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Microscale cavitation as a mechanism for nucleating earthquakes at the base of the seismogenic zone

Berend Verberne, Jianye Chen, André Niemeijer, Hans de Bresser, Gill Pennock, Martyn Drury, and Chris Spiers
Dept. of Earth Sciences, Utrecht University, Utrecht, The Netherlands (b.a.verberne@uu.nl)

Major earthquakes frequently nucleate near the base of the seismogenic zone, close to the brittle-ductile transition. Fault zone rupture at greater depths is inhibited by ductile flow of rock. However, the microphysical mechanisms responsible for the transition from ductile flow to seismogenic brittle/frictional behaviour at shallower depths remain enigmatic. We report ring shear experiments on simulated calcite fault gouge (median grain size $\sim$20 μm), under conditions close the flow-to-friction transition, using recovered samples for microstructural analysis. Gouge layers sheared at low sliding velocity (v = 0.1 μm/s) showed mechanical and microstructural characteristics suggestive of homogeneous, ductile flow, while samples sheared faster (1 <_ v <_ 100 μm/s) exhibited frictional behaviour, and localized slip. A boundary shear developed in a run performed at 100 μm/s showed uniform birefringence colours and uniform extinction, and an internal structure characterized by $\sim$0.3 to 1 μm sized polygonal grains and intergranular cavitation. Electron backscatter diffraction data on the shear band grains revealed that the calcite {104} or r-plane and <bar201> direction are aligned sub-parallel to the shear plane and shear direction respectively. Our interpretation is that the flow-to-friction transition in our experiments is characterized by a transition from dislocation and diffusion creep to dilatant deformation, involving incompletely-accommodated grain boundary sliding. With increasing shear rate or decreasing temperature, dislocation and diffusion creep become too slow to accommodate the imposed strain rate, leading to porosity development, hence weakening, strain localization, and a switch from stable flow to potential runaway fault rupture. The observed shear instability, triggered by the onset of microscale cavitation, provides a key mechanism for nucleating earthquakes at depths normally associated with ductile flow, corroborating the importance of shear localization and cavitation close to the brittle-ductile transition.