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Fluid-injection and the mechanics of frictional stability of shale-bearing faults

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Fluid overpressure is one of the primary mechanisms for triggering tectonic fault slip and human-induced seismicity. This mechanism is appealing because fluids lubricate the fault and reduce the effective normal stress that holds the fault in place. However, current models of earthquake nucleation, based on rate- and state- friction, imply that stable sliding is favored by the increase of pore fluid pressure. Despite this apparent dilemma, there are a few studies on the role of fluid pressure in frictional stability under controlled, laboratory conditions. Here, we describe laboratory experiments on shale fault gouge, conducted in the double direct shear configuration in a true-triaxial machine. To characterize frictional stability and hydrological properties we performed three types of experiments: 1) stable sliding shear experiment to determine the material failure envelope resulting in fault strength of μ=0.28 and fault zone permeability (k $\sim$ 10-19m2); 2) velocity step experiments to determine the rate- and state- frictional properties, characterized by a velocity strengthening behavior with a negative rate parameter b, indicative of stable aseismic creep; 3) creep experiment to study fault slip evolution with increasing pore-fluid pressure. In these creep experiments fault slip history can be divided in three main stages: a) for low fluid pressure the fault is locked and undergoes compaction; b) with increasing fluid pressurization, we observe aseismic creep (i.e. v=0.0001 μm/s) associated with fault dilation, with maintained low permeability; c) As fluid pressure is further increased and we approach the failure criteria fault begins to accelerate, the dilation rate increases causing an increase in permeability. Following the first acceleration we document complex fault slip behavior characterized by periodic accelerations and decelerations with slip velocity that remains slow (i.e. v$\sim$200 μm/s), never approaching dynamic slip rates. Surprisingly, this complex slip behavior is associated with fault zone compaction and permeability increase as opposite to the dilation hardening mechanism that is usually invoked to quench the instability. We relate this complex fault slip behaviour to the interplay between fault weakening induced by fluid pressurization and the strong rate-strengthening behaviour of shales. Our data show that fault rheology and fault stability is controlled by the coupling between fluid pressure and rate- and state- friction parameters suggesting that their comprehensive characterization is fundamental for assessing the role of fluid pressure in natural and human induced earthquakes.