Deciphering deformation mechanisms during seismic slip along wet carbonate faults

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Strong dynamic weakening at seismic slip velocities in experiments on calcite has been attributed to a combination of grain-size reduction and nanoscale diffusion. However, these experiments were performed mostly dry and it is unknown how fluid-rock interactions affect the deformation mechanisms. The resulting physico-chemical interactions are key in deciphering deformation mechanisms and rheological changes during and after (seismic) faulting in the presence of a fluid phase. It is the interaction of the nanoscale of granular fault materials with fluids that may drive changes in rheological behaviour and fault stability. Considering that faults in the upper crust are major fluid pathways, there is a particular need for deformation experiments under wet conditions that focus on the nanoscale interaction between gouge material and pore fluid.

In order to track and quantify potential fluid–mineral interaction processes in carbonate faults, we have conducted deformation experiments on calcite gouge with water enriched in $^{18}$O (97 at%) as pore fluid. The fault gouge was deformed in a rotary shear apparatus at $v = 1 \text{ m/s}$ and a normal load of $\sigma_n = 2$ and 4 MPa. Raman spectroscopy and nanoscale secondary ion mass spectrometry (nanoSIMS) were used to analyse isotope distribution in the post-experiment samples. The nanostructure was characterised in electron transparent thin foils, prepared in a focused ion beam – scanning electron microscope (FIB-SEM), using transmission electron microscopy (TEM).

Raman analyses confirm the incorporation of $^{18}$O into the calcite crystal structure, as well as the presence of amorphous carbon. We identify three new band positions relating to the possible isotopologues of $\text{CO}_3^{2-}$ (reflecting $^{16}$O substitution by $^{18}$O). In addition, we detected portlandite ($\text{Ca(OH)}_2$), pointing to the hydration reaction of lime ($\text{CaO}$) with water. Raman and NanoSIMS maps reveal that $^{18}$O is incorporated throughout the deformed volume, implying that calcite breakdown and isotope exchange affected the entire fault gouge.

Considering the oxygen self-diffusion rates in calcite (Farver, 1994) we conclude that solid-state $^{18}$O–isotope exchange cannot explain the observed incorporation of $^{18}$O into the calcite crystals during wet, seismic deformation. The hydration of portlandite and, calcite containing $^{18}$O implies the breakdown and decarbonation of the starting calcite and the nucleation of new calcite grains. Our results question the state and nature of calcite gouges during seismic deformation and challenge our knowledge of the rheological properties of wet calcite fault gouges at high strain rates. The observations suggest that the physico-chemical changes are a crucial part of the deformation mechanism and have implications for the development of microphysical models that
allow us to quantitatively predict fault rheology.

References