Frictional instability under fluid stimulation: insights from load-controlled experiments on pre-existing faults

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Introduction and method

Fluid pressure is an important parameter controlling fault reactivation as well as natural and induced seismicity. The effective normal stress is linearly reduced by an increase in fluid pressure (P_f) with $\sigma_{eff}= \sigma_n (1-\alpha P_f)$ which lowers the frictional strength of the fault increasing the potential for fault reactivation and seismic slip. The coefficient α is commonly assumed as equal to one and describes the hydro-mechanical coupling between the state of stress and fluid pressure. However, injection of fluids at high flow rates can affect the validity of this assumption over the entire fault volume resulting in rather unpredictable frictional instabilities. To investigate the role of fault injection rates in seismic fault reactivation, we performed four tests using the rotary shear apparatus SHIVA (Di Toro et al. 2010), installed in the HPHT laboratory at INGV, Rome (Italy). Samples consisted in hollow cylinders of Carrara marble (50/30 mm ext/int diameter) inserted in a vessel for fluid confinement (Violay et al. 2013) and put in frictional contact under an effective normal stress σ_{eff} =10 MPa. The fluid was water in equilibrium with Carrara marble. For comparison, one experiment was performed (s479) under room humidity (RH) conditions and one experiment at constant fluid pressure of 5 MPa (s814). In both cases, the shear stress was increased stepwise until the achievement of a frictional instability at a shear stress $\tau=\tau_p$ (i.e. slip rate > 1 cm/s, color coded in Figure 1). Two other experiments were performed (s816 and s909) at an injection rate of 0.5 MPa/ 20 s and 0.1 MPa/ 30 s respectively under a constant initial shear stress $\tau \sim 70\% \ \tau_p$(RH). For experiment s814, s816 and s909 the fluid pressure was imposed radially from the outer ring towards the inner of the hollow cylinders.

Results

The shear strength (τ_p) of the experimental fault under RH, constant fluid pressure and under a slow fluid injection rate (Q=0.1 MPa/ 30 s) shows no significant deviations from the Byerlee-Coulomb law for fault reactivation with a coefficient of apparent friction ranging between 0.6 and 0.8. Instead, under a fast fluid injection rate (Q=0.5 MPa/ 20 s), the experimental fault was less sensitive to fluid injection and the apparent friction coefficient to induce the frictional instability was $\mu = 1.3$, assuming $\alpha=1$.

Discussion

To explain the anomalous high value of the apparent friction coefficient estimated for experiment s816, we question the physical meaning of α. The assumption that $\alpha=1$ is valid in the case that solid bulk volume changes are totally counteracted by pore volume changes (Jaeger, Cook, and Zimmerman, 2005). However, α can differ significantly from one at the edge of the loaded experimental fault where fluids can penetrate trough the slipping zone. Here, the fault is critically stressed and subjected to transient elastic and fluid transport properties far from the equilibrium. In experiment s909, we tested the effect of four repeating cycles of loading and unloading by fluid pressure (Figure 1). The triggering of the main frictional instability was progressively delayed and the friction increased gradually from 0.6 (episode 1.) to 0.8 (episode 4.) in the Mohr space. This mechanical behaviour suggests that fault permeability decreased during the test, probably because of the gouge formation and wearing during transient slip events. The reduction of the permeability rendered less effective the fluid penetration within the experimental slipping zone inhibiting the achievement of the equilibrium between the imposed fluid pressure disturbance and the fluid pressure within the fault.

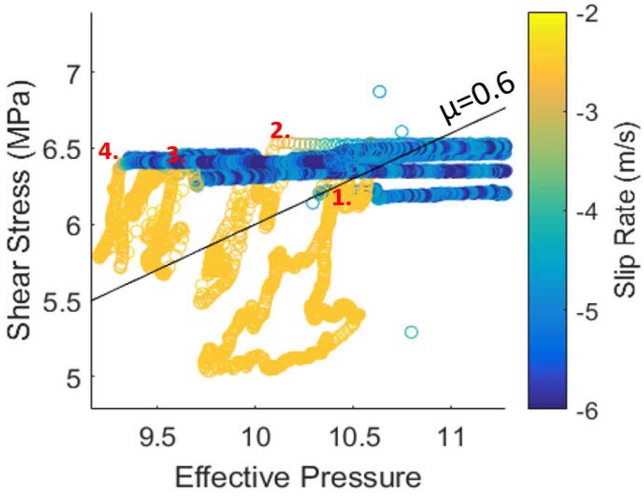

Fig. 1: experiment s909 was performed with a fluid injection rate of 0.1 MPa / 30 s and consisted in 4 cycles (red numbers) of fault loading by fluid pressure increase (consequently the effective pressure decreases as reported in abscissa). The series of experiments with fluid pressure show the high sensitivity of fault reactivation to fluid pressure. However, cycle after cycle, the friction coefficient at fault reactivation is gradually shifted towards higher friction values.

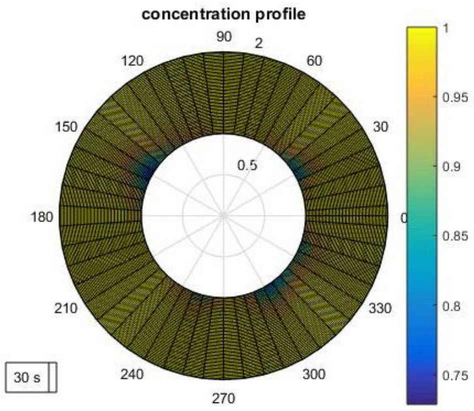

Fig. 2: numerical model of fluid propagation within the experimental fault. After 30s, the pressurized fluids penetrated the entire slipping zone (water concentration = 1) under the arbitrary assumption h_d=100 μm.

The propagation of the fluid pressure disturbance obeys the Navier-Stokes equation. Its simplest solution is the cubic law (Witherspoon et al., 1980) for a laminar flow through parallel plates separated by an aperture h_d. Recalling the Darcy's law for flow through porous media, the permeability can be rewritten in terms of h_d (m^2). By modelling water flow through the hydraulic aperture under a fluid pressure step of 0.1 MPa, assuming an average h_d = 100 μm and allowing random heterogeneities of h_d on the fault plane, we estimated that after 30 sec the fluid penetrated radially almost the entire fault surface (Figure 2) and was effective in reactivating the fault (Figure 1, episode 1.). The model suggests that the fault coupling coefficient α varies with the hydraulic aperture and the penetration time t_p,, i.e. $\alpha = f(h_d, t_p)$ which, as demonstrated in the case of experiment s909 (Figure 1), can evolve as h_d evolves. Using the cubic law, with a direct measure of t_p, of the effective pressure gradient, and a measured initial condition on h_d (namely the initial fault roughness) we aim at constraining the permeability change during the experiments and finding the best functional form of α in critically loaded faults.

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