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# Shear localization, velocity weakening behavior, and development of cataclastic foliation in experimental granite gouge

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ABSTRACT

Microstructural aspects of room-temperature deformation in experimental Westerly granite gouge were studied by a set of velocity stepping rotary-shear experiments at 25 MPa normal stress. The experiments were terminated at: (a) 44 mm, (b) 79 mm, and (c) 387 mm of sliding, all involving variable-amplitude fluctuations in friction. Microstructural attributes of the gouge were studied using scanning (SEM) and scanning transmission electron microscopy (STEM), image processing, and energy dispersive X-ray (EDX) analyses. The gouge was velocity weakening at sliding distances >10 mm as a core of cataclasites along a through-going shear zone developed within a mantle of less deformed gouge in all experiments. Unlike in experiment (a), the cataclasites in experiments (b) and (c) progressively developed a foliation defined by stacks of shear bands. The individual bands showed an asymmetric particle-size grading normal to shearing direction. These microstructures were subsequently disrupted and reworked by high-angle Riedel shears. While the microstructural evolution affected the effective thickness and frictional strength of the gouge, it did not affect its overall velocity dependence behavior. We suggest that the foliation resulted from competing shear localization and frictional slip hardening and that the velocity dependence of natural fault gouge depends upon compositional as well as microstructural evolution of the gouge.

## 1. Introduction

Understanding deformation processes in fault gouge is an essential step in constructing predictive models for fault behavior. Numerous studies of experimental and natural fault gouge have focused on processes of shear localization and their implications for creep and seismic behavior of faults (e. g. Logan et al., 1979; Marone and Scholz, 1989; Antonellini et al., 1994; Anders and Wiltschko, 1994; Chester and Chester, 1998; Cladouhos, 1999; Mair et al., 2000; Besuelle, 2001; Shipton and Cowie, 2001; Beeler, 2004; Mair and Abe, 2008; Hermundstad et al., 2010). More specifically, gouge microstructures that represent shear localization have been identified and shown to be the cause of mechanical weakening (Gu and Wong, 1994; Beeler et al., 1996). Within the framework of rate- and state-dependent rock friction, microstructural models and processes of shear localization have been sought in several studies including Logan and Rauenzahn (1987), Biegel and Sammis (1989), Wang and Scholz (1994), Beeler et al. (1996), Karner et al. (1997), Scruggs and Tullis (1998), Mair and Marone (1999), Karner and Marone (2001), and Rathbun and Marone (2010). Large-displacement frictional sliding experiments by Beeler et al. (1996), Scruggs and Tullis (1998), and Mair and Marone (1999) have indicated that at constant normal stress, temperature, and system stiffness, velocity-dependence of gouge friction depends upon the state of shear localization. Beeler et al. (1996) reported on microstructures and mechanical behavior of experimental Westerly granite gouge and showed that strength, velocity dependence of friction, and microstructures were displacement dependent and correlated. Details of the microstructural changes that underlie displacement dependence of gouge friction as well as the nature of deformation of gouge by shear localization are further investigated in this study.

The core region of natural faults, hosted by a variety of lithologies, often consists of extremely narrow, mostly foliated gouge (Brock and Engelder, 1977; House and Gray, 1982; Chester and

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Logan, 1986; Chester et al., 1993; Hadizadeh, 1994; Chester and Chester, 1998; Schulz and Evans, 2000; Lin, 2001; Tanaka et al., 2001; Wibberley and Shimamoto 2002; Boullier et al., 2004). Based on field data and laboratory tests, Ben-Zion and Sammis (2003) suggested that about 0.3 m of slip would be sufficient for such fault zones to stabilize geometrically into one or two principal slip zones. In natural fault gouge, the foliation is often defined by a combination of sharp particle size gradient and sheared alteration products like zeolites (Chester and Logan, 1986; Solum et al., 2003; Faulkner et al., 2003). Natural foliated cataclasites described by Chester et al. (1985) and Chester and Logan (1987), appeared as lens-shaped or anastomosing bodies in contact with primary slip surfaces in the fault core. Faulkner et al. (2003) suggested that relict internal structures in Carboneras fault zone in south east Spain indicate repeated strain weakening and strain hardening. Ben-Zion and Sammis (2003), however, argued that since fault zones tend to become more linear and tabular with time and displacement, fluctuations between localized and distributed deformation are not necessary to maintain active deformation. Models have been proposed for evolution of the core regions in strike slip faults, notably the adhesive wear sidewall rip out (Swanson, 2005), and non-mixing juxtaposition by localized slip (Chester and Chester, 1998). The implications of the development of foliation microstructures for strength of gouge are scarcely studied. An experimental study by Collettini et al. (2009) showed that naturally foliated gouge, with small structurally-distributed phyllosilicate content, was significantly weaker than its powdered samples. Studies of the Punchbowl fault zone and other inactive branches of the San Andreas Fault zone in southern California (Chester and Logan, 1986; Chester and Chester, 1998; Schulz and Evans, 1998; Evans et al., 2000; Solum et al., 2003) provide evidence of basic structural similarity between experimental and natural faults.

The large-displacement sliding experiments on simulated Westerly granite gouge by Beeler et al. (1996) reported the development of remarkable foliation microstructures, but analysis of the observed microstructures was not the primary focus of that study. This study presents a model in which shear localization in the gouge is primarily caused by non-uniform particle size reduction. In addition, we consider the relationship between shear localization microstructures, foliation, and gouge strength in order to provide some constraints for analyses of foliated cataclasites and other structures observed in the core region of natural fault zones.

## 2. Experimental material and methods

Frictional sliding experiments were performed on size-controlled powder of Westerly granite gouge in rotary shear at room temperature and humidity under 25 MPa normal stress. Technical specifics of the apparatus are described elsewhere (Tullis and Weeks, 1986; Beeler et al., 1996; Tullis, 1997). The undeformed synthetic gouge used in this study, prepared by grinding Westerly granite to particle size $\leq 88$ μm, consists of 28% quartz, 35% microcline, 32% plagioclase, 5% mica, and <1% opaque minerals. For each experiment, approximately 1 gram of the material was packed into in a ~2 mm layer of gouge with ~35% initial porosity in a ring-shaped sample holder. A compaction test (WGK257U) showed that raising normal stress to 25 MPa at the beginning of each experiment reduced the gouge layer thickness by ~110 μm (5.5%). The compaction run also provided references for the initial texture (Fig. 1a), particle size distribution (PSD), and porosity. The two solid granite rings (4.8 mm wall thickness) enclosing the gouge layer were lapped with #60grit on surfaces facing the gouge to an average roughness of ~10 μm. The term shear zone boundary was reserved for the interface boundary of the gouge with the granite rings. A nominal sliding surface area of 735 $\text{mm}^2$ resulted from the ring sample configuration. The sliding velocity was stepped between 1 μm/s (for 1 mm distance) and 10 μm/s (for 10 mm distance) in all the experiments. The dynamic coefficient of friction, $\mu_d$, was calculated as the ratio of shear to normal stress with a resolution of $3 \times 10^{-4}$ at 25 MPa normal stress.

The experiments were terminated at different sliding distances ($\delta$) with the objective of capturing microstructural states associated with the prevailing frictional conditions. The experiments were terminated after 44 mm of sliding (WGK258) involving a persistent reduction in friction, 79 mm of sliding (WGK266) involving that reduction followed by an upturn in friction, and after 387 mm of sliding (WGK262) involving several varied-amplitude fluctuations in friction. The deformed sample rings were impregnated with epoxy resin and cured prior to being sectioned perpendicular to shear plane as shown schematically in Fig. 1b–c. The microstructural observations were made on polished petrographic thin sections sputter-coated with gold–palladium. The sections were viewed in back-scattered mode in a high resolution Zeiss Supra model 55VP scanning electron microscope (SEM) at 15–20 KV, 0.25K × to 64K × magnifications. Optical microscopy included transmitted and reflected light imaging. The presented images are SEM back-scattered images unless otherwise stated in figure captions. Scanning transmission electron microscopy (STEM) using a JEOL 2011 STEM was carried out on sections selected by SEM and prepared by focused ion-beam techniques.

## 3. Textural measurements

Digital images of particles from typical regions of the deformed and undeformed gouge were manually traced with a l 2-pixel digital tip at 3 × screen magnification and transformed into calibrated line drawing overlays. Gouge particle size $S$, was represented by the equivalent circle diameter of particle image area A measured on overlays using the relationship$S = 2\sqrt{A/\pi}$. Image processing and measurements were carried out using SigmaScanPro v.5, MATLAB Image Processing Toolbox v.11, and Adobe Photoshop CS5 applications. To capture a wider particle size range we pooled the size data for each sample from a set of images taken telescopically by applying a zoom factor of 2. Duplicate sizes in a set were eliminated by discarding overlapping values (same values to 3 decimal places). Particle size data for this study consisted of 7100 measurements acquired from a total of 34 backscattered SEM images. The size-number data thus acquired was used to determine PSD, and two dimensional (2D) fractal dimensions of the studied gouge regions. Fractal dimension $D$ is slope of the log–log size ($S$) – number (N) distribution given by $N(S) = cS^{-D}$, where $c$ is a constant (Turcotte, 1986). Assuming an isotropic gouge, and consistent with the fractal theory proposed by Falconer (1985), 2D values are valid as 3D (volume) fractal dimension by adding 1.0 to 2D values (e.g. Sammis et al., 1987; Sammis and Biegel, 1989; Blenkinsop, 1991). Fractal dimension results in this study will be presented unchanged as 2D values. Accordingly, citations from other sources were made comparable by subtracting 1.0 from published 3D values.

The gouge porosity, here referred to as 2D image porosity $\Phi_I$, is total porosity estimated by image analysis of SEM and optical images of regions of varying PSD. The method and its validation with respect to volume porosity in actual rock material has been discussed elsewhere (e.g. Anselmatti et al., 1998; Solymar and Fabricius, 1999; Talukadar et al., 2002; Johansen et al., 2005; Hadizadeh et al., 2010). Anselmatti et al. (1998) and Talukadar et al. (2002) showed that volume porosity of an isotropic porous medium is well-represented by its 2D porosity determined through image analysis. In order to isolate and measure pore space areas, images were subjected to pixel intensity thresholding. The intensity range for pore areas in each image was determined visually,