Fluid viscosity controls earthquakes nucleation

Chiara Cornelio[1]*, Elena Spagnuolo[2], Francois Passelègue[1], Giulio Di Toro[3], Marie Violay[1]

[1] Laboratory of Experimental Rock Mechanics EPFL, Lausanne, Switzerland
[2] Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy
[3] Università degli Studi di Padova, Padua, Italy
* chiara.cornelio@epfl.ch

Introduction

Understanding how pore fluid viscosity controls fault mechanics can shed a new light on induced seismicity in engineering reservoirs. In particular, fluids involved during hydraulic fracturing purposes, waste water disposal, CO_2 and CH_4 storage have dynamic viscosities ranging from 1 mPa · s (water at 20°C) to 10^3 Pa · s (Economides, M.J. and Molte, K.G., 2000). Here we investigate in the laboratory the spontaneous nucleation of fault instability when the latter is subjected to stress perturbations in the presence of pressurized fluids with increasing viscosities.

Methods and results

We tested the effect of stress perturbations on experimental faults under both room-humidity conditions and in the presence of pressurized fluids with four different viscosities. We used a rotary shear apparatus installed at INGV-Rome (Di Toro et al. 2010) that, thanks to the large slip imposed to the samples, allowed us to investigate both precursory patterns and stability criteria for earthquake nucleation. The experimental procedure consisted in increasing step-wise the shear stress ($\Delta\tau = 0.5$ MPa every $\Delta t = 200$ s for $\tau < 3$ MPa, $\Delta\tau = 0.5$ MPa every $\Delta t = 1000$ s for $\tau > 3$ MPa) acting on faults consisting of two cylindrical samples (50 mm diameter) of granite in contact under a constant effective normal stress $\sigma_n' = 10$ MPa. The slip rate (V) and slip distance (δ) were allowed to adjust spontaneously following the shear stress perturbations until the frictional strength of the experimental fault decreased so rapidly to induce an abrupt acceleration of the slip rate (i.e., "main frictional instability", Fig 1). To avoid sample destruction, the maximum allowed slip rate at this stage was 0.1 m/s which is a typical seismic slip rate. The experiments with fluids were performed under drained conditions by keeping constant the fluid pressure $P_f = 2$ MPa in the pressure vessel (Violay et al. 2013). The fluid used in our experiment are composed by different proportions in weight of distilled water and glycerol 99.9 % in order to obtain four different fluid viscosities: 1.002 mPa · s (pure distilled water), 10.8 mPa · s (40/60%wt water/glycerol), 109 mPa · s (15/85%wt water/glycerol) and 1226 mPa · s (pure glycerol) at 20°C.

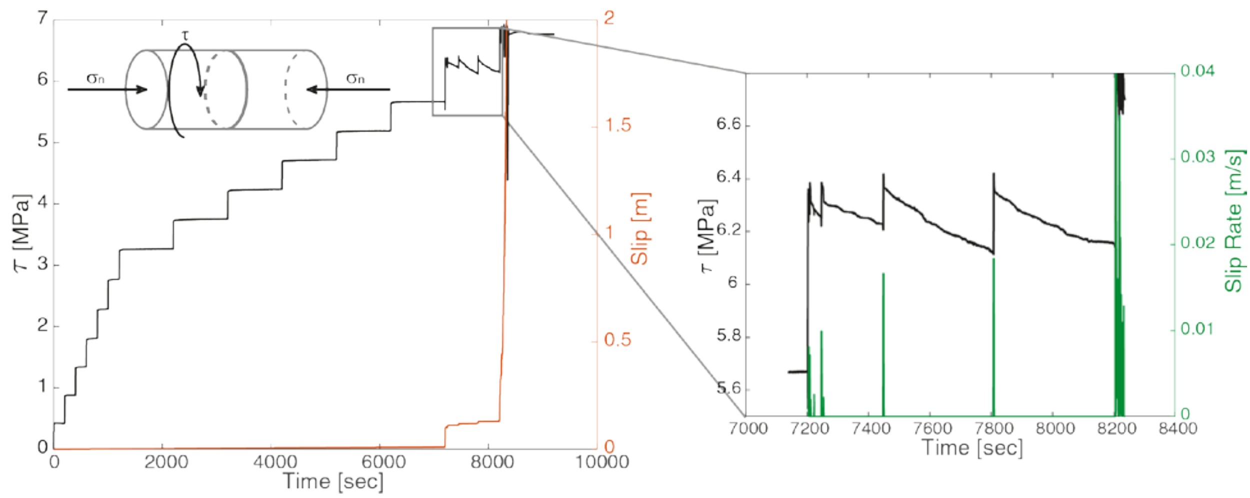

Fig. 1: Torque control experiment s1409 performed under room-humidity conditions. a) Evolution of shear stress τ (black line) and slip (orange line) during the entire duration of the experiment. b) Close up of the test during the precursory events before the main frictional instability. The slip rate (green line) increased at each slip event until it reached (time = 8200 s) the maximum allowed slip rate of 0.1 m/s.

Under room-humidity conditions, the increase in shear stress resulted in the spontaneous evolution from slow slip rate (V << 0.01 cm/s) and quite continuous slip (sort of creep) to short-lived slip but high slip rate (0.01 < V < 1 cm/s) events (on-fault seismic precursors) and eventually to long-lasting and high slip rate (V > 10 cm/s) slip events (on-fault main seismic event). Precursory activities manifested as shear stress oscillations due to the feedback between the shear stress imposed by the engine of the rotary machine and the evolving frictional strength of the experimental fault (Fig 1.b).

In presence of viscous fluids, the imposition of an increase in shear stress resulted in the direct evolution from the slow slip rate behaviour to fast slip rate event, without precursory frictional instabilities. The nucleation of the fast slip rate event strongly depended on the fluid viscosity, as it occurred at smaller imposed shear stresses with increasing viscosities (Table 1). In particular, for an increase in viscosity from $1 \text{ mPa} \cdot \text{s}$ (water) to $1226 \text{ mPa} \cdot \text{s}$ (pure glycerol), the shear stress necessary to destabilize the fault decreased from ~ 6.5 MPa to ~ 5 MPa.

Fast slip events terminated spontaneously after a short weakening stage because of a large slip re-strengthening. This stress recovery allowed us to proceed with the imposition of a new stress step. The slip rate during any of those spontaneous fast slip events was mainly influenced by the composition of the fluid. For the experiments performed with water, the maximum slip rate (V) achieved for each event increased gradually with the applied shear stress from a minimum of $\sim 0.04 \text{ m/s}$ at $\tau = 6.5$ MPa to a maximum of 0.1 m/s at $\tau = 8$ MPa. Using the mixtures of water/glycerol and pure glycerol, the slip rate of the first event reached directly the maximum slip rate of $\sim 0.1 \text{ m/s}$ also for lower value of imposed τ.

Table 1: Shear stress and maximum slip rate of the first events for the different conditions (room humidity and four viscosities).

η [mPa · s]	-	1	10.8	109	1226.6
τ 1st event [MPa]	6.385	6.329	6.106	6.169	5.136
V max [m/s]	0.009	0.0385	0.1024	0.1144	0.3763

In conclusion, the experimental evidence suggests that the injection of more viscous fluids in pre-loaded fault results in large seismic slip events without seismic precursors. As a consequence, also the logistic in seismic monitoring for seismic hazard should change with the type of fluid injected: for low viscosity fluids the seismic monitoring with operational protocols tied into a 'traffic light' system might be enough. For high viscosity fluids, seismic attenuation and especially measurements of deformation rates are more important.

References

Economides, M. J., & Nolte, K. G. (2000). *Reservoir stimulation*. Chichester, England: Wiley

Di Toro, G. et al. (2010), From field geology to earthquake simulation: A new state-of-The-art tool to investigate rock friction during the seismic cycle (SHIVA), Rend. Lincei, 21(SUPPL. 1), doi:10.1007/s12210-010-0097-x

Violay, M., S. Nielsen, E. Spagnuolo, D. Cinti, G. Di Toro, and G. Di Stefano (2013), Pore fluid in experimental calcite-bearing faults: Abrupt weakening and geochemical signature of co-seismic processes, Earth Planet. Sci. Lett., 361, doi:10.1016/j.epsl.2012.11.021