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Superplastic flow lubricates carbonate faults during earthquake slip

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Tectonic earthquakes are hosted in the shallower portion of crustal fault zones, where fracturing and cataclasis are thought to be the dominant processes during frictional sliding. Aseismic shear in lower crust and lithospheric mantle shear zones is accomplished by crystal plasticity, including superplastic flow acting at low strain rates on ultrafine-grained rocks. Superplasticity has also been observed at high strain rates for a range of nano-phase alloys and ceramics, and could potentially occur in fine-grained geological materials, if deformed at high strain rates and temperatures.

We performed a set of displacement-controlled experiments to explore whether superplastic flow can effectively weaken faults, and facilitate earthquake propagation. The experiments were performed on fine-grained synthetic gouges ($63 < f < 93$ μm) of undeformed, protolith carbonate rocks using a rotary shear apparatus, at target speed v = 1 ms-1, normal stresses σn = 12-18 MPa, displacements d from 0.009 to 1.46 m, room temperature and humidity conditions. Samples were recovered after each experiment to study the slip zone microstructures.

The integration of experimental data and microstructural observations shows that during sliding at seismic velocity, brittle fracturing and cataclasis control shear localization and grain size reduction in the slip zone at relatively low temperatures (T $\leq$ 100 °C). Stress levels predicted by such behaviours match those measured during the experiments. As temperatures rise due to frictional heating (T $\geq$ 500 °C), dislocation creep mechanisms start to accommodate intragranular strain, and play a key role in producing nanoscale subgrains (< 200 nm) in the slip zone. At this stage, despite of the presence of nanoparticles in the slip zone and the attainment of seismic slip rates, the measured frictional strength of experimental faults still lies within Byerlee's range of values μ = 0.8. This suggests that the slip zone bulk strength at this stage is controlled by cataclastic frictional sliding rather than by dislocation creep or nanopowder lubrication mechanisms. When T $\geq$ 800 °C are attained, micro-textures diagnostic of diffusion-dominated grain boundary sliding are widespread within the slip zone, and suggest bulk superplastic flow. Flow stresses predicted by superplasticity constitutive laws at the slip zone temperatures, grain sizes and strain rates attained during the experiments match those we measured in the laboratory (μ = 0.16). We propose therefore that the activation of diffusion creep at high temperatures (T $\geq$ 800 °C) leads to slip zone-localised superplastic flow and that this causes the dynamic weakening of carbonate faults at seismic slip rates. Note, however, that both cataclasis and dislocation creep operating at lower temperatures, during the earlier stages of slip, are critical, precursory processes needed to produce the nanoscale grain sizes required to activate grainsize sensitive mechanisms during superplastic flow. Finally, the re-strengthening observed during the decelerating phase of deformation can be explained by the falling temperature "switching off" slip zone-localized superplasticity, leading to a return to frictional sliding.

These results indicate that superplastic flow can effectively weaken faults, and facilitate earthquake propagation in the upper crust.