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Co-seismic frictional properties and microstructures of carbonate fault rocks in nature and experiment

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In several earthquake prone areas of Europe (e.g. Italy, Greece, Turkey) destructive mainshocks, as well as associated foreshocks and aftershocks, nucleate within and propagate through thick sequences of carbonate. To understand the frictional behavior of carbonate-bearing faults during co-seismic slip we performed an experimental study on 3mm-thick layers of calcite gouge (<250μm grain size) deformed in a purpose-built sample holder using SHIVA, a rotary-shear friction apparatus at INGV, Rome. We focus on results obtained at slip velocities of 1m/s-3.5m/s, normal stresses (σ_n) between 8MPa-27MPa, and total displacements of 1m-5m. Microstructures of the deformed gouge layers are compared to those found in the principal slip zones of carbonate-bearing faults exhumed from <4km.

For a typical experiment, the frictional strength, μ, of the gouge layer increases to a peak value of 0.65-0.9 followed by a rapid decay to a lower steady-state value between 0.15-0.4, before finally undergoing dynamic strength recovery to reach a value of 0.6-0.8. Overall, our results indicate that calcite gouges are lubricated during high velocity slip up to σ_n of at least 27MPa, confirming the results of previous experiments carried out at lower σ_n (<2-3MPa). Prior to peak friction, calcite gouges are characterized by a prolonged strengthening phase (up to 30cm of slip) that we interpret as the time taken to localize deformation along a through-going slip surface (a process that also includes grain comminution and heat production). The requirement to first localize slip may also account for the observation that the critical slip velocity before the gouges start to weaken is between 80cm/s and 1m/s. The strengthening phase accounts for a significant fraction of the total experimental fracture energy. In experiments where we deform the gouge layer a second time following a hold period of seconds to minutes, the behavior during the second pulse is similar to solid cylinders of calcite marble: peak friction is obtained in <0.1cm of slip (i.e there is no prolonged strengthening phase), and the critical slip velocity required to initiate weakening is around 10cm/s.

Deformed gouge layers are crosscut by a single, highly polished slip surface. The slip surface is flanked by a 100-300μm thick zone of fine-grained (1-5μm) calcite mylonite with strong shape- and crystallographic- preferred orientations. The slip surface itself is lined by polygonal, interlocking calcite grains whose boundaries often define triple-junctions with large interfacial angles. We interpret these fabrics as a record of crystal-plastic deformation and annealing processes induced by the large temperature rise during the experiments. Highly localized zones of crystal-plasticity have recently been identified within shallowly exhumed (<3-4km) carbonate-bearing faults otherwise characterized by pervasive brittle deformation. In such cases, the calcite crystallographic- preferred orientation is identical to that produced in our experiments. We suggest that localized crystal-plasticity within slipping zones in the shallow crust may be a signature of transient thermal perturbations associated with earthquake rupture.