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Localization-controlled transition to extreme weakening in granular fault gouge

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Observations of both ancient and active faults suggest that much slip during earthquakes occurs within thin (millimeter-scale) layers of granular fault gouge. It is therefore of primary importance to understand the rheological behavior of gouges at the conditions expected during earthquakes (slip velocities $\sim$0.1 – 1 m s^{-1}, normal stresses $>$50 MPa, total displacements typically $<$10 m). Previous experimental work at seismic slip velocities was hampered by the difficulty in confining granular materials under shear, leading to the use of low normal stresses ($<$2-3 MPa), large total displacements ($>$10 m), or unconfined gouge layers. Here, we simulate earthquake slip in 2-3 mm thick confined layers of calcite gouge by concomitantly imposing normal stresses up to 30 MPa and slip rates up to 3 m s^{-1}, for total displacements $<$ 5 m. This was achieved by using a purpose-built gouge sample chamber designed to operate with the SHIVA rotary-shear apparatus at INGV, Rome. Results from high velocity "slide-hold-slide" experiments show that gouges have a significant early phase of strengthening ($>$0.05 m of slip) that accounts in some cases for $>$50% of the experimental fracture energy. This strengthening phase is followed by weakening that initiates at a slip velocity (0.5 – 2 m s^{-1}) up to an order of magnitude higher than in solid rocks (0.05 - 0.2 m s^{-1}). Microstructural observations of experiments stopped during the transition from strengthening to weakening show that at peak strength the gouges are crosscut by a continuous c. 100-μm wide shear band that parallels the gouge layer boundaries. Immediately following the transition to weakening, the shear band internally develops discontinuous, elongate patches (up to 100 μm long and 20 μm wide) of recrystallized gouge that we interpret as local "hot spots". By the end of weakening, continued localization within the shear band forms a through-going, 2-3-μm wide slip zone that remains stable with increasing displacement. This discrete slip zone has a shiny surface appearance and is flanked by dynamically recrystallized gouge layers up to 300 μm thick with well-developed shape and crystallographic preferred orientations. Our current interpretation of the experiments involves the following; localization in the gouge layers occurs during the initial strengthening phase (accompanied by layer dilation). This causes progressively increasing inter-particle slip velocities within the zones of localization. After a critical amount of localization, the average inter-particle slip velocity is sufficiently high to induce local heating (and recrystallization) of particle contacts and a degradation in contact shear strengths. We believe that this corresponds to the onset of weakening in the gouge experiments. More generally, our results suggest that localization during the early stages of seismic slip may be one of the most important mechanical processes controlling the dynamic strength evolution of gouge-bearing faults.