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How do fluid-rock interactions control the frictional and transport properties of fault rocks?

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Faults in the upper crust form not only the principal loci of deformation but also key barriers to, or else conduits for, fluid flow. Their reactivation behaviour, frictional strength, slip stability, and transport properties play an essential role in controlling processes such as natural seismicity, induced seismicity, hydrocarbons trapping, and fault mineralisation. These properties are somehow determined by competition between cataclastic deformation mechanisms, creating or connecting porosity, and time-dependent deformation and mass transfer processes, causing compaction and healing. Under upper crustal (low temperature) conditions, fluid-rock interactions provide the dominant time-dependent processes. This contribution considers how such processes influence the evolution of the frictional and transport properties of fault rocks from an experimental and microphysical perspective.

In recent years, experiments conducted at Utrecht have enabled the compaction and porosity/permeability reduction behaviour of granular geomaterials such as fault gouges to be studied under a wide range of conditions favouring the operation of fluid-enhanced deformation mechanisms. These mainly 1-D compaction experiments have allowed pressure solution to be activated and characterised in granular quartz and calcite, and in a variety of granular evaporites. Comparison of the kinetics of compaction with microphysical models has enabled the elementary rate controlling mechanisms to be identified and hence a basis obtained for constructing compaction equations that can be extrapolated to natural conditions. These yield estimates of fault healing and sealing rates ranging from days to thousands of years, depending on fault rock composition, grain size, effective normal stress and temperature.

The effects of fluid-rock interaction on the frictional slip behaviour of gouge-filled faults, and on porosity-permeability evolution in such faults, are more complex. Low velocity friction experiments on evaporite and quartz gouges, with varying amounts of clay, show that fluid-assisted deformation processes are a requirement for obtaining strongly velocity-weakening slip capable of nucleating seismogenic behaviour. The frictional behaviour of calcite gouge, however, is less affected by fluids with velocity weakening apparently being controlled by time-dependent crystal plastic flow. Other fluids, such as supercritical carbon dioxide, have little effect on the frictional behaviour of either dry or wet gouges. An important trend emerging from all materials investigated at Utrecht to date is a transition from velocity strengthening at low temperatures, to velocity weakening at intermediate temperatures, and back to velocity strengthening at high temperatures, delineating three regimes of frictional behaviour. Interestingly, in wet evaporite and quartz-bearing systems, the velocity weakening regime seems to be characterised by significant porosity development.

Microphysical modelling of combined microgranular flow plus grain scale creep in localised gouge zones predicts similar three-regime behaviour to that seen in our gouge friction experiments. The key factor here controlling both frictional behaviour and porosity turns out to be competition between dilatation due to granular flow and compaction by the dominant creep mechanism. Together, the experimental and modelling results provide promising progress towards a mechanism-based constitutive framework suitable for computing the evolution of both the frictional behaviour and transport properties of gouge-filled faults under crustal conditions where fluid-assisted deformation mechanisms dominate.