On the relation between fault strength and frictional stability

Matt J. Ikari, Chris Marone, and Demian M. Saffer
Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania 16802, USA

ABSTRACT

A fundamental problem in fault mechanics is whether slip instability associated with earthquake nucleation depends on absolute fault strength. We present laboratory experimental evidence for a systematic relationship between frictional strength and friction rate dependence, one of the key parameters controlling stability, for a wide range of constituent minerals relevant to natural faults. All of the frictionally weak gouges (coefficient of sliding friction, $\mu < 0.5$) are composed of phyllosilicate minerals and exhibit increased friction with slip velocity, known as velocity-strengthening behavior, which suppresses frictional instability. In contrast, fault gouges with higher frictional strength exhibit both velocity-weakening and velocity-strengthening frictional behavior. These materials are dominantly quartzofeldspathic in composition, but in some cases include certain phyllosilicate-rich gouges with high friction coefficients. We also find that frictional velocity dependence evolves systematically with shear strain, such that a critical shear strain is required to allow slip instability. As applied to tectonic faults, our results suggest that seismic behavior and the mode of fault slip may evolve predictably as a function of accumulated offset.

INTRODUCTION

A common assumption in many studies of fault and earthquake mechanics is that earthquakes nucleate on mechanically strong portions of faults (asperities), whereas aseismic slip occurs on weak patches (e.g., Ruff and Kanamori, 1983; Tichelaar and Ruff, 1993; see also Scholz, 1992). However, theoretical treatments and experimental results have repeatedly demonstrated that earthquake source parameters and stick-slip frictional instability are independent of absolute fault strength, and depend only on relative changes in strength associated with slip velocity perturbations (e.g., Brune, 1970; Johnson and Scholz, 1976; Tullis, 1988). To date, there is little direct evidence linking the occurrence of rate-weakening frictional behavior (a requirement for fault slip instability) with absolute frictional strength; an exception is Beeler (2007), who reviewed laboratory data in support of a connection between aseismic slip and frictionally weak materials.

Previous laboratory studies have shown that the mineralogy of fault gouge exerts a first-order control on the frictional properties of faults, including both strength and sliding stability (Shimamoto and Logan, 1981a, 1981b; Logan and Rauenzahn, 1987; Morrow et al., 1992, 2000; Ikari et al., 2007). Other laboratory studies have highlighted the importance of net shear strain as a control on frictional behavior, with shear localization developing as shear strain increases, leading to rate-weakening friction (Marone et al., 1992; Beeler et al., 1996; Scruggs and Tullis, 1998; Marone, 1998; Mair and Marone, 1999) or stick-slip instability (Byerlee et al., 1978; Logan et al., 1992). Field observations of systematic changes in fault properties as a function of maturity, including development of internal fabric, shear localization, and evolution of structural complexity (Wesnousky, 1988; Cowie and Scholz, 1992; Collettini and Holdsworth, 2004; Sagy et al., 2007; Frost et al., 2009), seem to suggest that these processes may also allow unstable slip in natural faults. However, neither the general relationships between fault stability and shear strain nor the underlying processes are well understood.

Here we investigate the relationships between fault strength, stability, composition, and shear strain using laboratory experiments on a suite of gouge compositions relevant to natural faults. Specifically, we (1) provide a critical assessment of the link between fault strength and frictional rate dependence, as hypothesized by Beeler (2007); and (2) evaluate the effects of shear strain on frictional behavior, for shear strains (γ) of >100 (10,000%), normal stresses to 50 MPa, and low slip velocities relevant to earthquake nucleation (≤300 µm/s).

METHODS

We studied the frictional properties of synthetic and natural fault gouges spanning a wide range of mineral assemblages that are common in major fault zones (e.g., Vrolijk and van der Pluijm, 1999; Solum et al., 2003; Underwood, 2007; Smith and Faulkner, 2010). The natural materials include illite shale, chlorite schist, biotite schist, talc schist, serpentinite (all obtained from Ward's Natural Science, http://wardsci.com), andesine feldspar (aplite), and Westerly Granite. Synthetic gouges include monomineralic and bimineralic mixtures prepared from commercially obtained powders of Ca-montmorillonite (mean grain size 60 µm), kaolinite (maximum grain size 4 µm), muscovite (maximum grain size 90 µm), and sand-sized quartz (mean grain size 130 µm). Bimineralic gouges were prepared by mixing the Ca-montmorillonite or kaolinite with silt-sized quartz (<40 µm) in 50%–50% proportions by weight. The natural gouges were prepared from rock samples ground in a rotary mill and sieved to <106 µm for most gouges (<150 µm for Westerly Granite, <125 µm for talc schist). The biotite schist is nearly pure, with very minor quartz, while the illite shale and chlorite schist contain slightly higher amounts of impurities (~40–50 wt%), the majority of which are quartz and feldspar (Ikari et al., 2009).

Our goals were to measure frictional strength and rate dependence over a wide range of shear strain, which has been shown to be an important parameter because it allows effects of layer thickness to be accounted for during deformation (Logan et al., 1992). In this study we use engineering shear strain, calculated as $\gamma = \Sigma(\Delta x/h)$, where x is the load point displacement and h is the instantaneous layer thickness. Gouge layers were prepared to a uniform thickness of <3 mm and deformed in the double-direct shear configuration (Fig. 1A inset), in which the nominal frictional contact area and the normal stress are constant throughout shearing. Due to variable layer thinning among samples, not all samples reached the same maximum shear strains, but strains of ≥~50 were attained in all experiments. The coefficient of sliding friction µ was determined from the ratio of shear stress τ over normal stress σ_n, assuming that cohesion is zero. Load and displacement measurements are accurate to ±0.1 kN and ±0.02 µm. Our experiments included measurements of the friction rate parameter $a\text{-}b = \Delta\mu/\Delta \ln V$, where V is the sliding velocity (e.g., Dieterich, 1979; Scholz, 2002). Velocity-weakening (or rate weakening) behavior ($a\text{-}b < 0$) is a requirement for the occurrence of unstable fault slip that results in earthquake nucleation. To facilitate comparison between experiments we conducted velocity step tests at specified shear strains in the range of γ = 5–100 in each experiment. We sheared layers using a fast-acting servo-hydraulic controller, enforcing a displacement rate that varied in the range 1–300 µm/s during velocity step tests. When velocity step tests were not being performed, the sample was sheared at a constant background rate of 11 µm/s. Reproducibility in friction coefficient is typically within ~6%, and the average of a suite of $a\text{-}b$ measurements from a velocity step sequence varies by ~0.001. All experiments were conducted at room temperature and humidity (see Ikari et al., 2007, for additional details of the experimental arrangement).

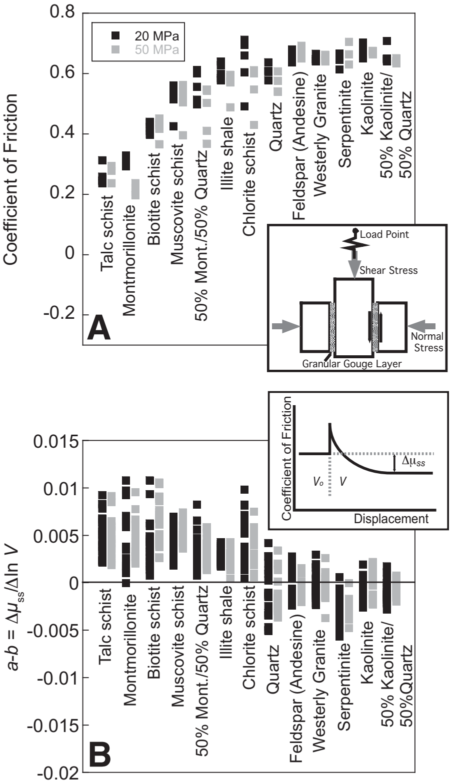

Figure 1. A: Measured coefficient of friction, *μ*, for all gouges in this study. Inset shows double-direct shear geometry. B: Friction rate parameter *a-b* for all gouges in this study. Inset shows example of velocity (*V*) step sequence and how $\Delta\mu_{ss}$ (ss—steady state) is measured and used to calculate *a-b*. Friction coefficient and *a-b* values are measured at constant normal stresses of 20 MPa (gray) and 50 MPa (black) and over entire range of shear strains in this study. See text for gouge descriptions.

RESULTS

Figure 1 shows the coefficient of friction during steady sliding for our suite of samples. The data show that gouges containing biotite, montmorillonite, and talc are frictionally weak ($\mu < 0.5$), whereas gouges rich in framework silicate minerals (quartz, andesine feldspar, Westerly Granite) are stronger ($\mu > 0.6$). However, other phyllosilicate gouges are not uniformly weak (Fig. 1A); those containing muscovite, montmorillonite/quartz, illite, and chlorite exhibit a range of friction coefficients between that of talc (μ = ~0.25) and quartz (μ = ~0.60). Kaolinite, kaolinite/quartz, and serpentine gouges are uniformly strong (μ ~0.65). Some of these materials also exhibit significant strain hardening (e.g., montmorillonite/quartz, chlorite), which results in larger ranges of the friction values (Fig. 1A); however, steady-state friction is generally reached for $\gamma \leq 10$. With the exception of montmorillonite, friction values of all gouges are nearly identical at 20 and 50 MPa normal stress.

Examination of the friction rate parameter *a-b* (Fig. 1B) over the range of gouge compositions reveals two distinct populations; gouges that exhibit strictly velocity-strengthening behavior (*a-b* > 0), and gouges that exhibit both velocity-strengthening and velocity-weakening behavior (*a-b* < 0), depending on experimental conditions. None of the gouges we studied exhibited strictly velocity-weakening behavior. Values of *a-b* for strictly velocity-strengthening gouges range from ~0 (montmorillonite, 20 MPa) to 0.011 (montmorillonite, 20 MPa and biotite, 20 MPa), and values of *a-b* for gouges that exhibit some velocity weakening range from –0.006 (serpentine, 20 MPa) to 0.004 (quartz, 20 MPa). Notably, the weakest gouges are uniformly velocity strengthening, whereas the frictionally stronger gouges exhibit both velocity weakening and velocity strengthening (Fig. 2). The velocity-strengthening gouges are all rich in phyllosilicate minerals, whereas the set of velocity-weakening gouges includes those rich in framework minerals, but also some phyllosilicates (kaolinite, kaolinite/quartz, serpentine). For all gouges, fault frictional stability at 50 MPa is nearly identical to that observed at 20 MPa.

We also find a clear dependence of *a-b* on shear strain for the gouges that exhibit velocity weakening (Fig. 3). For example, in Westerly Granite gouge at 50 MPa, *a-b* evolves from velocity strengthening (values to 0.0027) to velocity weakening (values as low as –0.0037) over shear strains of <5 to ~30 (Fig. 3A). In contrast, the effect of shear strain on the parameter *a-b* is minimal for exclusively velocity-strengthening gouges, which exhibit slight decreases in *a-b* at high slip velocities but no indication that velocity weakening will occur overall (e.g., chlorite gouge at 20 MPa; Fig. 3B). We note, however, that the range of *a-b* values at a given shear strain can be large, especially for the velocity-strengthening gouges (Fig. 3B). This is a consequence of increases in *a-b* with increasing slip velocity, observed consistently in velocity-strengthening gouges (e.g., Saffer and Marone, 2003; Ikari et al., 2009). Qualitatively, we consistently observe evidence of shear localization in recovered end products of our experimental gouges, including separation of gouge layers along through-going surfaces, and striated and slickensided surfaces.

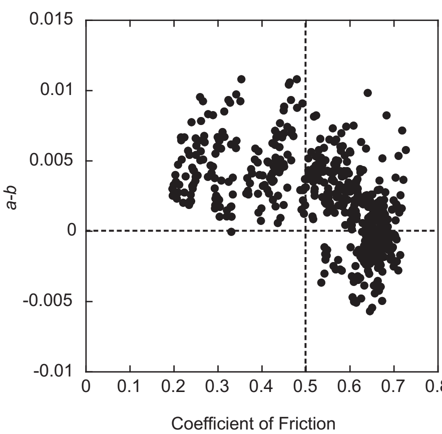

Figure 2. Friction rate parameter *a-b* as function of coefficient of friction for all gouges in this study.

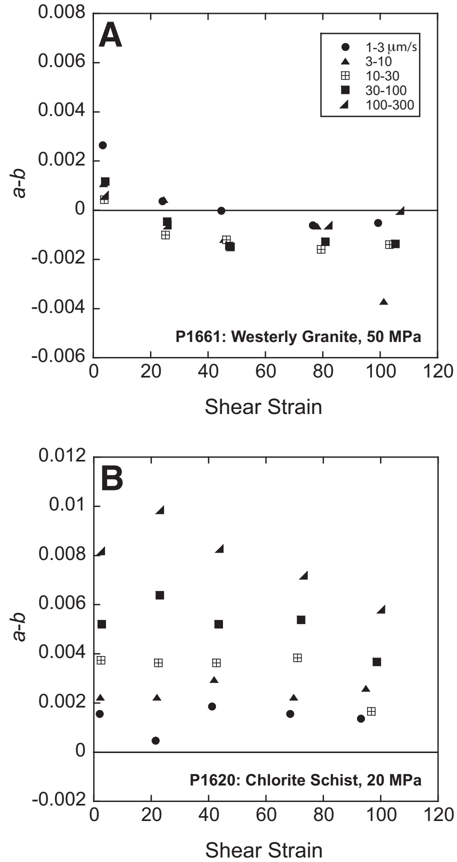

Figure 3. Friction rate parameter *a-b* as function of shear strain for (A) Westerly Granite at 50 MPa as example of velocity-weakening group. B: Chlorite gouge at 20 MPa as example of velocity-strengthening group.

DISCUSSION

For the compositionally diverse gouges in this study, our friction measurements show that many gouges have strengths typical of most Earth materials (μ ~0.6), but that some gouges, notably phyllosilicates, are much weaker with friction coefficients as low as ~0.25 (Fig. 1A). This weakness has been previously attributed to the strength of bonds between sheet silicate surfaces (Morrow et al., 2000). We observe that the weaker gouges are coincidentally the same gouges that exhibit strictly velocity-strengthening behavior; therefore our data demonstrate a systematic relationship between frictional strength and stability that carries important implications for links between absolute fault strength and slip stability (Figs. 1 and 2). Whereas velocity-strengthening frictional behavior can occur in materials of any frictional strength, velocity weakening occurs only in strong gouges, with $\mu > 0.5$ (Figs. 1 and 2). Recalling that a-b = $\Delta\mu/\Delta \ln V$, many previous works have pointed out that: (1) frictional instability, and thus the potential for seismic slip, depends on the velocity-dependent changes in friction in rather than the absolute value of strength; and (2) there is no a priori reason to assume a relationship between frictional strength and rate dependence. This is a consequence of the individual parameters a and b being treated as empirically derived constants that are assumed to be independent of fault strength. However, it has been suggested that the friction rate parameter b, in particular, should be considered a function of the overall friction level because it describes strength loss due to changes in contact area, which is enhanced by dilatancy characteristic of strong fault materials (Beeler, 2007). Dilatancy may be suppressed in the weak materials if deformation is accommodated by separation of phyllosilicate sheets with low bond strength. In this context, rate and state friction laws are consistent with a dependence of fault stability on frictional strength, as supported by our experimental results.

The links between frictional strength, net shear strain, and frictional stability have important implications for slip behavior on natural faults (Fig. 4). Fault maturity, defined here as the development of internal structure and localization features with accumulating slip, may also play an important role in natural faults. For example, our results suggest that immature faults hosted in phyllosilicate-rich rocks should exhibit low frictional strength and a tendency for stable creep, due to velocity-strengthening frictional behavior (path 1 in Fig. 4). In this case, aseismic slip is expected to persist with increasing fault offset because the velocity dependence of friction for these materials is largely independent of shear strain (Fig. 3). Unstable slip on such a fault would require modification of the gouge composition, or processes that change its physical properties or increase its frictional strength, such as cementation or consolidation (Bernabé et al., 1992; Moore and Saffer, 2001; Marone and Saffer, 2007) (path 2, Fig. 4). Immature faults in strong minerals, such as those with a nonphyllosilicate protolith, may evolve from being frictionally stable (velocity strengthening) to unstable (velocity weakening) with increased shear strain (Fig. 3A; path 3 in Fig. 4). A transition from stable to unstable behavior as a function of increasing fault maturity and offset may result from shear localization, as noted in previous works (Byerlee et al., 1978; Shimamoto and Logan, 1981a, 1981b; Logan et al., 1992; Marone et al., 1992; Beeler et al., 1996; Scruggs and Tullis, 1998; Mair and Marone, 1999) and which we observe quantitatively in our experimental gouges. Formation of localization features in laboratory experiments is thought to result from the kinematic constraint of rigid forcing blocks on the deforming fault material (e.g., Mandl et al., 1977), a condition analogous to localized deformation along principal slip surfaces within highly competent country rock (e.g., Chester and Chester, 1998; Frost et al., 2009). A mature fault with velocity-weakening frictional behavior could also be forced back into the stable regime. This could occur via large-scale brecciation during seismic slip that disrupts the fault structure (Sibson, 1986), or by authigenic growth of weak, velocity-strengthening minerals (e.g., Wintsch et al., 1995; Vrolijk and van der Pluijm, 1999; Warr and Cox, 2001) (path 4, Fig. 4). Previous work has shown that only a small fraction of a weak, stable mineral phase need be present in the bulk gouge in order to control its frictional behavior (Logan and Rauenzahn, 1987), and extremely low abundances of a weak phase may cause significant weakening if the weak mineral occurs as a thin lining or film on slip surfaces in foliated fault rock (Collettini et al., 2009; Niemeijer et al., 2010; Smith and Faulkner, 2010; Schleicher et al., 2010).

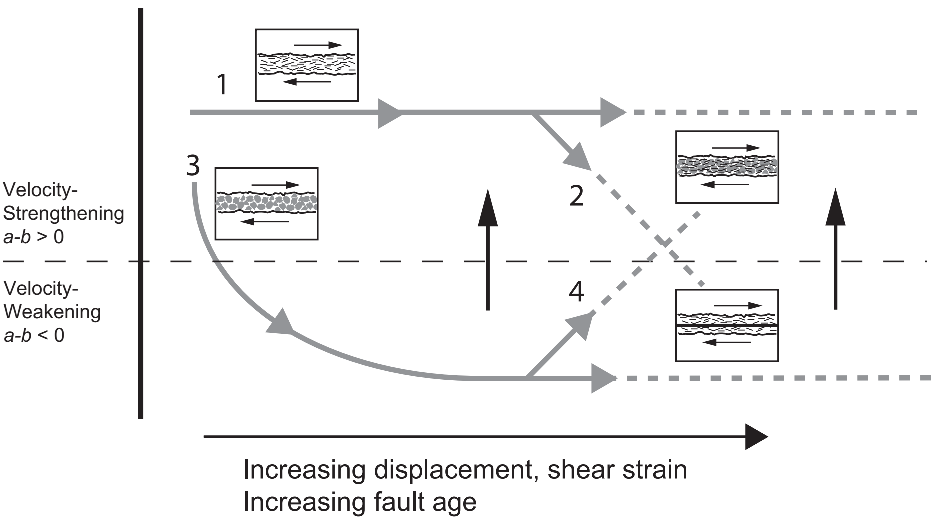

Figure 4. Schematic illustration of evolution of fault frictional stability for fault gouges that are derived from phyllosilicate-rich protolith (initially phyllosilicate-rich gouges) and gouges derived from quartzofeldspathic protolith (gouges initially containing no phyllosilicates). Initially phyllosilicate-rich gouge will remain velocity strengthening (path 1), but may change to velocity weakening if cohesion increases and extreme slip localization occurs (path 2). Strong quartzofeldspathic gouges will become velocity weakening with critical amount of accumulated shear strain (path 3), but may transition to velocity strengthening if frictional weakening due to authigenic clay growth occurs (path 4).

CONCLUSIONS

We find a systematic relationship between absolute frictional strength and the potential for unstable fault slip. Weak gouges, with coefficients of friction $\mu < 0.5$, exhibit only stable sliding behavior, whereas strong gouges, with coefficients of friction $\mu \geq 0.5$, exhibit both stable and unstable slip. Weak gouges are those rich in phyllosilicate minerals. Strong gouges are rich in quartzofeldspathic minerals as well as certain phyllosilicates, and exhibit a systematic decrease in the frictional stability parameter a-b with increasing shear strain. A key implication of our work is that absolute fault strength and sliding stability are linked for a wide range of materials common in natural faults, even though such a relationship is rarely acknowledged. Our observation that a-b evolves with shear strain suggests that immature, low-offset faults in quartzofeldspathic rock may become seismogenic with increasing displacement. In contrast, most phyllosilicate-rich faults are expected to exhibit stable creep unless the gouge mineralogy changes or strengthening of gouge occurs and slip becomes localized.

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