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Brittle deformation in shear experiments at elevated pressures and temperatures

Matěj Peč (1), Holger Stünitz (2), and Renée Heilbronner (1)

(1) University of Basel, Department of Geosciences, Switzerland (matej.pec@unibas.ch), (2) University of Tromsø, Department of Geology, Norway

Many of the largest earthquakes in the continental crust nucleate at the bottom of the seismogenic layer in depths around 10 – 20 km indicating that the build-up stresses can be released by brittle failure under elevated confining pressures and temperatures. In addition, experimental studies, field observations and theoretical models predict that the strength of the lithosphere should be at its peak around these depths and that the rocks reach maximum compressive strength deforming by “semi-brittle” flow. Thus, the understanding of processes taking place under these conditions is of great interest for a better understanding of the seismic cycle and the rheology of faults in general.

We performed a series of experiments where crushed Verzasca gneiss powder (grain size $\leq$ 200 μm) with varying water content (“pre-dried” and 0.2 wt% H2O added) was placed between alumina and Verzasca forcing blocks pre-cut at 45° and weld-sealed in gold and platinum jackets. The experiments were performed at 500, 1000 and 1500 MPa confining pressure, at temperatures of 300°C and 500°C and shear strain rates of $\sim$ 1.5 x 10ˆ-4 in a solid medium deformation apparatus (modified Griggs rig).

The peak strength of the gouge at 500 MPa confining pressure is similar to that of intact rocks of the same material irrespective of the forcing blocks used. All but one sample show strain hardening in the examined shear strain range (up to $\sim$ 2.6) and we observe that the 300°C experiments are systematically stronger by 100 - 500 MPa than the 500°C experiments, irrespective of the water content.

At higher confining pressures (1000 and 1500 MPa) we observe a peak strength at shear strains of $\sim$1 – 1.5 followed by strain weakening which eventually evolves into a steady state flow at a stress level $\sim$ 60-130 MPa lower than peak strength. The strength difference between 300°C and 500°C samples is 200 – 300 MPa and does not increase with increasing confining pressure.

Microstructural observations at different strains show the development of an S-C-C’ fabric with C’ slip zones being the dominant feature. At low strains, the gouge zone is pervasively cut by closely spaced C’ shears containing extremely fine-grained material (< 100 nm grain size). With increasing strain, deformation localizes into less densely spaced C’ – C slip zones that develop predominantly in feldspars and show “flow” structures (grain size is below the resolution limit of a field emission SEM). Quartz grains show the least fragmentation and represent the rheologicaly strongest phase. Feldspar grains fracture more easily and are the weakest phase. The development of the microstructure evolves with finite strain and does not show any dependence on temperature.

CL observations and EDX maps show complex changes in chemical composition (especially in Ca, Na and K) of both plagioclase and K-feldspar in highly strained domains indicating that mechanical disintegration of the grains leads also to changes in mineral chemistry even on short time scale ($\sim$ 3 hours).

Our results indicate that in “semi-brittle” flow, fracturing produces large amounts of extremely fine-grained material, which is a pre-cursor to viscous deformation accompanied by chemical changes. The exact nature of the viscous deformation is not yet clear however two possible mechanisms are envisaged; dissolution – precipitation creep or viscous flow of the possibly amorphous material in the slip zones.