Mechanism of formation of tectonic “giant pseudotachylytes”

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Tectonic pseudotachylytes are fault rocks resulting from the solidification of friction melts produced during seismic slip (Sibson, 1975). Because associated with seismic faulting processes, pseudotachylytes have been used to estimate several earthquake source parameters, including the magnitude of frictional traction, rupture directivity, energy budgets, etc. (Di Toro et al., 2005; Andersen et al., 2008; Pittarello et al., 2008; Johnson et al., 2021). Most of this information cannot be retrieved by the inversion of seismic waves (Beeler et al., 2016) and, thus, pseudotachylytes probably represent the only direct geological product of seismic slip able to provide information of physical process occurring at inaccessible seismogenic depths. The study of these rocks may be contribute to a full understanding of earthquake mechanics, linking geology, seismology and experimental rock deformation disciplines.

Frictional melting results from the almost instantaneous (<1 ms) increase from ambient temperature at seismogenic depths (e.g., 200-450°C) to the melting point of the rock-forming minerals (> 1000°C). This is due to the dissipation of frictional heat along the slipping zone during seismic rupture propagation and slip (McKenzie and Brune, 1973). The average thickness of tectonic pseudotachylytes measured along fossil faults exposed for tens of meters along strike is usually less than few centimeters, including fault patches that might have slipped for almost 1 m during the propagation of paleoearthquakes of estimated magnitudes from M_w5 to M_w7 (Di Toro et al. 2006). Instead, *giant pseudotachylytes* (meter-thick) have been associated to two different environments: (1) impact-related *superfaults* (i.e. Vredefort area in South Africa, Shand, 1916; Spray, 1997), and (2) earthquake-related fossil faults hosted in the continental basement of the Italian Alps, Central Australia, etc. (Techmer et al., 1992; Toffol et al., 2022). How these latter tectonic *giant pseudotachylytes* form remain unclear. Is their extraordinary thickness (1) the result of many seismic events? Or, (2) the result of a single large in magnitude earthquake (e.g., $M_w>7$, coseismic slip >3 m)? Or, (3) associated with fault geometrical heterogeneities (fault barriers, fault splays, etc.) where the loading conditions might differ from the average ones along the fault?

We propose to study the mechanism of formation of *giant pseudotachylytes* with a multidisciplinary approach, including field, experimental and seismological studies. The case study will be the *giant pseudotachylytes* exposed along outcrops extending for hundreds of meters along the Sesia River (Ivrea-Verbano, NW of Italy; Techmer et al., 1992).

Figure 1. "Giant pseudotachylyte". The black in color 0.7 m thick pseudotachylyte cuts yellowish peridotites exposed along the Sesia River (Ivrea-Verbano, NW Italy). How did these pseudotachylytes form?

Preliminary field studies show that the *giant pseudotachylytes* (up to 1 m thick) might be the result of individual seismic slip events in lower crust and mantle rocks of the Ivrea-Verbano complex. Though this field area has been the goal of several studies focused on the description and mechanism of formation of the pseudotachylytes (usually < 5 cm thick, Obata and Karato, 1995; Ueda et al., 2008; Ferrand et al., 2018; Souquiere and Fabbri, 2010), critical info regarding the formation of the *giant pseudotachylytes* are still missing. In particular, this PhD proposal focuses on the following questions for which no complete answers have been yet provided:

1) What are, based on crosscutting relations, mineral assemblages, fluid inclusions, etc. the ambient conditions (temperature, depth, presence of fluids, etc.) at the time of the formation of *giant pseudotachylytes*? Depending also on their age, these pseudotachylytes might be related to (a) the subcontinental extension and opening of the Piedmont-Ligurian ocean (Late Permian-Early Cretaceous), (b) the Pre-Alpine accretionary complex (Late Cretaceous) or to the Meso- to Neo-Alpine collisional to post-collisional stages (Cenozoic). Albeit attempts to date these pseudotachylytes have been done in the past years (Souquiere et al., 2011), their age still remains uncertain and it could be constrained by collecting new data on crosscutting relations that in turn would also bound the fault loading conditions;

2) what is the spatial arrangement of the *giant pseudotachylytes* in the area? And how are individual *giant pseudotachylytes* distributed along fault strike (along complexities such as fault steps, jogs, etc.)?

3) Is there any relation between their extraordinary thickness and lithological properties of the wall rocks (composition, anisotropies, fabric, etc.)?

4) Given the constraints from the points 1 to 3, what are the loading conditions (depth, stress, focal mechanism, etc.) that determine the formation of *giant pseudotachylytes*? Are these conditions typical of peculiar earthquake sequences (e.g., rare but devastating intra-plate earthquakes)?

Addressing these questions will allow the Ph.D. candidate to achieve the main goals of the project, or:

(1) the determination of the *Mechanism of formation of tectonic giant pseudotachylytes* and,
(2) to which type of geodynamic environment and of earthquakes (rare intra-plate, New Madrid M_w ~7.3, 1812; thrust-type in collisional belts, Wenchuan Mw 7.9, 2008; Nepal Mw 7.8, 2015) they might be related to.

To achieve these goals, the scientific approach will include (1) field geology surveys (UAV, photogrammetric modeling of the outcrops, etc.) to quantify the structure of the *giant pseudotachylytes* fault-bearing network, their distribution along strike, the crosscutting relations with other structural features; (2) microstructural-microanalytical (FEG-SEM equipped with CL, WDS & EBSD, image-analysis, XRF, XRPD, micro-Raman spectroscopy, etc.) investigations for the geochemical-microstructural-mineralogical characterization of the pseudotachylytes, their wall rocks and the other structural features; (3) a limited number (in fact, hundreds of experiments were performed on similar rocks in the last 20 years) of rock deformation experiments with ROSA (at UNIPD) and SHIVA (at INGV-Rome) to reproduce the loading and ambient conditions resulting in the formation of friction melts; (4) numerical models, constrained by the results of the field and laboratory studies (points "1" to "3") to investigate the mechanism of formation of *giant pseudotachylytes*, including seismological analysis (i.e., P- and S- wave velocities/anisotropy measured on rock samples) and a comparative study of actual earthquakes occurring under the same ambient conditions.

Given the multidisciplinary approach, the main goals of this proposal can be achieved in a 3-year long project, letting the Ph.D. candidate to gain an extraordinary background from structural geology to numerical modeling and seismology.