakening behavior and large frictional healing, i.e. likely conditions for unstable seismic slip to occur. This indicates a potential

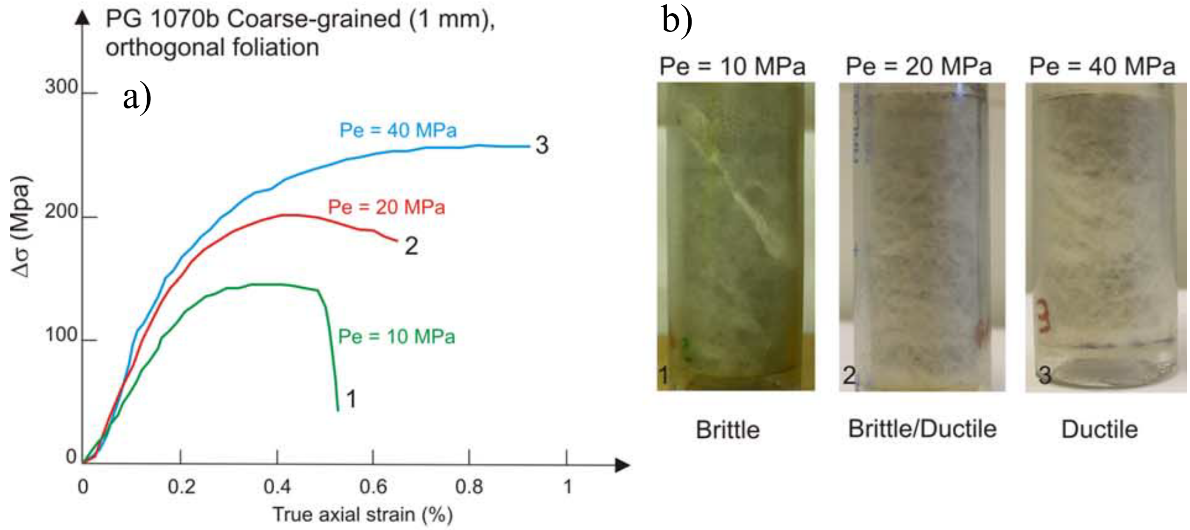


Figure 3. a) Triaxial compression experiments exhibiting different rheological behaviors as a function of different effective stresses applied and b) relative samples extracted from the apparatus after being deformed. From De Paola et al. (2009).

major contribution of Triassic Evaporites failure to the overall seismicity record.

2. Research objectives

General objective: Understanding the ductile to elasto-frictional behavior in evaporite-bearing rocks.
Specific objective: Comprehension of Triassic Evaporites embrittlement during deformation and implications for seismogenic faulting in Northern Apennines.

3. Implications

I will perform a comprehensive study on the rheology of TE, with direct implications for improving our understanding on the time-space evolution of the seismicity in the Apennines. In addition, because anhydrite rocks are usually considered as efficient sealing horizons, the proposed extensive analysis of the rheology of these rocks will have implications for all the industrial activities that require the characterization of low permeability rocks to store geoenergy (CO_2 or Hydrogen) or nuclear waste.

4. Work plan

During the first year of my PhD course, I will firstly characterize the $\sim$ 15 m thick “San Donato” borehole samples available at the Department of Earth Sciences of La Sapienza University of Rome. The first characterization will be performed by hand samples analysis integrated with macroscopical observation of interbedding thicknesses, deformation structures (e.g. fractures) and their relative dip and strike orientation. Data will be then compared and integrated with composite log and drilling report observations with a particular focus on the boundary conditions during drilling such as temperature and fluid pressure. This phase will take around 2 months. Subsequently, a microstructural/microanalytical analysis will follow, exploiting the numerous facilities present in the Department of Earth Sciences of La Sapienza University of Rome (optical microscope, SEM, EBSD, image-analysis, XRD, XRPD, etc.) to evaluate the deformation mechanisms that operated during the several deformation phases that TE encountered. During this phase it will be also possible to recognize brittle and ductile processes and/or fluid-rock interaction processes and grain-to-grain mechanical relationships. Even this phase will take around 2 months. At the end of this phase I will have a complete view of the cores that will help in understanding which are the best parts to be re-cored for the following experimental phase.

The third and central phase of my research plan will involve a systematic series of triaxial compression tests on selected borehole samples, following a two-step plan:

1. Triaxial experiments at constant hydrostatic fluid pressure and different values of confining pressure and strain rate, to explore the role of an increase in strain rate in evaporites embrittlement. This could give an answer to the increase of seismicity rate within the TE, in areas which experienced an increase in strain rate following the Norcia mainshock.

2. Triaxial experiments with different levels of fluid pressure and with active and passive ultrasonic waves, to test the role of fluid pressure in TE rheology. This will provide the right experimental dataset to merge laboratory observations with borehole data, seismic reflection profiles and earthquake tomography.

The experiments will be performed using the deformation apparatus ”BRAVA 2” in triaxial configuration, available at the Rock Mechanics and Earthquake Physics Laboratory of the Department. The purpose of this suites of tests is to constrain the rheology of TE during deformation at different boundary conditions and test possible ”embrittlement processes” which could explain the microseismicity recorded after the 2016 Norcia mainshock [11]. This research stage will take about 14 months.
Microstructural/microanalytical analysis will be performed to characterize the microstructures produced in the experimentally deformed samples. Then, a comparison between experimental data, borehole measurements and seismic data will be performed, to upscale laboratory measurements in terms of Vp/Vs ratio, stress-strain relationship and permeability evolution. These stages will take about 4 months.
Once the deformation style of TE has been identified, frictional experiments (velocity steps and slide-hold-slide tests) on borehole-derived gouges could be performed, leveraging the ”BRAVA 2” apparatus in double direct shear configuration, to couple mechanical/seismic/borehole data with frictional (RSF and healing parameters) measurements and explain the large healing (both magnitude $\Delta\mu$ and rate β) and the velocity weakening behavior observed in previous works. This research phase will take about 8 months. In the meanwhile, I will cooperate with people working in the Rock Mechanics and Earthquake Physics Laboratory to continue the development of ”BRAVA 2” and ”BIG BIAX” deformation apparatus.

5. Milestones

Key results envisaged for my PhD project are: a) macro-microscopic characterization of ”San Donato” borehole samples (4 months), b) triaxial experiments on selected and cut borehole samples and data analysis (14 months), c) coupling of seismic data, borehole data, microstructural/microanalytical analysis and experimental measurements (4 months) and d) frictional experiments using ”BRAVA 2” apparatus with associated data analysis (8 months).

6. Dissemination plan

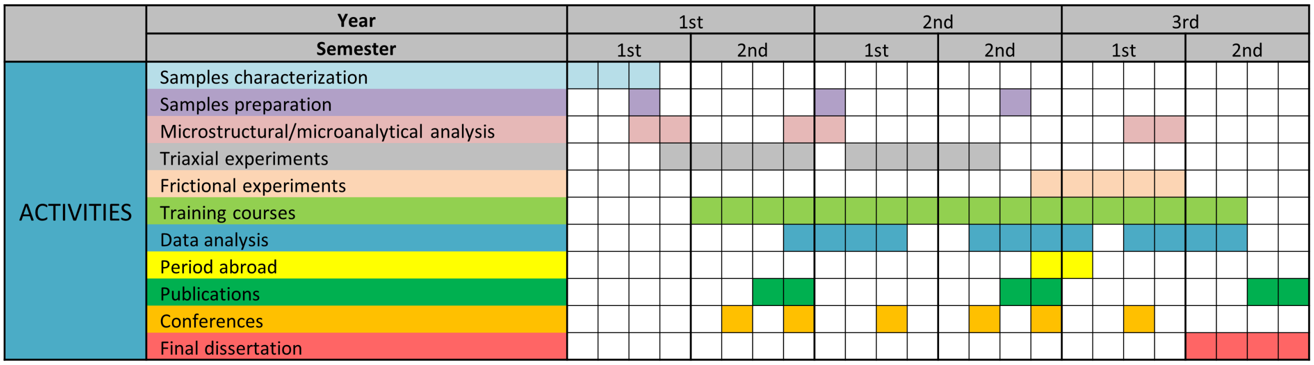
My PhD course will result in writing and publishing at least three scientific papers on peer-reviewed journals, about: 1) bimodal deformation style associated to TE seismic/aseismic behavior accompanied by a microstructural/microanalytical analysis, 2) frictional properties of TE and associated microstructural/microanalytical analysis and 3) coupling of triaxial loading, frictional, borehole and seismic measurements to assess the role of TE during the seismic sequences recorded in the Apennines.
The last $\sim$ 6 months of my PhD will be occupied by writing the PhD thesis.

7. List of training activities

During the first year of my PhD course, I plan to attend institutional courses provided from the Department of Earth Sciences of La Sapienza University of Rome, for all three years. I also plan to attend national/international conferences (EGU, AGU, SGI) and ERC Tectonic seminars for all three years of the PhD programme.

8. Mobility abroad

I plan to spend at least 1 month at the Department of Earth Sciences of Durham University (UK), to complete the suite of experiments in the Rock Mechanics Laboratory and interact with people working in such research group.



	Year	1st								2nd								3rd							
	Semester	1st				2nd				1st				2nd				1st				2nd			
ACTIVITIES	Samples characterization	■	■	■																					
	Samples preparation			■						■						■									
	Microstructural/microanalytical analysis			■	■				■	■										■	■				
	Triaxial experiments				■	■	■	■	■		■	■	■	■	■										
	Frictional experiments																■	■	■	■	■				
	Training courses					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■		
	Data analysis								■	■	■	■			■	■	■	■		■	■	■	■		
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	Conferences						■		■			■			■		■			■					
	Final dissertation																					■	■	■	■

Figure 4. Gantt chart of my PhD project.

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