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Strain localization and the onset of dynamic weakening in calcite fault gouge

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ABSTRACT

To determine the role of strain localization during dynamic weakening of calcite gouge at seismic slip rates, single-slide and slide–hold–slide experiments were conducted on 2–3-mm thick layers of calcite gouge at normal stresses up to 26 MPa and slip rates up to 1 $\mathrm{m\,s^{-1}}$. Microstructures were analyzed from short displacement (<35 cm) experiments stopped prior to and during the transition to dynamic weakening. In fresh calcite gouge layers, dynamic weakening occurs after a prolonged strengthening phase that becomes shorter with increasing normal stress and decreasing layer thickness. Strain is initially distributed across the full thickness of the gouge layer, but within a few millimeters displacement the strain becomes localized to a boundary-parallel, high-strain shear band c. 20 μm wide. During the strengthening phase, which lasts between 3 and 30 cm under the investigated conditions, the shear band broadens to become c. 100 μm wide at peak stress. The transition to dynamic weakening in calcite gouges is associated with the nucleation of micro-slip surfaces dispersed throughout the c. 100 μm wide shear band. Each slip surface is surrounded by aggregates of extremely fine grained and tightly packed calcite, interpreted to result from grain welding driven by local frictional heating in the shear band. By the end of dynamic weakening strain is localized to a single 2–3-μm wide principal slip surface, flanked by layers of recrystallized gouge. Calcite gouge layers re-sheared following a hold period weaken nearly instantaneously, much like solid cylinders of calcite marble deformed under the same experimental conditions. This is due to reactivation of the recrystallized and cohesive principal slip surface that formed during the first slide, reducing the effective gouge layer thickness to a few microns. Our results suggest that formation of a high-strain shear band is a critical precursor to dynamic weakening in calcite gouges. Microstructures are most compatible with dynamic weakening resulting from a thermally triggered mechanism such as flash heating that requires both a high degree of strain localization and a minimum slip velocity to activate. The delayed onset of dynamic weakening in fresh calcite gouge layers, particularly at low normal stresses, may inhibit large coseismic slip at shallow crustal levels in calcite-bearing fault zones.

1. Introduction

Fault gouge is formed in mid- to upper-crustal fault zones by particle fracturing, surface wear and fluid–rock interactions (Engelder, 1974; Sibson, 1977; Scholz, 1987). Despite the overall geometrical complexity of fault systems, a range of field and seismological observations show that incremental fault displacements at seismogenic depths are often focused within slip zones a few centimeters thick that surround lenses of variably fractured and brecciated host rocks (e.g. Chester and Chester, 1998; Faulkner et al., 2003; Wibberley and Shimamoto, 2003). Microstructural studies also demonstrate more extreme localization of slip, commonly within gouge layers less than a few millimeters thick or across discrete slip surfaces (e.g Chester and Chester, 1998; De Paola et al., 2008; Boullier et al., 2009; Heesakkers et al., 2011; Smith et al., 2011; Fondriest et al., 2012). It has been suggested that the bulk of coseismic slip along individual fault strands occurs in highly localized gouge-bearing slip zones (e.g. Sibson, 2003), although significant off-fault deformation can be induced by dynamic stresses (e.g. Dor et al., 2006) and distributed coseis-

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mic strains must occur at fault irregularities such as bends and stepovers (Sibson, 1986; Pavlis et al., 1993).

Laboratory experiments have demonstrated that bare rock surfaces and gouge layers experience dynamic weakening when the slip velocity and sliding displacement approach values characteristic of earthquakes (Di Toro et al., 2011). A variety of physical mechanisms have been proposed to explain the dynamic weakening behavior observed in the laboratory and postulated to occur in natural faults. In particular, mechanical and microstructural data collected from experiments performed on solid rocks (bare surfaces) are consistent with the activity of flash heating and weakening at asperity contacts (Rice, 2006; Beeler et al., 2008; Goldsby and Tullis, 2011; Kohli et al., 2011), silica gel lubrication (Goldsby and Tullis, 2002; Di Toro et al., 2004) and frictional melting (Di Toro et al., 2006; Nielsen et al., 2008).

Gouge layers deformed at high velocities typically show a narrow (<100 μm) and fine-grained shear localization zone cut by a discrete sliding surface or multiple surfaces coated with extremely small ("nano") or sintered grains (Han et al., 2010; Kitajima et al., 2010; De Paola et al., 2011; Fondriest et al., 2013; Smith et al., 2013; Yao et al., 2013). The onset of dynamic weakening in experiments performed with blocks of granite (Reches and Lockner, 2010) was attributed to wear of the solid rock, formation of a gouge layer, and the development of a thin actively deforming zone that was suggested to lubricate the sliding surface. In the experiments of Goldsby and Tullis (2007, 2011) and Kohli et al. (2011) the evolution of shear stress during slip acceleration and deceleration prompted the authors to suggest that flash heating and weakening occurred following strain localization in a thin gouge layer formed by wear between solid rock cylinders. Recently, Proctor et al. (2014) compared the frictional behavior of serpentinite gouges and solid rings (bare surfaces) of serpentinite. They found that higher slip velocities were required to initiate dynamic weakening in the gouges compared to the solid samples, and concluded that flash weakening in the gouges was delayed due to initially distributed deformation.

In general, the above experimental studies have shown that the presence of gouges is likely to be an important factor in the dynamic evolution of fault strength during seismic slip. This is in addition to the critical role played by gouges in determining the stability of faults during the nucleation phase of earthquakes (e.g. Logan et al., 1979; Marone et al., 1990; Beeler et al., 1996; Mair and Marone, 1999; Ikari et al., 2011). However, most previous experimental studies performed at high-velocities have focused on gouge microstructure at the end of relatively large-displacement experiments, and thus the correlation between microstructure (e.g. strain localization) and mechanical behavior, particularly during the early stages of slip, remains poorly understood.

The objective of the present paper is to report on an experimental and microstructural investigation of strain localization and its influence on dynamic weakening in granular calcite gouges. Calcite is an important, and in some cases dominant, mineral in many seismically active regions worldwide, where main shocks and aftershocks nucleate within and propagate through thick sequences of carbonates (Italy, e.g. 2009 Mw 6.3 L'Aquila earthquake; Greece, e.g. 1995 Ms 6.6 Western Macedonia earthquake). We employed a rotary–shear friction apparatus to deform layers of calcite gouge at high slip velocities and moderately high normal stresses. By tightly controlling the total experimental displacements, we systematically investigated the relationships between gouge mechanical behavior and microstructural evolution prior to and during the transition to dynamic weakening.

2. Methods

2.1. Sample preparation and starting materials

Gouge experiments were performed with SHIVA (Slow- to High-Velocity rotary–shear friction Apparatus; Fig. 1a) at the INGV, Rome (Di Toro et al., 2010; Niemeijer et al., 2011) using a sample holder for incohesive materials (gouge) with rotary and stationary parts (Fig. 1b, c). The rotary side of the gouge holder consists of a base plate and inner and outer rings that prevent gouge extrusion during the experiments. The inner and outer rings slide over a base disc located in the stationary base plate. Both the rotary base plate and the stationary base disc have a crosshatch pattern of surface roughness where in contact with the gouge layer (Fig. 1d). The amplitude of roughness (i.e. peak to trough height) at the gouge layer boundary is 200 μm and the wavelength (i.e. distance from peak to adjacent peak) is 400 μm (Fig. 1d).

Normal load on the gouge layer is applied directly through the stationary base plate by the axial loading column of SHIVA (Fig. 1b; Di Toro et al., 2010). Five outer springs and one inner spring modulate the normal load applied to the inner and outer sliding rings (Fig. 1b). Calibration tests (Smith et al., 2013) indicate that the contribution to measured torque values from the sliding rings is negligible (<2.5% of measured torque) at the normal stresses used in these experiments (generally >8.5 MPa, two experiments at 4 MPa).

The gouge starting material (Fig. 1e) was prepared by grinding Carrara marble in a pestle and mortar. The resulting gouge was passed through a 250-μm sieve and all particles that passed through the sieve were included in the starting gouge. Powder X-ray diffraction analysis together with Scanning Electron Microscope observations indicate that the starting material is composed of >99 wt% calcite, with <1 wt% dolomite, quartz, and muscovite as accessory phases (typical minor phases in Carrara marble: Smith et al., 2013). Each experiment used 5 g or 3 g of calcite gouge, resulting in ring-shaped gouge layers (35/55 mm int./ext. diameters; Fig. 1b–d) with initial thicknesses of, respectively, c. 3 mm and c. 2 mm (Fig. 1b–d).

2.2. Experimental and analytical procedures

Experiments were performed under room-dry conditions (room humidity varied between 50% and 80%) at constant normal stresses of 4–26 MPa and maximum slip velocities up to 3.4 $\mathrm{m\,s^{-1}}$. Angular rotation (and total displacement) in each experiment was controlled using two digital optical encoders located on the rotary column. A high-resolution encoder (0.2 μm resolution for 35/55 mm int./ext. diameter samples) was used to measure displacements up to 0.01 m. A lower-resolution encoder (400 μm resolution for 35/55 mm int./ext. diameter samples) was used to measure displacements greater than 0.01 m. Horizontal displacements of the axial column were measured using a Direct Current Differential Transformer (50 mm range and ∼50 μm resolution, installed behind the ball bearing housing on the axial column) and in some experiments a Linear Variable Differential Transformer (LVDT, 3 mm range and ∼0.03 μm resolution, installed in contact with the gouge holder). Experimental data (e.g. axial load, torque, axial displacements, angular rotation) were acquired at a frequency up to 25 kHz, and determination of total displacement, slip rate, and shear stress followed methods outlined in Di Toro et al. (2010).

Two types of experiments were performed: single-slide experiments and slide–hold–slide experiments. In single-slide experiments, only one slip pulse was imposed on the gouge layer before it was recovered for microstructural analysis. In slide–hold–slide experiments, two slip pulses were imposed under identical conditions, separated by a hold period lasting 40–60 s during which