# Interaction between coseismic brittle deformation and ductile flow in the lithosphere

*(Proposer: Prof. Giorgio Pennacchioni)*

The strength envelope describes how the rock strength changes with depth, as a function of pressure and temperature, in order to represent the rheological stratification of the lithosphere. In the simplest models, the crust and the lithospheric mantle are assumed to consist of wet quartz and olivine, respectively. These models account for the widely accepted view of a continental lithosphere involving a strong upper crust and a strong lithospheric mantle with a weak and ductile lower crust in between: the so called "jelly-sandwich" model. In this case the lithosphere is subdivided into large portions where rocks deform by either brittle fracture or ductile flow, separated by relatively narrow zone of transition (e.g. Chen and Molnar, 1983).

However, there is an increasingly evidence from exhumed middle and low continental crust units that much of the Earth's lower crust is essentially dry (Jamtveit, 2016; Pittarello et al., 2012; Menegon et al., 2017). Since water reduces the creep strength dramatically (Hirth and Kohlstedt, 1996), lower crustal dry rocks can be very strong even at high metamorphic grade and very unlikely deform ductilely or react unless infiltrated by aqueous fluids. In addition, field observations show that, even hydrated portion of the middle to lower crust, capable to flow at very low differential stresses, need brittle precursors in order to localize ductile deformation (e.g. Pennacchioni and Mancktelow, 2007). Because ductile deformation in metamorphic rocks is commonly localized, this implies the occurrence of transient brittle instabilities during dominant ductile flow. Therefore, it is becoming increasingly clear that the bulk rheology and dynamics of the lithosphere cannot be understood in terms of simple brittle and ductile models, but only by considering the intimate interplay in space and time between brittle fracturing, fluid-rock interaction and ductile flow. A particularly relevant observation is that, in a few cases, there is evidence of the coeval association between mylonites and pseudotachylytes (Fig. 1) reflecting the transient interaction between coseismic brittle fracturing and ductile flow under a wide range of metamorphic conditions. Tectonic pseudotachylytes are very fine-grained or glassy rocks representing quenched frictional melts associated with seismic slip along a fault in silicate rocks and traditionally are considered as representative fault rocks of the base of the brittle crust. Actually, the largest volumes of pseudotachylytes are found in association with high grade dry rocks (Fig. 2) forming the low continental crust instead then in the brittle upper crust. The common occurrence of mutual overprint between mylonites and pseudotachylytes (or fractures) indicates that we need to develop new, non-steady-state rheological models of the lithosphere to account for the intimate interplay between brittle deformation and flow at any structural level and metamorphic environment.

The PhD project will be based on the study of different examples of associations of coeval pseudotachylytes/fractures and mylonites from exhumed tectonic units of different levels of the continental crust. The case studies will include:

- world-wide examples of some of the largest volumes of deep-seated pseudotachylyte (e.g. Musgrave Ranges, Central Australia – Camacho et al., 1995; Hawemann et al., 2018; Lofoten, Norway – Steltenpohl et al., 201; Menegon et al., 2017).
- examples of pseudotachylyte and fractures from "shallow" greenschist facies wet mylonites (e.g. eastern Alps – Pennacchioni and Mancktelow, 2007)

This study will be based on (i) extensive field campaigns including detailed mapping and sampling; (ii) use of conspicuous collections of samples of pseudotachylyte/mylonites from previous studies; (iii) modern microstructural/petrologic analysis of selected samples (SEM-BSC&SE; SEM-CL;

EBSD; OC; TEM-FIB; Raman; EMPA; SIMS; FTIR); (iv) Numerical modelling.

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Collaborators: Luca Menegon - University of Oslo, Norway; Michel Bestmann – University of Erlangen, Germany; Bernhard Grasemann – University of Vienna, Austria; Ake Fagereng – University of Bristol, UK; Marco Scambelluri – University of Genova, Italy; Luiz Morales – ETH Zurich, Switzerland)

The goal of the PhD study will be:

- understand the role (at the macro and microscale) of brittle deformation in the process of strain localization in the ductile field including the analysis of either coupling between fracturing, fluid infiltration and fluid-induced weakening or material weakening induced by brittle deformation;
- determine (by microstructural/CPO analysis, piezometry and deformation mechanism maps modelling) the stress-strain rate evolutionary histories associated with transient episodes of brittle (coseismic) deformation alternating with ductile flow at different structural levels in the crust;
- develop calibrated dynamic models (constrained by field and sample study), or validate existing models (e.g., self-localizing thermal runaway - Kelemen and Hirth, 2007; downward propagation of earthquake ruptures from the brittle-ductile transition zone - Ellis and Stöckhert, 2004) for the brittle-ductile interaction at depth
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The PhD candidate is expected to have a solid background in structural geology, microstructural analysis (and especially in EBSD analysis) and MatLab-based numerical modelling.

References

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Fig. 1 – Ductile shear zone exploiting a pseudotachylyte fault veins still preserving undeformed injection veins intruding the host tonalite. Locality: Lofoten, Norway

Fig. 2 – Pseudotachylyte breccia within a mylonitic high-grade gneiss. Locality: Musgrave Ranges, Central Australia.