Evolution of shear fabric in granular fault gouge from stable sliding to stick slip and implications for fault slip mode

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ABSTRACT
Laboratory and theoretical studies provide insight into the mechanisms that control earthquake nucleation, when fault slip velocity is slow (<0.001 cm/s), and dynamic rupture when fault slip rates exceed centimeters per second. The application of these results to tectonic faults requires information about fault fabric with shear and its impact on the mode of faulting. Here we report on laboratory experiments that illuminate the evolution of shear fabric and its role in controlling the transition from stable sliding (v < 0.001 cm/s) to dynamic stick slip (v > 1 cm/s). The full range of fault slip modes was achieved by controlling the ratio $K = k/k_c$, where $k$ is the elastic loading stiffness and $k_c$ is the fault zone critical rheologic stiffness. We show that $K$ controls the transition from slow-and-silent slip ($K > 0.9$) to fast-and-audible ($K < 0.7$, $v$ = 3 cm/s, slip duration 0.003 s) slip events. Microstructural observations show that with accumulated strain, deformation concentrates in shear zones containing sharp shear planes made of nanoscale grains, which favor the development of frictional instabilities. Once this fabric is established, fault fabric does not change significantly with slip velocity, and fault slip behavior is mainly controlled by the interplay between the rheological properties of the slipping planes and fault zone stiffness.

INTRODUCTION
Understanding the relationship between the evolution of fault fabric and fault slip behavior is a long-standing problem in fault mechanics. Tchalenko (1970) used shear box experiments to document fault zone evolution from Riedel shears to boundary-parallel shears with increasing strain. The similarities of the experimental fault zone structure with earthquake faulting were interpreted as indicating similarities in the deformation mechanism. Several laboratory and field studies have expanded on the kinematic descriptions, with the aim of developing an integrated understanding of the evolution of fault zone microstructure and friction constitutive properties (e.g., Sibson, 1977; Logan et al., 1979; Yund et al., 1990; Marone and Kilgore, 1993; Beeler and Tullis, 1996). For quartz-feldspathic fault gouge, increasing strain causes an evolution from distributed to localized deformation along fault-parallel shear planes. This microstructural evolution is accompanied by a transition from a velocity-strengthening (i.e., asertic creep) to velocity-weakening behavior, which is a necessary condition for frictional instability, neglecting cohesion (e.g., Marone, 1998).

In the last decade, high-velocity friction experiments have shown that at earthquake slip velocities (≥10 cm/s), significant grain-size reduction and localization occurs in granular materials (e.g., Goldsby and Tullis, 2002; Di Toro et al., 2011; De Paola et al., 2015; Smith et al., 2015). These studies have been fundamental to characterizing fault rocks produced during the earthquake slip phase; however, these experiments are conducted with imposed coseismic velocities, whereas along natural faults, the instability arises spontaneously and is driven by the elastic interaction between the fault zone and the surroundings (e.g., Scholz, 2002). Stick-slip frictional sliding experiments have provided the foundation for earthquake physics (e.g., Brace and Byerlee, 1966; Scholz et al., 1972). Recently, stick-slip experiments on bare rock surfaces have documented the melting ofasperity contacts of the slipping surface during large stress drops (e.g., Hayward et al., 2016; Passelègue et al., 2016). However, the mechanisms for strain localization and fault weakening during stick-slip frictional instabilities within fault gouge are still poorly understood. In this manuscript we build on recent works that documented the spectrum of fault slip behavior, from stable sliding to stick slip on quartz gouge (Leeman et al., 2016; Scuderi et al., 2016), to characterize the evolution of shear fabric and infer the controlling mechanism for different fault slip behavior.

METHODS
Frictional stick-slip instabilities occur when the fault weakening rate with slip exceeds the maximum rate of elastic unloading, resulting in a force imbalance and acceleration (e.g., Scholz, 2002). In the simplified case of an experimental fault obeying rate- and state-friction (RSF) laws, the occurrence of stick-slip instabilities is controlled by the interaction between the system elastic stiffness, $k$, and the fault frictional properties, which can be written in terms of a critical rheologic stiffness $k_c$ (Gu et al., 1984). The condition for the nucleation of instability, when sliding velocity is still slow, is:

$$k < k_c = \frac{\sigma'_e (b - a)}{D_c},$$

where $\sigma'_e$ is the effective normal stress, $(b - a)$ is the friction rate parameter, and $D_c$ is the critical slip distance. The ratio $K = k/k_c$ describes fault stability: under quasi-static conditions, where accelerations are negligible, sliding is stable for $K > 1$ and unstable for $K < 1$.

We conducted laboratory experiments using the double-direct shear configuration in a biaxial deformation apparatus (Fig. 1A). Fault zones were composed of quartz gouge (MIN-U-SIL® 99.5% SiO₂), with a grain size in the range of 2–50 μm and mean size of 10–15 μm. Gouge layers were sheared at constant velocity of 10 μm/s and normal stresses ranging from 13 to 35 MPa (Table DR1 in GSA Data Repository1). We performed velocity step experiments to retrieve the RSF parameters and characterize the fault critical rheologic stiffness, $k_c$ (Fig. DR2 in the Data Repository). To explore a range of stability conditions, we artificially reduced the shear loading stiffness by inserting an elastic element in the loading column.

1GSA Data Repository item 2017242, summary of experiments and boundary conditions, methods and calculations, and supplemental information, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

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With decreasing (Fig. 1A). For these conditions, the transition from stable to unstable sliding occurs at a normal stress of 14 MPa (Fig. 1B), and we explored a range of normal stresses up to 35 MPa to study the transition from stable to unstable sliding (Figs. 1B and 1C). At the end of the experiments, we collected samples for scanning electron microscopy and transmission electron microscopy investigations. We also analyzed microstructures for experiments at low and high shear strain that were performed at higher stiffness, resulting in stable sliding at normal stress of 25 MPa (Fig. 1B).

COUPLING BETWEEN MECHANICAL AND MICROSTRUCTURAL EVOLUTION

Our experiments document a spectrum of slip behaviors from stable to quasi-dynamic (i.e., the acceleration is slow with negligible inertia effects) and fully dynamic sliding (i.e., abrupt acceleration) (Figs. 1B and 1C). With decreasing $K$ the recurrence time of stick-slip cycles becomes longer, the stress drop increases from ~0.4 to ~2.4 MPa, and the slip velocity increases from ~150 μm/s for $K = 0.9$ to ~3 cm/s for $K = 0.5$ (Fig. 1C).

We document a systematic evolution of the microstructure with shear strain ($\gamma$) and fault slip behavior (Fig. 2). At low strain, when shear is stable, grains are angular and unfractured with a grain size comparable to that of the starting material (Fig. 2A). Grain-size reduction is evident within proto–B-shear zones that are up to 200 μm wide. With increasing strain (Fig. 2B) the B-shear zones become more continuous and contain subparallel discrete slip surfaces, Y-shears, where the grain size reduces to ~1 μm. From low to high strain (Fig. 2C) we document an evolution of ($a$–$b$) from velocity strengthening to velocity weakening and a reduction of $D_s$ from 15 to 1 μm, consistent with previous work (Marone and Kilgore, 1993). These changes result in an increase of $k_c$ for shear strains up to ~5. For $\gamma > 8$, $k_c$ reaches a steady value that does not vary appreciably with greater shear (Fig. 2C), indicating that the fault zone has achieved a nearly stable microstructural and mechanical state. We also document a reduction of layer dilation upon velocity steps with increasing strain, which is a further indication of shear localization (Fig. 2D; Fig. DR3).

Comparing the fault zone fabric observed during stable sliding at high strain with the microstructure developed after both slow slip and fast stick slip, we do not observe significant differences (Fig. DR4). In both cases, most of the deformation occurs along B-shear zones and is localized along Y-shears (Fig. 2E). The Y-shears consist of tightly packed zones of randomly oriented quartz nanograins, with grain dimensions of 50–500 nm, characterized by angular to sub-spherical shape and intense dislocations (Fig. 2E, green inset). In some instances, grains with dimensions of 0.5–1 μm are fractured and show sharp grain surfaces. Some amorphous material is present at the boundaries of the smaller grains, however the development of amorphous material in high-strain zones is not a prominent feature of the microstructure (De Paola et al., 2015). Nanograins, <200 nm, likely form by dislocation pileup within larger grains. Outside the B-shear zones, the quartz grains are larger and contain pervasive fractures (Fig. 2E, red inset).

DISCUSSION

Our experiments show that fault slip behavior is controlled by the interplay between the effective shear loading stiffness ($k' = k/\sigma_n'$) and the effective fault rheological stiffness [$k' = (b - a)/D_s$] and their evolution with stress, strain, and fabric development (Fig. 3; Fig. DR5). The stiffness $k'$ varies with fault porosity and particle contact stiffness, which are influenced by fault normal stress and shear-enhanced compaction, increasing at low strains before reaching steady-state values for $\gamma > 3$. The fault zone rheologic stiffness, $k'_{\text{fault}}$, grows from negative to positive values at low strains as ($a$–$b$) transitions from velocity strengthening to velocity weakening (Fig. 2C), and then it increases slowly at higher strain. The evolution of $k'$, with increasing strain is further compounded by reduction of $D_s$ from 15 μm, the average initial grain size, to sub-micrometric values, which corresponds to the grain size within Y-shears (Fig. 2E).

Our results illustrate how fabric development influences fault slip behavior and the spectrum of slip modes. At low strain (Fig. 3), shear deformation is distributed and is mainly accommodated by grain rotation, translation, and fracturing. Limited grain-size reduction occurs along proto–B-shear zones and R shears, resulting in large values of $D_s$ and velocity strengthening behavior. With increasing strain, the B-shear zones become more continuous, and further localization forms Y-shears, causing
smaller values of $D$ (Marone and Kilgore, 1993). Shear localization is also documented by a reduction of layer dilation with strain (Fig. 2D), which is associated with the transition from velocity-strengthening to velocity-weakening behavior (e.g., Beeler and Tullis, 1996). At this point, the experimental fault has the necessary condition for instability $[(a – b) < 0]$. The sufficient condition for instability, which dictates the mode of fault slip, is determined by the stiffness ratio $K = k/k' = k'/k''$ (Figs. 1 and 3). Small stick-slip instabilities initiate spontaneously when $K = 1$, i.e., near the intersection between the black and red curves shown in Figure 3. With further shear, as $K$ decreases, stress drop and peak slip velocity increase until a nearly steady state for a given $K$, with stick-slip behavior characterized by slow, quasi-dynamic slip or fast, dynamic slip (Fig. 1C; Fig. DR6). We relate this transition to the growth and interconnectivity of the Y-shears within the B-shear zone. After the initial growing phase, stick-slip evolution is controlled by $K$. Slow earthquakes with slip velocity of ~100 µm/s, stress drop of 0.5 MPa, and slip duration of 0.5 s occur for $k'_0 = k'$ (Fig. 3), and faster events with slip velocity up to 3 cm/s, stress drop 2.4 MPa, and slip duration 0.003 s are observed when $k'_0 > k'$ (Fig. 3). Our data predict that with increasing stress, lower values of $K$ can induce a faster slip velocity favoring dynamic weakening processes resulting in a large strength drop (e.g., Passelègue et al., 2016).

Our results show that once localization is well established, fault zone microstructure (i.e., continuous B-shear zones containing interconnected Y-planes) is approximately independent of the mode of faulting. The similarities in microstructures, in particular localization along Y-shears, for experimental faults that experienced different slip velocities, ranging from 0.001 to 3 cm/s, indicate that at the tested boundary conditions, once localization is well established, the slip behavior is mainly controlled by the stiffness ratio $K$. Under these conditions, minor changes in frictional rheology, $k''$, and/or elastic stiffness of the surroundings result in dramatic changes in the mode of fault slip. For instance, in an experiment started at normal stress of 35 MPa, after recording a series of dynamic stick slips, we reduced the normal stress to 15 MPa and observed stick slips with larger stress drop (1 MPa versus 0.5 MPa) and faster slip velocities (1.5 mm/s versus 0.15 mm/s) in comparison to standard experiments that started at 15 MPa normal stress (Fig. DR7). The different fault slip mode, for the same applied normal stress, results from the inherited fault zone stiffness, produced by greater grain-size reduction resulting in lesser porosity. That...
Figure 3. Data showing evolution of loading stiffness $k'$ (red dots and open circles) and rheologic stiffness $k''$ (filled black circles). Data for $k'$ include both shear load-unload cycles and stick-slip cycles (details in Fig. DR5 in Data Repository [see footnote 1]). Values of $k''$ are calculated from rate and state friction (RSF) parameters (Fig. 2C); gray region shows evolution of $k''$, with mean fit represented by black line. Regions noted by 1, 2, and 3 represent inferred evolution of microstructure as reported in schematic at bottom.

is, the elastic stiffness acquired at 35 MPa is maintained when we reduce the stress to 15 MPa, dictating the fault slip behavior. These data indicate that structural and microstructural evolution of the loading medium surrounding the area of slip localization can significantly influence fault slip behavior and the mode of faulting.

As applied to tectonic faults, our results suggest that a single fault segment can experience a spectrum of fault slip behavior depending on the evolution of fault rock frictional properties and elastic conditions of the loading system. This mechanical prediction is consistent with the observation that some slow and fast earthquakes occur on the same fault (e.g., Kato et al., 2012). In addition, the stiffness ratio $K$ represents a general mechanism for fault slip behavior because it includes all of the key parameters used to model the spectrum of fault slip behavior such as fluid pressure (e.g., Kodaira et al., 2004), the evolution of frictional properties with fault maturity and depth (e.g., Ampuero and Rubin, 2008), and other viscous processes (e.g., Fagereng et al., 2014) that likely influence the effective normal stress and can alter the stiffness of the loading system.

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- Figure DR6 The role of applied normal stress in the stiffness of the loading system.
Table DR1: Summary of experiments and boundary conditions.

| Experiment number | Normal stress (MPa) | Spring | Target of the experiment | Microscopy analyses |
|-------------------|---------------------|--------|--------------------------|---------------------|
| b266              | 13                  | Yes    | Stable Sliding           | No                  |
| b267              | 14                  | Yes    | Stick-slip               | No                  |
| b268              | 13.5                | Yes    | Stable sliding           | No                  |
| b371              | 15                  | Yes    | Stick-slip               | SEM                 |
| b372              | 25                  | Yes    | Stick-slip               | No                  |
| b390              | 15                  | Yes    | Stick-slip               | SEM                 |
| b391              | 25                  | Yes    | Stick-slip               | SEM/TEM             |
| b416              | 15                  | No     | Rate & State friction parameters | No |
| b417              | 25                  | Yes    | Stick-slip               | No                  |
| b417              | 25                  | Yes    | Stick-slip               | No                  |
| b418              | 20                  | Yes    | Stick-slip               | No                  |
| b418              | 20                  | Yes    | Stick-slip               | No                  |
| b433              | 25                  | No     | Rate & State friction parameters | No |
| b511              | 25                  | No     | Stable sliding $\gamma = 4$ | SEM                 |
| b512              | 25                  | No     | Stable sliding $\gamma = 15$ | SEM                 |
| b540              | 30                  | Yes    | Stick-slip               | SEM                 |
| b540              | 30                  | Yes    | Stick-slip               | SEM                 |
| b541              | 35                  | Yes    | Stick-slip               | SEM                 |
| b542              | 15                  | Yes    | Stick-slip               | SEM                 |
| b543              | 35                  | Yes    | Stick-slip               | SEM                 |
| b544              | 35                  | Yes    | Stick-slip               | SEM/TEM             |
| b615              | 35                  | Yes    | Stiffness during loading/unloading | No |
| b616              | 15                  | Yes    | Stiffness during loading/unloading | No |
| b617              | 35,15               | Yes    | Stiffness during loading/unloading | No |

All tests were conducted under 100% relative humidity (RH) to ensure experimental reproducibility. All experiments were run at shear velocity of 10 μm/s, except for experiments to retrieve RSF parameter, which included velocity steps tests of 1-3-10 μm/s.
Figure DR1. To characterize the evolution of the rate- and state-friction parameters we performed a series of velocity steps (from 1 to 10 $\mu$m/s) with increasing strain, at normal stresses of 15 and 25 MPa. To determine the rate- and state-friction parameters, $(a-b)$ and $D_c$, we modelled each velocity step using an iterative singular value decomposition technique, which solves the rate- and state-friction equations using the Ruina evolution law coupled with the elastic interaction of the testing machine (Reinen and Weeks, 1993; Blanpied et al., 1998). The inset in red shows the details of one velocity step with the comparison between experimental data (in black) and the result from the inversion model (red).
Figure DR2. In order to investigate the degree of shear localization in response to step changes in the imposed slip velocity, we analyzed changes in gouge layer thickness measured at constant normal stress. (Panel A) Data from a typical velocity step test. Note overall geometric layer thinning with superimposed variations. Dilation associated with velocity perturbations was measured after removing geometric layer thinning due to simple shear (Scott et al., 1994). (B) Enlargement of a velocity step (grey box in Panel A), showing the evolution of frictional strength; a linear trend has been removed. (C) Raw data for layer thickness evolution during the velocity step shown in (B). Dashed red line represents the linear trend removed in order to analyze dilation, as in panel D. (D) Detrended data from Panel C showing layer dilation at higher slip velocity. (E) Comparison of layer dilation at two values of shear strain for experiments performed at 15 (grey) and 25 MPa (black) normal stress. Data have been offset so that 0,0 corresponds to the velocity step. Note that for both normal stresses the instantaneous dilation is smaller at higher strain, indicating a greater degree of shear localization.
Figure DR3: Details on fabric evolution from stable sliding to stick-slip

Microstructures for gouge layers sheared at different normal stresses and loading stiffnesses. Lower two rows are layers from dynamic, stick-slip failure. Upper row is a stable sliding experiment. Despite the different stick-slip velocities the microstructures are nearly identical. Note localization along Y-shear planes contained within B shear zones for each case. In these zones of localization the only difference between stable and unstable failure is that for higher stick-slip velocities the B shear zones show a higher level of grain-size reduction.
Figure DR3 continued

Details of the nanostructure of Y-shear planes for different stick-slip experiments. Nanoscale structures are very similar for the two boundary conditions; each consisting of nanograins, with grain-size of < 500 nm, with intense dislocations. Nanograins likely form by dislocation pile-up during strain accumulation.
Bright-field phase-contrast images showing the occurrence of dislocations through the so-called dark contrast features. Grains from the starting material (top left) were invariably contrast-free, independently from crystal orientation (i.e., the grains were perfectly homogeneous also during crystal tilting under the TEM beam). Also, grains outside the slipping zone are angular with few dark contrast features indicating low degree of internal deformation. Conversely, grains in the shear zones are more rounded and always characterized by dark contrast features, indicating a high level of internal deformation (i.e. dislocations).
Figure DR3 continued

Thin amorphous films surrounding the surface of grains along the highly localized slipping zone.
Figure DR4. Data showing the technique used to measure loading stiffness as a function of shear stress and shear strain. The effective loading stiffness is determined by apparatus stiffness, fault gouge stiffness, and normal stress: $k' = k/\sigma_n$. We evaluate $k$ from load/unload cycles (panel A) and from (panels B and C) the linear, elastic sections of the stick-slip loading curves. Both methods produce similar values, indicating that the shear stress dependence of $k'$ is minor.
Figure DR5: Growth of frictional instabilities

Figure DR5. Here we show an example of the spontaneous emergence of unstable sliding with small stick-slip instabilities that initiate when $K = 1$, i.e. near the intersection between black and red curves in figure 3. With increasing displacement we observe a growing phase in stress drop and slip velocity before reaching a nearly steady state, stick-slip behaviour.
Figure DR6: The role of applied normal stress in the stiffness of the loading system.

Figure DR6. Elastic stiffness $k$ and its evolution with shear displacement and normal stress. (A) Data for $k$ at two normal stresses as determined from load/unload cycles. Red line shows data for an experiment at 15 MPa normal stress. Black and green lines show an experiment that started at 35 MPa normal stress and was reduced to 15 MPa after ~ 15 mm of shear displacement. Note that sliding is unstable for the run in which normal stress was reduced. These stick-slips are different in comparison to the “standard” stick-slips observed at 15 MPa (red curves in figure B) because they have shorter duration of
the stress drop, larger stress drop (1.0 vs. 0.5 MPa), shorter rise time and faster slip velocity (1.5 vs. 0.15 mm/s). These faster stick-slip events recorded at 15 MPa result from a decrease of the stiffness of the loading system that it is acquired at 35 MPa and it is maintained when the normal stress is reduced at 15 MPa (Figure C). We interpret this increase in stiffness as a product of fabric development and fault zone stiffness. In particular the lower stiffness of the loading system is likely promoted by a more pronounced grain-size reduction favoured by higher stresses rather than stick-slip velocities, because stable values of stiffness at 35 MPa are reached after 5 mm of displacement, hence before the onset of stick-slip instabilities.

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