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Thermo-mechanical pressurization of experimental faults in cohesive rocks during seismic slip

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ABSTRACT

Earthquakes occur because fault friction weakens with increasing slip and slip rates. Since the slipping zones of faults are often fluid-saturated, thermo-mechanical pressurization of pore fluids has been invoked as a mechanism responsible for frictional dynamic weakening, but experimental evidence is lacking. We performed friction experiments (normal stress 25 MPa, maximal slip-rate $\sim 3\ \mathrm{ms}^{-1}$) on cohesive basalt and marble under (1) room-humidity and (2) immersed in liquid water (drained and undrained) conditions. In both rock types and independently of the presence of fluids, up to 80% of frictional weakening was measured in the first 5 cm of slip. Modest pressurization-related weakening appears only at later stages of slip. Thermo-mechanical pressurization weakening of cohesive rocks can be negligible during earthquakes due to the triggering of more efficient fault lubrication mechanisms (flash heating, frictional melting, etc.).

1. Introduction

During earthquakes, few millimetres thick slip zones within fluid-saturated, cohesive or non-cohesive rocks are sheared over several meters (80 m for the Tohoku 2011 Mw 9.0 earthquake, Fujiwara et al., 2011) at slip rates of meters per second and under normal stresses up to hundreds of MPa (Sibson, 1973; Rice, 2006). The frictional power per unit area (product of the slip rate per frictional shear stress, in the range of $1\text{–}100\ \mathrm{MW\,m}^{-2}$) is dissipated as heat and rock fragmentation in the slipping zone (Sibson, 1973). This large power triggers several mechano-chemical processes that may induce frictional weakening (Di Toro et al., 2011; Goldsby and Tullis, 2011; Reches and Lockner, 2010). Thermo-mechanical pressurization (TMP) of pore fluids trapped is one of the possible processes responsible for fault dynamic weakening (Sibson, 1973; Rice, 1992, 2006; Lachenbruch, 1980; Brantut et al., 2010; Bizzari and Cocco, 2006; Segall and Rice, 2006; Wibberley and Shimamoto, 2005). Given the widespread presence of fluids in natural slipping zones, TMP has been thoroughly investigated from a theoretical point of view. TMP models are based on two competing processes: fluid and rock expansion in response to shear heating and the fluid storage capacity of the rock (Rice, 2006; Segall and Rice, 2006; Platt et al., 2014).

Several experimental studies were carried on to investigate TMP (Mizoguchi et al., 2009; Brantut et al., 2008; Ferri et al., 2010; De Paola et al., 2011; Mitchell et al., 2015; Faulkner et al., 2011; Ujiie et al., 2011, 2013). Experiments approached seismic deformation conditions by imposing slip rates (V) of $\sim 1\ \mathrm{ms}^{-1}$, slip (δ) up to tens of meters, and effective normal stresses (σ_n^{eff}) of tens of MPa on clay-, calcite- and dolomite-rich gouges under room-humidity and wet conditions. The measured large weakening (up to 80–90% of friction drop at $1\ \mathrm{ms}^{-1}$) was attributed to: (1) in part (<20%) thermochemical pressurization associated to the breakdown of clays and release of H_2O (Brantut et al., 2008, 2010; Ferri et al., 2010) or to the breakdown of calcite and dolomite and release of CO_2 (De Paola et al., 2011; Mitchell et al., 2015) in the case of room-humidity experiments and, (2) thermal pressurization in the case of wet experiments on clay-rich gouges (Faulkner et al., 2011; Ferri et al., 2010; Ujiie et al., 2011, 2013). However, technical issues related to fluid and gouge confinement impeded measuring the pore fluid pressure in the sample chamber. We installed on the rotary shear machine SHIVA (Slow-to-High-Velocity-Apparatus,

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INGV Rome, Suppl. Material S1) an on-purpose designed pressure-vessel that allows shearing cohesive rocks immersed in fluids and to measure the pore fluid pressure during the experiments (Violay et al., 2012). Previous experiments were performed under drained conditions on Carrara marbles and gabbros (Violay et al., 2012, 2014a, 2014b). We report new results obtained by shearing basalts and Carrara marbles under undrained conditions. Though the actual experimental configuration does not allow shearing saturated gouges, the results for cohesive rocks are intriguing: the contribution of TMP during shearing of cohesive rocks at seismic slip rates is negligible compared to the contribution from other weakening mechanisms.

2. Material and methods

To investigate seismic slip in the presence of pore fluids, 33 friction experiments (Table 1) were conducted at room temperature on hollow cylinders (50/30 mm external/internal diameter) of Etna basalt (Electron Micro-Probe Analysis reported in Table 2) and Carrara marble (99.9% calcite, X-Ray Diffraction and X-Ray Fluorescence analysis, Violay et al., 2012). Samples were jacketed with aluminium rings, sealed with epoxy to prevent fluid leaks and inserted in the fluid pressure vessel (Nielsen et al., 2008; Suppl. Material S1). The description of SHIVA (Di Toro et al., 2010; Niemeijer et al., 2011) and of the experimental configuration used to perform experiments with pressurized fluids can be found in Suppl. Material S1. The main difference with respect to previous studies conducted with fluids (Violay et al., 2012, 2014a, 2014b) was the disposition of the closed valves, which allowed imposing undrained conditions (see Suppl. Material S1 for full description). Experiments were performed (1) under room-humidity conditions and immersed in water, (2) drained conditions (the specimen is saturated and continuously connected to the water reservoir, (Paterson and Wong, 2005), resulting in constant fluid pressure and preventing fluid pressurization) and (3) undrained conditions (the specimen was first saturated and then isolated from the water reservoir: fluid pressurization was induced by reduction in pore volume, (Paterson and Wong, 2005) and by increase in fluid volume due to thermal expansion during shearing). A K-Type thermocouple was inserted at about 3 mm from the slip surface of the sample to measure the temperature evolution of the fluid during the experiments. The thermocouple was installed in the "stationary side" (i.e., normal stress loading column) of SHIVA.

Experiments were performed by spinning two rock cylinders at accelerations of 7.8 ms^{-2}, $V = 3\ \mathrm{ms}^{-1}$, $4\ \mathrm{m} < \delta < 8\ \mathrm{m}$, normal stress ($\sigma_n$) from 15 to 35 MPa and initial fluid pressure $P_f(t_0) = 5$ MPa (Violay et al., 2012, 2014a, 2014b). Mechanical data (axial load, torque, slip, angular rotation) were acquired at a frequency up to 25 kHz. δ, V and shear stress (τ) were determined using methods described in Di Toro et al. (2010), Niemeijer et al. (2011) and Tsutsumi and Shimamoto (1997). The two rock-types were selected because are common crustal rocks and for their relatively low porosity ($< 5\%$) and low permeability ($<10^{-17}\ \mathrm{m}^2$) (e.g., Vinciguerra et al., 2005). The slip zones of experiments conducted on basalts could be recovered because the two rock cylinders were welded by glass due to the solidification of the frictional melt produced during shearing. The microstructures were investigated with an optical microscope and electron probe micro-analyzer (JEOL, JXA-8200 at ETH, Zurich). The chemical compositions of grains and glasses were determined on carbon-coated, polished thin sections using an Electron Probe Micro-Analyzer (EPMA) JEOL, JXA-8200 (ETH, Zurich) with a focused beam about 1 μm in diameter under accelerating voltage of 15 kV and current 15 nA. The slipping zones of experiments conducted on Carrara marble could not be recovered *in-situ* (only few dispersed remnants were found) because they consisted of non-cohesive material that was flushed away during the ejection of the fluid from the vessel after the experiment.

3. Results

3.1. Mechanical data

Experiments performed under identical ambient and deformation conditions resulted in systematically reproducible mechanical data for both Etna basalt and Carrara marble (Figs. 1–4). We present the measurements of the friction coefficient for comparison with data obtained at different initial effective normal stresses and the measurements of the shear stress for comparison of data obtained at a given imposed initial effective normal stress (all mechanical data are summarized in Table 1). We define the friction coefficient (μ) based on effective normal stress ($\mu = \tau/\sigma_n^{eff}(t)$ or Terzaghi's principle for $\sigma_n^{eff}(t) = \sigma_n(t) - \alpha P_f(t)$ with $\alpha = 1$, incorporating instantaneous σ_n and P_f). However, since $P_f(t)$ varies during the experiment due to effect of thermal expansion, to illustrate more clearly the effect of TMP we also present the results in Fig. 4 based on the initial value of $P_f(t_0)$ alone ($\mu = \tau/\sigma_n^{eff-0}(t)$ with $\sigma_n^{eff-0}(t) = \sigma_n(t) - P_f(t_0)$).

For Etna basalt, the coefficient of friction decayed almost exponentially from a peak value $\mu_\mathrm{p} = 0.59 \pm 0.08$ at about slip initiation (i.e., 0.64 ± 0.05 for room humidity conditions, 0.58 ± 0.05 for drained and 0.53 ± 0.07 for undrained conditions) to a steady-state value μ_ss that decreased with increasing effective normal stress (Figs. 1 and 4). The μ_ss was determined from the average value of the friction coefficient between 4.5 and 5.5 meters slip, except for experiment s921 where μ_ss was determined between 2.5 and 3.5 meters slip. The initial decay of the friction coefficient (and thus of the shear stress) was similar independently of the ambient conditions (Fig. 3). At $\sigma_n^{eff}(t_0) = 20$ MPa (i.e. σ_n^{eff} at the initiation of the experiment or $P_f(t_0)$), the residual friction coefficient after 5 cm of slip ranged from $\mu_{\mathrm{r\_5\,cm}} = 0.20$–$0.25$ for the room humidity (s485 and s541), to $\mu_{\mathrm{r\_5\,cm}} = 0.26$–$0.28$ for the drained (s921 and s926) and to $\mu_{\mathrm{r\_5\,cm}} = 0.22$–$0.24$ for the undrained (s922, s925, s927 and s933) experiments (Table 1). The $\mu_{\mathrm{r\_5\,cm}}$ corresponded to a percentage of friction drop with respect to μ_p (or $\%\Delta\mu = 100\ (\mu_{\mathrm{r\_5\,cm}} - \mu_\mathrm{ss})/(\mu_\mathrm{p} - \mu_\mathrm{ss})$) ranging from 80.2% (s485, room humidity conditions), to 56.4% (s921, drained conditions) (Fig. 4, and Table 1). Given the larger μ_p in room humidity experiments, the drop in percentage of the friction coefficient in the first 5 cm of slip was slightly larger in room humidity conditions ($73.06 \pm 5.24\%$) than in both drained ($67.96 \pm 8.36\%$) and undrained ($68.35 \pm 3.65\%$) conditions (Fig. 4).

Instead, the steady-state shear stress (τ_ss, was determined from the average value of shear stress between 4.5 and 5.5 meters slip, except for experiment s921 where τ_ss was determined between 2.5 and 3.5 meters slip) was about 20% lower under undrained than under drained and room-humidity conditions, for similar V, δ, and initial $\sigma_n^{eff}(t_0)$ (Figs. 2, 3, Suppl. Material S2). For instance, at initial $\sigma_n^{eff}(t_0) = 20$ MPa, the coefficient of friction decayed from a peak value $\mu_\mathrm{p} = 0.55 \mp 0.07$ (corresponding to a shear stress of 11 ± 1.4 MPa) towards a steady-state value $\mu_\mathrm{ss} = 0.11 \mp 0.01$ (shear stress of 2.2 ± 0.2 MPa) under room-humidity conditions, $\mu_\mathrm{ss} = 0.11 \mp 0.01$ (shear stress of 2.2 ± 0.2 MPa) under drained conditions and $\mu_\mathrm{ss} = 0.09 \mp 0.01$ (shear stress of 1.8 ± 0.2 MPa) and under undrained conditions (Table 1; Fig. 2). Under undrained conditions, an overpressure dP (such that $P_f = P_f(t_0) + dP$, (with $P_f(t_0)$ the fluid pressure at the initiation of the experiment) was measured with increasing slip (Fig. 2A) following a power law best fitted by $dP = 8.4\ (\mp 0.6)\ \delta^{0.2(\mp 0.07)}$ [MPa] (for $\sigma_\mathrm{n} = 25$ MPa, $V = 3\ \mathrm{ms}^{-1}$ $P_f(t_0) = 5$ MPa). Overpressure dP decreased immediately by ∼60% after the slip was stopped (Fig. 2A). Conversely,