Geophysical Research Abstracts
Vol. 21, EGU2019-13165, 2019
EGU General Assembly 2019

Earthquake nucleation in presence of viscous fluids: Thermal Pressurization or Elastohydrodynamic Lubrication?

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Fluids are pervasive in most fault zones and contribute to the nucleation and the propagation of upper-crustal earthquakes. Fluid pressure reduces the normal effective stress, lowering the frictional strength of the fault and potentially triggering earthquake ruptures. Fluid injection induced earthquakes, such as those nucleating in geothermal reservoirs, evidence the effect of fluid pressure on the fault stress. While numerous studies estimated the frictional strength of faults based on fluid pressure and flow rate, here we investigate the role of fluid viscosity during earthquake nucleation.

We reproduced the earthquake cycle in experimental granitic faults under both room-humidity and drained pore fluid conditions (i.e., P_f=2 MPa, with fluids viscosities of 1, 10, 108 and 1226 mPa.s at 20 °C), using the rotary shear apparatus SHIVA. The experimental procedure consisted in increasing step-wise the shear stress ($\Delta\tau$=0.5 MPa every t=1000 s) acting on the faults loaded at a constant effective normal stress σ_n=10 MPa and allowing the slip-rate and slip to adjust spontaneously. In all the investigated environmental conditions, once a shear stress $\geq$6 MPa (corresponding to a friction coefficient $\geq$0.6) was overcome, the samples underwent to successive irregular slip episodes with a maximum (regulated by the operator) slip-rate of 0.1 m/s. This unstable slip phase was accompanied by multiple and rapid spontaneous shear stress drops. It is possible to divide this unstable phase in a sequence of short-lived events ending with a long-lived slip-event. Short-lived events had slip distances smaller than 0.25 m during which the shear stress, after dropping from the imposed shear stress τ_{imp} to a minimum value τ_{min}, recovered spontaneously up to a peak shear stress τ_{peak}. We compared the stress drop for each short-lived event induced during experiments conducted in the different fluid saturated conditions with the theoretical stress drops estimated considering the thermal pressurization (TP) and the Elastohydrodynamic lubrication (EHL) processes.

Our results show that (1) the viscosity of the fluid does not influence the onset of the fault reactivation and (2) all experiments performed with pressurized fluids followed the same trend in terms of stress drops versus slip evolution during the main events. These suggest that a single mechanism or a combination of mechanisms were controlling earthquake nucleation in fluid-saturated condition. The numerical models of TP explain well the fault weakening measured in the experiment conducted under water-saturated conditions (viscosity: 1 mPa.s), and the first short-lived slip-events observed using fluids with intermediate viscosity. However, TP models overestimate the weakening behavior of the short-lived events following the first one and all the short-lived events with a more viscous fluid. Instead, the EHL models estimate closely the latter short-lived events for intermediated viscosity and all the short-lived events in presence of high viscous fluid.

In conclusion, the experimental evidence suggests that while the injection of more viscous fluids in pre-loaded faults does not prevent the onset of fault reactivation, the increasing viscosity of the fluids controls the activation of the dominant weakening mechanism during the short-lived slip-events, by making the EHL prevailing on the TP.