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The effect of water on strain localization in calcite fault gouge sheared at seismic slip rates

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ABSTRACT

Strain localization during coseismic slip in fault gouges is a critical mechanical process that has implications for understanding frictional heating, the earthquake energy budget and the evolution of fault rock microstructure. To assess the nature of strain localization during shearing of calcite fault gouges, high-velocity ($v_{\max} = 1$ m/s) rotary-shear experiments at normal stresses of 3–20 MPa were conducted under room-dry and wet conditions on synthetic calcite gouges containing dolomite gouge strain markers. When sheared at 1 m/s, the room-dry gouges showed a prolonged strengthening phase prior to dynamic weakening, whereas the wet gouges weakened nearly instantaneously. Microstructural analysis revealed that a thin (<600 μm) high-strain layer and through-going principal slip surface (PSS) developed after several centimeters of slip in both dry and wet gouges, and that strain localization at 1 m/s occurred progressively and rapidly. The strain accommodated in the bulk gouge layer did not change significantly with increasing displacement indicating that, once formed, the high-strain layer and PSS accommodated most of the displacement. Thus, a substantial strain gradient is present in the gouge layer. In water-dampened gouges, localization likely occurs during and after dynamic weakening. Our results suggest that natural fault zones in limestone are more prone to rapid dynamic weakening if water is present in the granular slipping zones.

1. Introduction

Field and trench observations from large fault zones show that while the surface trace of a fault can have a complex and broadly distributed geometry (Rockwell and Ben-Zion, 2007), co-seismic slip at depth is often localized within subcentimeter-thick gouge- and cataclasite-bearing principal slip zones (Sibson, 2003). There is also evidence that within these principal slip zones, localization to the sub mm-scale takes place during individual coseismic slip events (e.g., Chester et al., 1993; Chester and Chester, 1998; Boullier et al., 2009; Fondriest et al., 2012, 2013; Siman-Tov et al., 2013; Smith et al., 2013), although distributed coseismic deformation also occurs, e.g. at fault irregularities (Sibson, 1986; Pavlis et al., 1993; Aben et al., 2016).

The degree of strain localization and the thickness of the active principal slip zone strongly influence the dynamic behavior of faults (Ben-Zion and Sammis, 2003; Heermance et al., 2003; Rockwell and Ben-Zion, 2007), including the production of frictional heat and the evolution of thermally-sensitive weakening mechanisms. For example, Platt et al. (2014) modeled the shear strength evolution of a fluid-saturated gouge layer sheared at seismic slip rates (1 m/s), taking into consideration the role of thermally-driven weakening mechanisms. They found that during the early stages of deformation the shear strength evolution is similar to that modeled for uniform shearing (Rempel and Rice, 2006), but the onset of strain localization is accompanied by an

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acceleration in dynamic weakening because localization focuses frictional heating into a thinner zone and consequently thermal pressurization becomes more effective (Lachenbruch, 1980).

In high-velocity experimental studies on gouge layers, shear localizes to a thin (<300 μm) and highly-comminuted slip zone cut by one or more discrete slip surfaces (Han et al., 2010; Kitajima et al., 2010; De Paola et al., 2011; Fondriest et al., 2013; Smith et al., 2015). Evidence of intense strain localization and frictional heating is preserved as zones containing gouge material that is ultracomminuted, decomposed, recrystallized or sintered (e.g., Sawai et al., 2012; Togo and Shimamoto, 2012; Smith et al., 2013; Yao et al., 2013). The observed dynamic weakening that accompanies strain localization has been attributed to flash heating in a thin (≤30 μm) layer of wear material (Goldsby and Tullis, 2011; Kohli et al., 2011) or rapid diffusional processes in nanograins accompanying superplastic behavior (Verberne et al., 2013, 2014b; De Paola et al., 2015; Green et al., 2015). In the case of carbonate rocks, flash weakening could be enhanced by decarbonation due to frictional heating and formation of CaO nanograins (Han et al., 2007, 2010; Violay et al., 2014). The formation of nanograin material may be responsible for the velocity-weakening behavior of carbonate gouges sheared at low velocity (~1 μm) and elevated temperatures of 80–100 °C (Verberne et al., 2010, 2014a, 2014b) as well as for the low steady-state shear stress at high velocity (c. 1 m/s; De Paola et al., 2015; Green et al., 2015) due to enhancement of grain boundary sliding mechanisms.

Results from high-velocity experiments on room-dry calcite (Smith et al., 2015) and serpentinite (Proctor et al., 2014) gouges showed that strain was localized to a high-strain shear band prior to dynamic weakening, consistent with the idea that extreme localization in gouges is a necessary precursor to dynamic weakening (Goldsby and Tullis, 2011). However, the effect of water on localization and dynamic strength evolution in carbonate gouges has not yet been studied. This is important because field studies of natural slip zones in carbonates have shown that localized slip is commonly associated with the formation of veins and microstructures that indicate gouge fluidization (Smith et al., 2011; De Paola et al., 2012; Fondriest et al., 2012; Rowe et al., 2012), suggesting that in many carbonate-bearing fault zones coseismic slip occurs in the presence of hydrous fluids. The presence of water was found to significantly decrease the strength of clay-bearing gouges sheared at low to high velocities (Morrow et al., 2000; Kitajima et al., 2010; Ujiie and Tsutsumi, 2010; Faulkner et al., 2011; Han and Hirose, 2012; Verberne et al., 2014a; Bullock et al., 2015). The aim of this experimental study was to understand the strain-localization process in wet calcite gouges. To this end, we conducted rotary-shear experiments over a wide range of total displacements on dry and wet calcite gouges including the systematic use of strain markers.

2. Material and methods

Two different rotary-shear apparatus were used in this study: the Slow-to High Velocity Apparatus (SHIVA; Di Toro et al. (2010)) installed at the Istituto Nazionale di Geofisica e Vulcanologia in Rome, Italy, and the Pressurized High-Velocity apparatus (Phv) installed at the Kochi Institute for Core Sample Research/JAMSTEC in Nankoku, Japan (Tadai et al., 2009; Tanikawa et al., 2012). The gouge holder used in conjunction with SHIVA allowed us to easily construct a strain marker within the gouge layers, but pore-fluid conditions could not be controlled. Experiments under controlled pore-fluid conditions were performed using the Phv apparatus, which is equipped with a servo-controlled pore-fluid pressure system. Using the two different apparatus provides the additional advantage of being able to test the reproducibility of the mechanical data.

2.1. Experimental Set-Up of the SHIVA apparatus

A total of 18 high-velocity, rotary-shear experiments were performed with SHIVA using strain markers (Table 1). The gouge experiments were performed at a target maximum slip rate of 1 m/s, acceleration and deceleration of 6 m/s^2, normal stresses ranging from 3 to 20 MPa, total displacements from 0.011 to 2.5 m, and under room-dry or water-dampened conditions (Table 1). The design and capability of SHIVA are described in Di Toro et al. (2010) and Niemeijer et al. (2011). The annular gouge holder used with SHIVA (description and calibration tests in Smith et al., 2013) is built mainly from steel. The gouge layer has inner and outer diameters of 35 and 55 mm and is contained above and below by base discs and to the sides by steel rings that slide over the upper base disc (Fig. 1a). As the confining rings are in contact with the base discs, but are not designed to carry load, springs located underneath the rings ensure that the normal load is mainly supported by the gouge layer (Smith et al., 2013). To minimize the contribution of the sliding rings to the measured torque, the contact area of the rings with the base disc was lubricated with high-temperature grease prior to each experiment. The axial displacement of the gouge layer, i.e. its compaction or dilation, was measured using a DCDT (Direct Current Differential Transformer) with a resolution of c. 50 μm, which is installed on the stationary axis. The axial displacement as well as the torque, normal load, rotation velocity and displacement were measured with a sampling rate of 25 kHz.

2.2. Experimental Set-Up of the "Pressurized high-velocity" ("Phv") apparatus

A total of 24 high-velocity, rotary-shear experiments were performed with the Phv apparatus under room-dry and controlled pore pressure conditions (Table 2). Experiments with the Phv apparatus were also performed at a target maximum slip velocity of c. 1 m/s but with a slower acceleration of 0.5 m/s^2. Additionally, in some experiments the gouge samples were pre-sheared for a displacement of c. 30 cm at a velocity of 1 mm/s (Table 2). The gouge holder used with the Phv apparatus has inner/outer diameters of 30 and 60 mm.

Pore fluid in the Phv apparatus is introduced to the gouge layer (marked yellow in Fig. 1b) through the stationary part of the gouge holder (grey parts in Fig. 1b). The fluid outlet is located in the center of the annular holder; thus, the pore fluid has to pass through the gouge material before passing into the fluid-outlet tube in the rotary part of the gouge holder (white parts in Fig. 1b) and further into the outlet tube within the stationary part. The saturated gouge is confined with inner and outer Teflon sleeves and several o-rings (Fig. 1b). Fluid pressure is monitored upstream and downstream of the sample using two pressure gauges and is adjusted via a servo-controlled moving piston. As the pressure gauges are located outside the sample chamber, the pore pressure cannot be perfectly controlled. Applied effective normal stresses and pore-fluid pressures ranged from 3 to 12 MPa and from 0.2 to 10.5 MPa, respectively (Table 2). The experiments were performed with room-dry and water-saturated calcite gouges, but without the use of strain-markers. The experimental data were recorded at a sampling rate of 1 kHz.

2.3. Sample preparation and analysis techniques

The calcite gouge was derived by crushing pieces of Carrara marble. The dolomite gouge used for the strain markers in the SHIVA experiments was derived by crushing cohesive dolostones