PhD project proposal

The role of fault maturity and lithological heterogeneities in fault zone thickness: insights from field and seismological data.

Candidate: **Francesca Rossi**

PhD cycle: **XXXIX**

Curriculum: **Earth Science**

Suggested internal tutor: **Prof. Cristiano Collettini** (La Sapienza)

External tutor: **Dr. Stefano Pucci (INGV)**

Candidate e-mail address: francesca.rossi3@uniroma1.it

1. State of the art

A typical fault zone architecture comprises a highly deformed core surrounded by a damage zone composed of rocks with higher fracture density and lower elastic moduli than the host rock [1]. Perrin [2] divides the damage zone in two regions: a dilatant region characterized by *mode I* cracks; and a shear deformation region with *mode II* and *III* cracks (Fig. 1). This last deforms by an elasto-frictional rheology promoting earthquake nucleation [3].

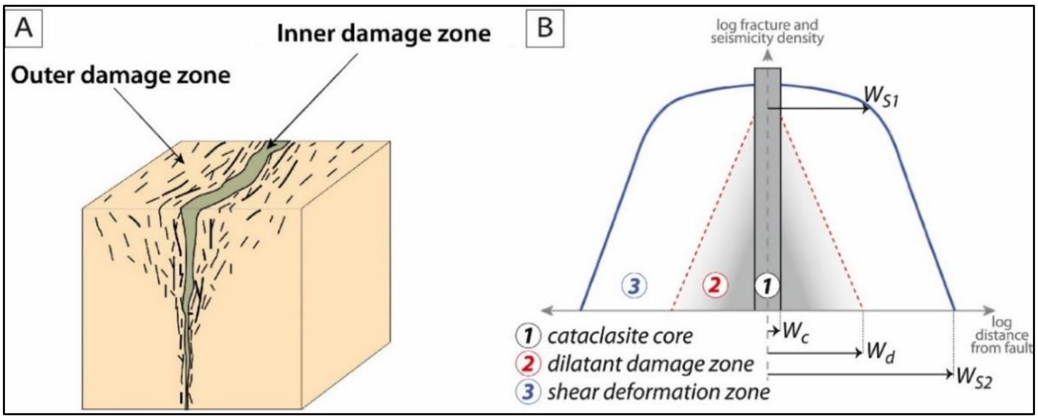

Figure 1 *A) Schematic representation of inner and outer damage zone, fault core is not represented [7]; B) Schematic representation of fault zone structure the three main zones [2].*

An important question in fault mechanics is how these damage zones form and whether the same mechanisms govern damage zone development throughout the growth of the fault [4]. One approach to this question has been the study of how fault damage zone scales with fault displacement [5,6]. Field observations indicate that the thickness of the damage zone scales linearly with accumulated fault displacement, which represents one of the most important measures of fault maturity [6,4] (i.e., the degree of evolution of its structural properties [2,7]). As a fault accumulates displacement (D) also the dimensions of the fault surface (L) increases (i.e., along-strike propagation) to maintain the scaling relationship D/L constant [8,9]. It has been observed [2] that the shear deformation region of large faults exhibits a narrowing trend following a power law relationship with cumulative fault displacement. This narrowing is associated with smoothing of the fault surface (Fig.2B), enhanced by increasing fault displacement and maturity [10,11]. However, for displacements larger than 3 km, fault zone thickness tends to remain constant at several hundreds of meters [4]. It has been observed also a strong correlation between fault zone thickness and lithology: faults hosted by phyllosilicate-rich rocks often exhibit thick deformation zones, while faults hosted by other lithologies as granites and carbonates display more localized deformation [12].

Investigating the influence of lithology on damage zone thickness is a key research objective.

In the Central Apennines, two main seismic sequences have occurred in the last two decades: the L'Aquila 2009 sequence and the Amatrice-Visso-Norcia (AVN) 2016-2017 sequence. Both sequences occurred in the same extensional regime, so with similar initiation age [13]. However, the faults activated during the AVN seismic sequence reached higher cumulative displacement (~1500 m), compared to the L'Aquila 2009 sequence, where the cumulative displacement was lower (~800 m). Differences were also observed in seismicity distribution, with the AVN sequence displaying seismicity in larger off-fault volumes [14,15] compared to L'Aquila. These differences could be related to lithology. The AVN sequence occurred in the Umbria-Marche domain, characterized by a lithologically heterogeneous stratigraphic succession with Triassic Evaporites and marly formation [13,15]. In contrast, the L'Aquila sequence occurred in the Lazio-Abruzzi domain, with a monotonous succession of massive platform limestones [13]. In this context, understanding how the mechanical properties of these lithologies influence damage zone evolution and the seismogenic behaviour of active faults is of utmost importance.

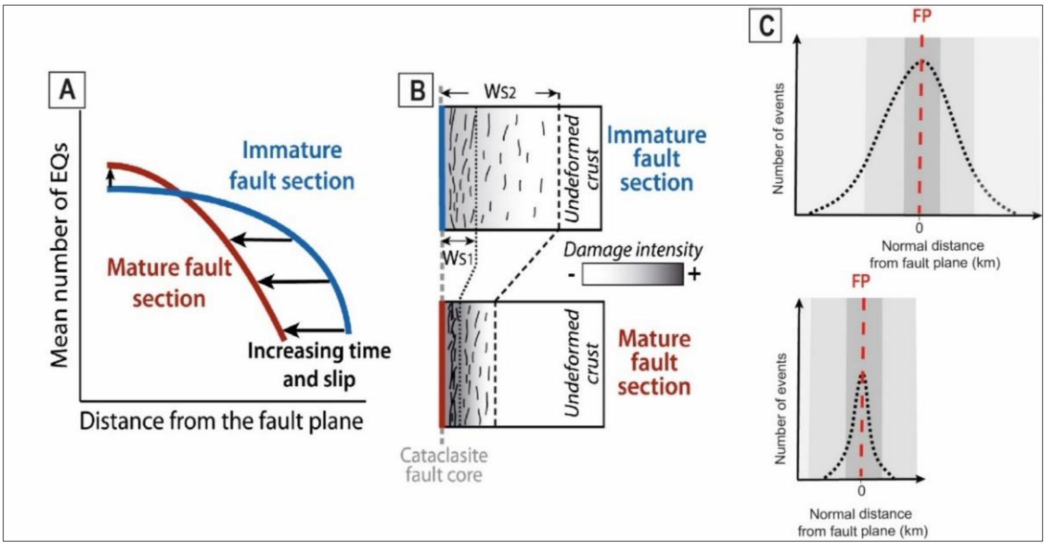

Figure 2 *(A and C) Fault-normal distributions of aftershocks for immature (blue curve) and mature (red curve) fault sections; (B) representation of the structural arrangement of immature (blue) and mature faults (red) [2].*

Our knowledge about active fault zone structure has been mainly based on direct observation provided by geological studies of exhumated faults [16,17] or drilling projects that cored active faults [17]. Additionally, high-resolution earthquake detection and location have been used to describe the geometry of faults imaging their damage zones [17,18,19].

However, the integration of geological and seismological data to study the influence of lithology on fault maturity and its mechanical behaviour is a poorly studied topic, mainly due to the lack of adequate case studies. Here, Central Apennines, due to the wide knowledge of surface and subsurface geology [20] and to the presence of high-resolution seismic catalogue [14,17,21], offer a perfect study area to integrate geological, structural, and seismological data in a comprehensive model [15].

2. Research objectives:

2.1 General objective: understanding the relationship between fault maturity and fault zone thickness in field and in seismological data.

2.2 Specific objective: understanding the role of lithological heterogeneities and fault maturity in controlling the width of the shear deformation zone in different tectonic settings.

3. Implications and applications

The research will be instrumental in enhancing our understanding of fault growth mechanisms over time and identifying the relationship between the thickness of the fault zone, fault maturity, and seismicity distribution. The understanding of this relationship can improve our knowledge in predicting the possible spatial distribution of seismic activity within a fault system activated by a seismic sequence, for example several seismic sequences terminates where faults are characterized by numerous brunches [17].

The evaluation of the structural maturity of the faults can also have implication on seismic hazard. The maturity, in fact, can strongly influence magnitude, stress drop and ground motion amplitude.

4. Work plan

My research activity aims to study the geometrical and structural characteristics of seismogenic faults integrating structural, coseismic and long-term throw studies, with earthquakes distribution from seismic catalogues. My project focuses on three case studies of highly destructive seismic sequences: L'Aquila (2009) and Norcia (2016) in Italy and Kahramanmaraş-Gaziantep (2023) in Turkey.

These three regions have been selected to understand the role of lithology and seismo-tectonic setting in fault maturity evolution and associated thickness of the fault zone. The comparison between L'Aquila and Norcia allows to characterize the role of lithologies since these two seismic sequences occurred in the same seismo-tectonic setting (i.e., normal faulting) with a comparable magnitude distribution, but with different stratigraphic successions. Comparing the central Italy with the Turkey seismic sequence, we can understand the role of both lithology and seismo-tectonic setting, i.e., extensional vs. strike-slip.

My research (Fig. 3) will integrate surface structural and geological data with subsurface seismological data, organized in three tasks for each study areas:

- **Task 1: Seismological Analysis**
  The first phase will involve the implementation and analysis of high-resolution seismic catalogues for the three seismic sequences [22,14,23]. I will create vertical boxes normal to the main structures and project the events within 1km of each box [17]. I will also calculate the number of aftershocks to build histograms describing earthquakes occurrence around the fault plane (Fig.2C). With this, I will examine seismicity's spatial distribution, gaining insights into subsurface structural characterization of earthquakes fault.

- **Task 2: Fieldwork and Structural Analysis**
  By this task I will collect surface structural data focusing on fault zone structures (i.e., damage zone) and fault system geometries (e.g., throw measurements). Through fieldwork, I'll characterize the fault zone surface, measuring fault zone thickness (i.e., fault core and damage zone) and deformation along secondary strands. Once obtained the geological data, I'll merge it with detailed geological cross-sections that I will reconstruct. This integration will provide a starting framework of fault systems of the study region. From this, I'll calculate long-term throw and slip rate of the main structure of the systems providing insights into growth mechanics and structural evolution of the fault zone components within the fault systems.

- **Task 3: Data integration**
  In this task I will integrate results obtained by correlating structural and throw data with spatial distribution of seismicity. For the two seismic sequences of Italy, where subsurface geology is constrained by borehole data and seismic reflection profiles, I will be able to connect fault maturity, lithology, and fault-zone thickness. For the fault reactivated during the recent 2023 Turkey earthquake I'll try to adopt a similar integrated approach where possible or limit the comparison to surface geology and seismological data.

The results of my approach will provide a clear picture on how the elements of the fault zone structure evolve with increasing fault maturity, and long-term throw and how these are related to the seismogenic potential of the faults belonging to a single fault system. During my master's thesis I had the opportunity to get practice with the main phases of this research, building a series of geological section and processing seismic data with Python.

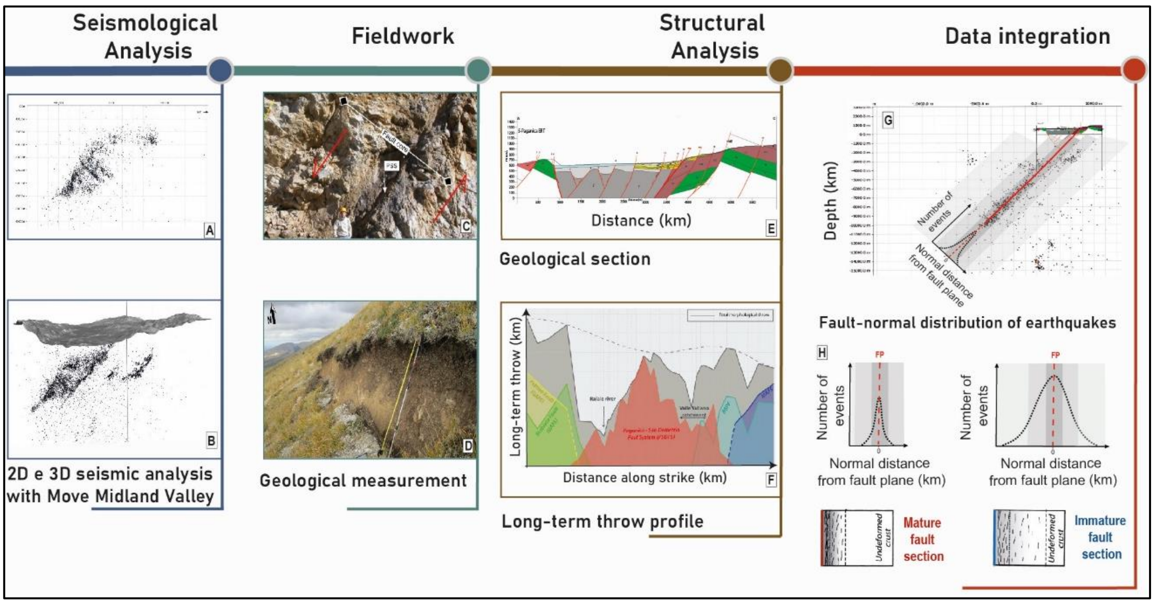

Figure 3 *Summary of the work envisioned for my PhD project. Using seismic data and fieldwork, I'll identify and analyse the main structure of the system. Integrating data, I'll characterize the damage zone from surface to subsurface depths, revealing lithology's mechanical properties' influence.*

5. Milestones and publications

'Milestones' are used to benchmark the progress of my PhD project:

A. Structural and seismological characterization of the fault system activated during L'Aquila 2009 seismic sequence.
B. Structural and seismological characterization of the fault system activated during AVN 2016-2017 seismic sequence.
C. Comparison of the features found for A and B.
D. Structural and seismological characterization of the fault system activated during Turkey 2023 seismic sequence and comparison with Central Italy.

6. Dissemination plan

During my PhD I will partecipate to National and International conferences: EGU, SGI, AGU. With my research on Central Apennines and Turkey, I will create two comprehensive datasets for at least two potential articles on ISI journals.

7. Training-through-research activities and abroad mobility

During my PhD I will attend:
- Courses provided by the Earth Sciences PhD course of La Sapienza University.
- Courses on Python coding.
- ERC Tectonics seminars.

A period of formation abroad at the University of California, Santa Cruz (UCSC) under the supervision of Dr. Heather Savage with which I'll gain experience on fault zone thickness and fault slip.

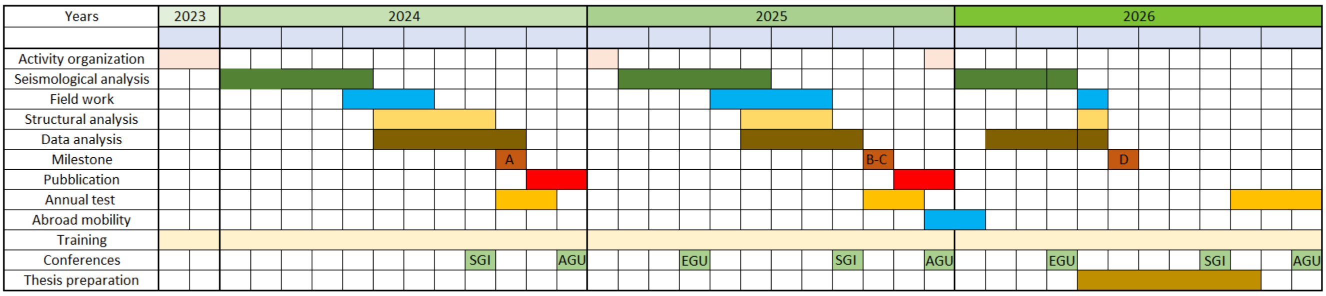

Figure 4 *GANNT chart of the activities planned during my PhD.*

8. References

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