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The microstructural evolution of clay-bearing carbonate faults during high-velocity friction experiments

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Seismicity in the Northern Apennines, Italy, nucleates within and propagates through a multilayer sequence comprising limestones with marl interbeds. Observations from the Gubbio fault (1984, Ms = 5.2) indicate that the majority of earthquake displacement is localized within principal slip zones (PSZs), <1.5 mm wide, characterized by cataclasites and gouges containing up to 50% phyllosilicate. To assess the effect of clay content on the frictional behaviour of such carbonate faults during earthquake propagation, we performed high-velocity friction experiments, using a rotary-shear apparatus, on gouges containing 50:50, 80:20 and 90:10 ratios of calcite:montmorillonite and calcite:illite-smectite (mixed-layer). Starting grain size was 180-250 μm. Experiments were conducted at 1.3 m/s slip rate, 9 MPa normal load and under both dry and water-saturated conditions.

The dry calcite+clay gouges produce a typical slip-weakening curve comprising a slip-hardening phase during the early stages of slip, during which friction evolves to a peak value (μp) of 0.62-0.76. μp is followed by a dramatic decrease in frictional strength within the first 0.5 m of slip to a constant steady-state value (μss) of 0.23-0.33. The frictional behaviour of the wet calcite+clay gouges is profoundly different, in that they undergo negligible slip-hardening, and instead attain steady-state sliding almost immediately at the onset of slip with μss «0.2. As little as 10-20 wt.% phyllosilicate is enough to produce this dramatic weakening.

The dry and wet gouges show significant microstructural differences in both the initial (post-compaction, pre-shearing) phase and after shearing. Initial microstructure of the dry gouges is characterized by discrete calcite grains and irregular ‘clumps’ of clay. The microstructure of the sheared dry gouges is then characterized by a sharp principal slip surface (PSS) and the development of a strong fabric and localized PSZ, up to 65 μm wide, composed of nanoparticles and often containing bubbles as evidence for frictional heating and thermal decomposition of calcite.

Initial microstructure of the wet gouges, on the other hand, is characterized by a distributed and interconnected network of wet clay surrounding calcite grains. The microstructure of the sheared wet gouges is characterized by a diffuse PSS, limited fabric development, and no PSZ; deformation is much more distributed. In addition, grain-size reduction in the wet gouges is $\sim$1 order of magnitude less than in dry gouge equivalents. Thus, we attribute the contrasting frictional behaviour and microstructural evolution in the dry vs. wet gouges to the fact that in the wet gouges, distributed slip preferentially occurs on the pre-existing, weak clay network. This reduces the need for grain-breakage to occur before slip is able to localize, explaining the lack of a slip-hardening phase. Shear induced compaction of the wet clay-bearing gouges is also likely to generate a considerable pore-fluid overpressure within the impermeable clay network, further contributing to their weak behaviour.

The lack of resistance to frictional sliding shown by the wet clay-bearing gouges contrasts with the traditional concept that phyllosilicates, due to their velocity-strengthening nature, should have a stabilizing role in upper crustal fault zones, and has significant implications for seismic hazard in the Apennines.