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Effects of fluids on frictional strength, slip stability and porosity of gouge-filled faults

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This contribution considers what we know about the frictional and transport properties of active faults from observations on natural fault rocks and from experiments, and how microphysical modelling is gradually leading to a mechanistic basis for predicting Rate and State dependent Friction (RSF) under conditions where fluids are chemically active.

Microstructural studies on natural fault rocks deformed under mid and upper crustal conditions, including those recovered from drilling projects such as SAFOD, frequently show evidence for i) fluid-related reactions forming an anastomosing phyllosilicate network, ii) pressure solution and cataclasis of clast phases, and iii) dilatation and cementation of fractures, cracks and pores. Moreover, decades of friction experiments on simulated granitic, gabroic, quartz and more recently calcite and phyllosilicate-quartz gouges, at elevated temperatures, have shown that the presence of an aqueous pore fluid, or even water vapour, drastically changes the frictional behaviour of these materials. This has long been recognised to point to fluid-assisted deformation mechanisms, such as stress corrosion cracking or pressure solution, as playing a role in determining frictional behaviour. Indeed, recent low velocity friction experiments on evaporite and quartz gouges, with varying amounts of phyllosilicate, show that fluid-assisted deformation of the evaporite or quartz clast phases are a requirement for strongly velocity-weakening slip capable of causing stick-slip fault behaviour. Other fluids, such as supercritical carbon dioxide, have little effect on the frictional behaviour of either dry or wet gouges, with the exception of smectite rich gouges. An important trend emerging from all gouges containing quartz, and tested at hydrothermal conditions and sliding velocities below 100 micrometer/s, 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 steady state frictional behaviour. In experimental studies where dilation has been measured or estimated, the velocity weakening regime seems further characterised by significant porosity development.

Putting all this information together leads to the conclusion that a micromechanism-based description of the frictional behaviour of gouge-filled faults, under mid to upper crustal conditions, needs to account for mechanisms such as pressure solution and stress corrosion cracking of clast phases, and for both dilatant and non-dilatant slip on intervening, weak phyllosilicates. First attempts to do this, assuming pressure solution as the fluid-assisted clast deformation mechanism, successfully predict three-regime behaviour of the type seen in hydrothermal gouge friction experiments on phyllosilicate-quartz mixtures, as well as other key observations. Both steady state and transient frictional behaviour similar to that seen in experiments can be predicted. The key factor here controlling both frictional response (i.e a, b, a-b and Dc in the terminlogy of RSF modelling) and porosity turns out to be competition between dilatation due to intergranular slip on phyllosillicates versus flow and compaction by pressure solution. In particular, velocity weakening slip, hence rupture nucleation, and postseismic fault healing are predicted to be caused by the effects of the fluid phase in promoting compaction by pressure solution during dilatant shear.