Pore fluid in experimental calcite-bearing faults: Abrupt weakening and geochemical signature of co-seismic processes

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ABSTRACT

While it is widely recognized that fluids influence fault strength and earthquake nucleation, propagation and arrest, their effects on co-seismic sliding friction are only conjectured. To shed light on these effects, 55 high velocity ($>1 \, \mathrm{m \, s^{-1}}$) friction experiments were conducted at room temperature on Carrara marble samples in the presence of pore fluid (up to 15 MPa pore pressure), room-humidity and "vacuum" (10^{-4} mbar) conditions. In all the experiments, the friction coefficient evolved from a peak value of 0.6–0.8 to a steady-state value of 0.1 in about 1–1.5 m of slip. However, experiments performed in the presence of pore fluid had a large and more abrupt decrease in friction at the initiation of sliding (65% after 20 mm of slip), whereas experiments performed under vacuum and room humidity conditions showed initial velocity-strengthening behavior followed by a more gradual reduction in friction. This indicates that calcite-bearing rocks are more prone to slip in the presence of water. Under room-humidity conditions, CO_2 was detected during the entire duration of the experiment. In the presence of pore fluid, HCO_3^- and Ca^{2+} were detected for slips >0.1 m. The lack of decarbonation products (HCO_3^- and Ca^{2+}) in pore fluid experiments for slip <0.1 m implies that the abrupt weakening is not related to decarbonation (or that the abundance of the reaction products is below the resolution of the analytical methods). Given the modest thermal expansion of water, the estimated thermal pressurization during the abrupt weakening appears to be negligible. Instead, we suggest that abrupt weakening is due to subcritical crack-growth, hydrolytic weakening and brittle failure of the asperities on the sliding surfaces. Modeling shows that the occurrence in nature of co-seismic (water-present) decarbonation reactions similar to those triggered in the laboratory could yield sufficient reaction product to be detected in aquifers located in the proximity of active faults.

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1. Introduction

Fluids play a fundamental physical (pore fluid pressure, temperature buffering, etc.) and chemical (dissolution, hydrolytic weakening, etc.) role in controlling fault strength and earthquake nucleation, propagation and arrest (Sibson, 1973, 2000; Lachenbruch, 1980; Rice, 1992, 2006; Hickman et al., 1995). Long-lasting earthquake sequences in Italy (e.g., Umbria-Marche 1997–1998, L'Aquila 2008–2009) are often hosted in carbonate-bearing rocks (limestones and dolostones) and associated with elevated pore fluid pressures at seismogenic depths (Miller et al., 2004; Terakawa et al., 2010; Chiaraluce et al., 2011). Moreover, changes in spring flow rates and water chemical and isotopic compositions have been measured before and after moderate to large magnitude earthquakes (Sato et al., 2000; Tsunogai and Wakita, 1995; Carucci et al.,

2011). The compositional change has been related to physical and chemical processes promoted by seismic faulting in the presence of H_2O and CO_2 (Sulem and Famin, 2009). Consequently, surface monitoring of the chemical evolution of spring water in seismic areas may constrain the physical and chemical processes controlling seismic faulting at depth (Italiano et al., 2009).

Until now, technical challenges related to pore fluid confinement impeded to investigate the role of water in experiments that reproduce deformation conditions typical of earthquakes moderate to large in magnitude (i.e., slip rates of $\sim 1 \, \mathrm{m \, s^{-1}}$, displacements up to 10 m, effective normal stresses of >10 MPa) (e.g., De Paola et al., 2011b). Here we surpass this limitation thanks to the technical improvements of the recently built rotary shear apparatus (SHIVA: Slow to HIgh Velocity Apparatus) equipped with an on-purpose designed pressure-vessel (modified from a design of Takehiro Hirose) and vacuum chamber. This allowed us to perform experiments on calcite-bearing rocks in the presence of pore fluid and under conditions which reproduced, at least in part, the co-seismic deformation expected in the upper crust. In

case of central Italy, the upper crust is dominated by carbonates and hosts prolonged and complex earthquake sequences (e.g. L'Aquila 2008–2009: Chiaraluce et al., 2011). Our results suggest that calcite-bearing rocks are more prone to slip in the presence of pore fluid and it may be speculated that this has a causative relation with the complex evolution of seismic sequences hosted in carbonate-bearing rocks. We also suggest that the physico-chemical processes operating during seismic slip might produce geochemical anomalies which can be measured at the surface in natural aquifers associated with seismogenic fault zones.

2. Methods

2.1. Experimental methods

2.1.1. SHIVA

Experiments were performed with SHIVA (SHIVA: Slow to HIgh Velocity Apparatus), which uses two brushless engines (maximum power 300 kW) and an air actuator (2 t amplified to 5 t thanks to a lever) in a rotary shear configuration to slide hollow rock cylinders (50/30 mm ext./int. diameter) at (1) nominally infinite displacement, (2) slip rates V ranging from 10 μm s^{-1} up to 6.5 m s^{-1}, (3) accelerations up to 65 m s^{-2}, and (4) normal stresses σ_n up to 40 MPa (for details on the apparatus, the control and acquisition system, etc., see Di Toro et al. (2010) and Niemeijer et al. (2011)). Mechanical data (axial load, torque, axial displacement, angular rotation) were acquired at a frequency up to 25 kHz. Slip, slip-rate and shear stress were determined using methods outlined in Tsutsumi and Shimamoto (1997) and Di Toro et al. (2010). To perform experiments in the presence of fluids, SHIVA was equipped with a pressurizing system which consisted of (1) a pore fluid pressure vessel (i.e., the samples were immersed in the fluid), (2) a membrane pump with a 30 cm^3 fluid capacity, (3) a pressure multiplier that imposes up to 15 MPa of fluid pressure (P_f), (4) a pressure regulator and, (5) valves and pipes (see Fig. 1).

2.1.2. Fluid experiments

The procedure for experiments performed in the presence of pore fluid consisted of the following steps (Fig. 1): (1) valves A, B, C were opened and the pressure vessel was filled with water (to wet the surfaces of the samples with water); (2) valves A and C were closed to confine water inside the vessel; (3) σ_n was increased to 3 MPa to bring the samples into contact; (4) σ_n and P_f were increased simultaneously to the target P_f, (5) once the target P_f was achieved, σ_n was further increased to apply the target effective normal stress ($\sigma_n^{eff} = \sigma_n - P_f$); (6) a velocity function was imposed onto the sample and single or multiple runs were performed. The acceleration and deceleration imposed to the samples ranged from 7.8 m s^{-2} to 36.9 m s^{-2}. Spinning of the sample up to 3000 rpm (or V of 6.5 m s^{-1}) and under high (up to 40 MPa) effective normal stress might result in abrupt fluid expansion due to thermal heating and, possibly, cavitation. In order to maintain P_f and σ_n^{eff} constant, the inlet water valve (A in Fig. 1a) was kept open during the experiment so that the fluid expansion was accommodated by the movement of the membrane pump (Fig. 1a). After the experiment, inlet valve A was closed, the sample was unloaded slowly and the water in the pressure vessel collected for chemical analysis.

Experiments were performed on hollow cylinders of Carrara marble (grain size ~300 μm, >99% calcite; X-Ray Powder Diffraction Rietveld method determination). Sample preparation included the insertion of Carrara marble hollow cylinders into aluminum jackets and the sealing of narrow openings between the rock and the jacket with epoxy to prevent fluid leaks from the sample chamber (for details about sample preparation, see Nielsen et al. (2012)) (http://istituto.ingv.it/l-ingv/produzione-scientifica/rapporti-tecnici-ingv/numeri-pubblicati-2012).
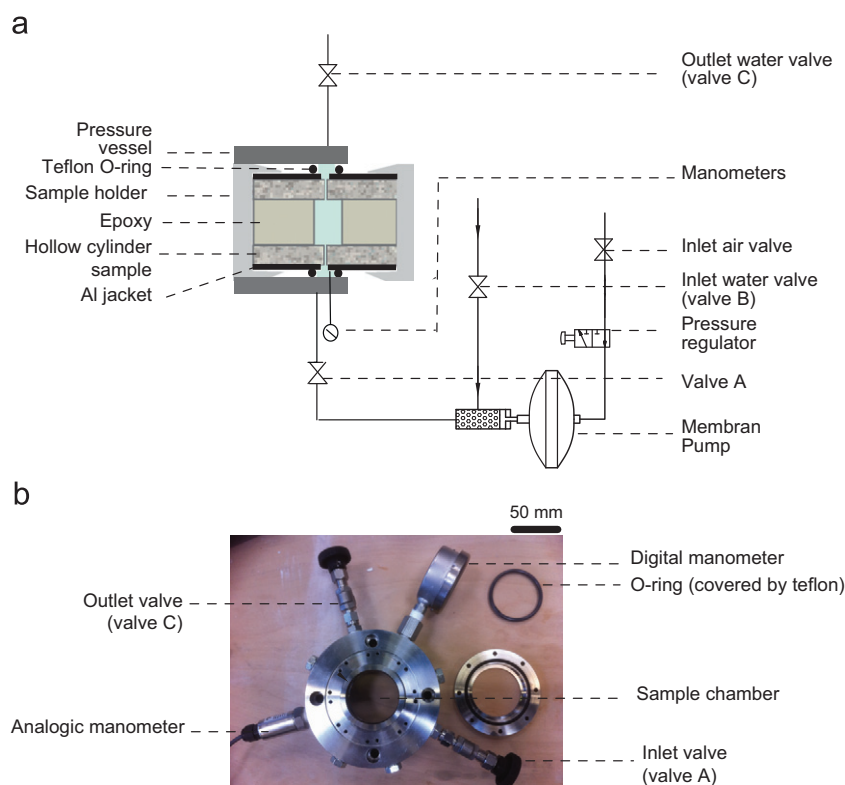

Fig. 1. Experimental configuration (a) Experimental pore fluid system. It consists of: (1) a liquid fluid pressure vessel, (2) a membrane pump, (3) pressure multiplier, (4) pressure regulator, (5) valves and pipes. (b) Photo of the fluid pressure vessel.