Nano-scale viscous flow, slip zone thickness and dynamic weakening during earthquakes: an experimental investigation

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Viscous flow at high strain rates is a well-known deformation mechanism occurring in metals, but has only recently been associated with the behaviour of natural fault materials during earthquakes in mobile belts. In particular, microstructures attributed to grain boundary sliding have been recognised in high velocity shear experiments where the recrystallized materials commonly have a nanometric grainsize.

We designed and performed a set of friction experiments using a rotary shear apparatus with pure calcite microgouge (60 μm < D < 90 μm) and nanogouge (D ~ 200nm). Experiments were run at different velocities, from sub-seismic (<10 cm/s) to seismic (up to 1.4m/s), and were arrested at different finite slip values in order to document the evolution of microstructures and link these to the mechanical data.

Experiments show a characteristic four stage evolution of the friction coefficient when the material is sheared at seismic velocities (v>10 cm/s): I) an increase from initial Byerlee's values, f = 0.6-0.7, up to peak values, f = 0.8-0.9; II) a sudden decrease to low values, f < 0.4; III) the attainment of low steady-state values, f = 0.15-0.3; and IV) a sudden increase to final value, f < 0.6, upon machine deceleration. The latter stage is not recognised in nanogouge experiments.

Microstructural analysis of samples recovered after each stage studied backscattered SEM images of polished cross-sections through the principal slip zones (PSZ). During Stage I, initially widespread brittle deformation (Riedel shear bands) localises into a planar Y shear producing intense cataclastic comminution (<200 nm). By Stage II, the Y shear band develops sharp boundaries showing patches of sintered material in the regions immediately adjacent to, and outside of the PSZ. On reaching Stage III, the Y-shear band becomes a well-developed nanograin recrystallized (viscous) PSZ, sharply bounded by continuous planar 'mirror' fault surfaces. It is characterised by an equigranular texture with triple junctions, low porosity and oblique shape preferred orientations. A sintering gradient is also developed centred on the PSZ and appears to propagate outwards into the surrounding deactivated layers. At Stage IV) fracturing and reworking of the material occurs and is limited to the PSZ, possibly due to thermal cracking upon cooling.

Mirror surfaces are interpreted here to be dynamic equilibrium boundary discontinuities between the PSZ where viscous grain boundary sliding occurs, and the outer deactivated layers that are dominated by sintering and quasi-static grain growth. The thickness of the PSZ is a function of the grain size, temperature, velocity and available flow stress. The evidence of rheological decoupling is best preserved in Stage III microstructures of nanogouge experiments where mirror surfaces are marked by an abrupt grain size change.

Our findings illustrate the critical role that extreme comminution and localisation play in the onset of seismic weakening in carbonate gouges. Under steady state conditions (Stage III), the thickness of the viscous PSZ is an important physical parameter that controls dynamic weakening behaviour.

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