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Brittle-viscous rheological cycles in the dry and strong continental lower crust

Menegon L.[1], Pennacchioni G.[2] & Malaspina N.[3]

1. School of Geography, Earth and Environmental Sciences, Plymouth University, UK. 2. Dipartimento di Geoscienze, Universita' degli Studi di Padova, Italy. 3. DISAT, Universita' di Milano-Bicocca, Italy.

Corresponding email: luca.menegon@plymouth.ac.uk

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Many rheological models of the lithosphere predict a weak aseismic lower crust below the strong brittle upper crust. An alternative view, based on the distribution of crustal seismicity, is that the lower crust could also be strong and seismic. It has been suggested that a strong, seismogenic lower crust results from the dry conditions of granulite facies rocks, which inhibit crystal plastic flow. Given that large parts of the lower crust consist of granulites, investigating deformation processes and strain localization in these rocks is a major goal of structural geology and tectonics, the results will provide insights to the earthquake distribution and cycle and to large-scale lithosphere dynamics.

This study investigates exhumed networks of shear zones from Nusfjord (Lofoten, Norway) to understand initiation and localization of viscous shearing in the dry and strong lower crust. In the study area, different sets of ultramylonitic shear zones are hosted in massive granulitic anorthosites. Field evidence indicates that ductile shearing exploited pseudotachylyte veins (solidified frictional melt produced during coseismic slip) and the associated damage zone of fracturing. Field- and thin section observations indicate that frictional melting occurred at the same deep crustal conditions of mylonitization, which were estimated at 650-750 °C, 0.7-0.9 GPa using thermodynamic modelling of mineral equilibria. Mutually overprinting pseudotachylytes and mylonites indicate brittle-viscous deformation cycles, and possibly represent the geological record of the transition from coseismic slip to postseismic creep in the lower crust.

Detailed microstructural (EBSD) analysis of the ultramylonites suggests that diffusion creep and grain boundary sliding were the main deformation mechanisms. The metamorphic assemblage in the mylonitized pseudotachylytes requires ca. 0.4 wt% of water, indicating that brittle deformation triggered fluid infiltration in otherwise dry anorthosites. Accordingly, nucleation of hornblende in dilatant sites indicates that fluids were channelized in the ultramylonites. The infiltrated aqueous fluid assisted grain boundary diffusion and nucleation of fine-grained hydrated phases, resulting in phase mixing and strain localization in the ultramylonites deforming by grain size sensitive creep.

In summary, this study indicates that brittle (coseismic) fracturing was essential to weaken the dry and strong lower crust by activating grain size sensitive creep in the fine-grained hydrated material resulting from grain size reduction. Coseismic fracturing resulted in the ductile shear zones localized to the brittle precursors. In the absence of intense fracturing dry granulites would not undergo deformation and metamorphism, and would survive metastably in the course of Wilson cycles. This has obvious implications for long-term continental dynamics and for strain localization at plate boundaries, and will need to be included in future geodynamic models.