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Fossil Earthquakes in Limestone? Natural Clast-Cortex Grains and Constraints from Low- to High-Velocity Friction Experiments

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Many destructive earthquakes in central Italy (e.g. L'Aquila Mw 6.3, 6 April 2009), and in other areas worldwide, nucleate within and rupture through limestones. During individual earthquakes a majority of fault displacement is accommodated by thin principal slip zones (PSZs). Unlike silicate-bearing rocks, where the occurrence of solidified friction melts (pseudotachylytes) represents unequivocal evidence of ancient seismic faulting, carbonate-bearing rocks lack clear indicators of earthquake ruptures. Here, we present microstructural observations of the PSZs of seismically-active normal faults that cut limestones in central Italy, and compare these PSZs to experiments on layers of simulated calcite gouge using a low- to high-velocity rotary shear apparatus at INGV, Rome. Geological constraints indicate that the natural PSZs are exhumed from $<$2km depth and $<$100°C, whilst SEM and XRD observations suggest they are composed of c. 100% calcite. The PSZs consist of a 2-10 mm thick layer of ultracataclasite that contains peculiar rounded grains up to c.1mm in diameter consisting of a central (often angular) clast surrounded by a laminated outer cortex of ultra-fine grained calcite. These *clast-cortex grains* resemble other types of accretionary grain that are thought to form during fluidization processes, including *accretionary lapilli* within pyroclastic surges, and *armoured carbonate grains* from the basal decollements of mega-landslides. We suggest that the clast-cortex grains within the limestone slip zones formed during fluidization of the ultracataclasite layer at high strain rates during earthquake rupture. To test this idea, we are carrying out a series of rotary-shear experiments using 3 mm-thick layers of wet (20 wt% distilled H_2O) calcite gouge ($<$125 μm) deformed at a constant normal stress of 1.5 MPa and slip velocities between 1 mm/s and 6.5 m/s. At slip velocities $<$10 cm/s the calcite gouge displays a steady-state frictional strength (μ) of 0.6-0.7 and is dominated by cataclastic fabrics that are cross-cut by well-organized Riedel shears. At slip velocities $>$1 m/s (i.e. seismic slip velocities), the calcite gouge shows an initial peak friction of 0.5-0.7 followed by a rapid decay in friction (in $<$1m of slip) to a steady-state value of 0.1-0.3. In other words, the calcite gouge dynamically weakens at high slip rates. SEM observations of the gouge layers deformed at $>$1 m/s show a localized zone of deformation 200-300 μm thick; inside this zone relatively large, angular clasts of calcite are wrapped by an outer cortex of much finer-grained material. Such microstructures closely resemble simple examples of natural clast-cortex grains. Although the accretionary mechanisms that allow such grains to form are still under investigation, we tentatively suggest that clast-cortex grains may be a diagnostic microstructure of seismic slip in limestones. Future experiments will cover a wider range of slip velocities (1 μm/s – 6.5 m/s) and normal stresses (1-10 MPa) and will be used to constrain the velocity/stress regime in which clast-cortex grains form, and to investigate their microstructural evolution with increasing slip.