Micromechanical processes of frictional aging and the affect of shear stress on fault healing: insights from material characterization and ultrasonic velocity measurements

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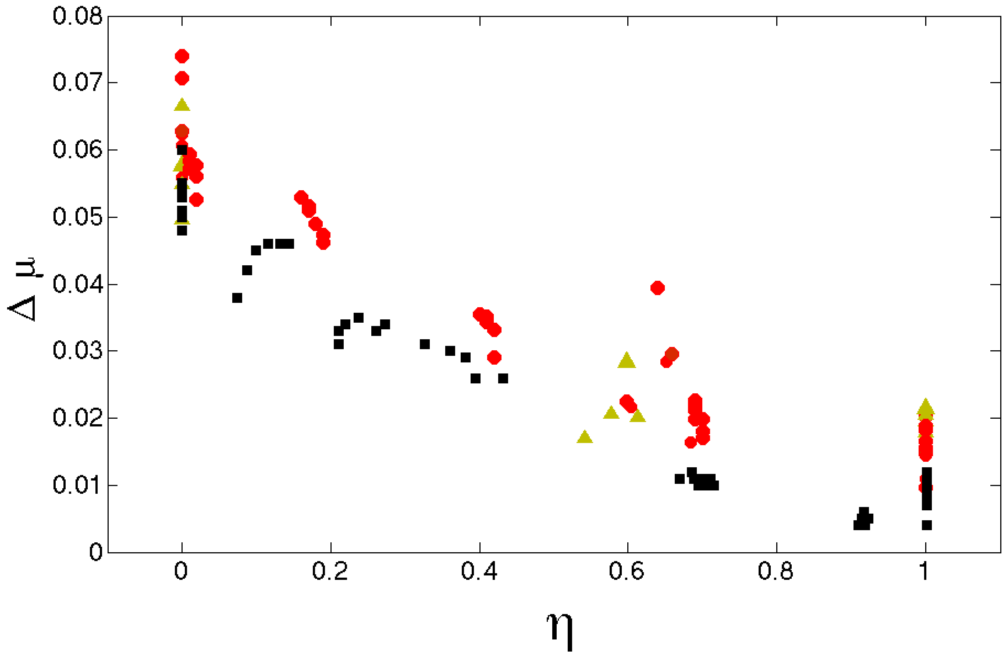
During the seismic cycle, faults repeatedly fail and regain strength. The gradual strength recovery is often referred to as frictional healing, and existing works suggest that healing can play an important role in determining the mode of fault slip ranging from dynamic rupture to slow earthquakes. Laboratory studies can play an important role in identifying the processes of frictional healing and their evolution with shear strain during the seismic cycle. These studies also provide data for laboratory-derived friction constitutive laws, which can improve dynamic earthquake models.

Previous work shows that frictional healing varies with shear stress on a fault during the interseismic period. Unfortunately, the micromechanical processes that cause shear stress dependent frictional healing are not well understood and cannot be incorporated into current earthquake models. In fault gouge, frictional healing involves compaction and particle rearrangement within sheared granular layers. Therefore, to address these issues, we investigate the role grain size reduction plays in frictional re-strengthening processes at different levels of shear stress. Sample material was preserved from biaxial deformation experiments on granular Westerly granite. The normal stress was held constant at 25 MPa and we performed several 100 second slide-hold-slide tests in each experiment. We conducted a series of 5 experiments each with a different value of normalized shear stress (ranging from 0 to 1), defined as the ratio of the pre-hold shear stress to the shear stress during the hold. The particle size distribution for each sample was analyzed.

In addition, acoustic measurements were recorded throughout our experiments to investigate variations in ultrasonic velocity and signal amplitude that reflect changes in the elastic moduli of the layer. Acoustic monitoring provides information about healing mechanisms and can provide a link between laboratory studies and tectonic fault zones.



Key Observations: Frictional healing (delta mu) increases with decreasing normalized shear stress(eta). Magnitude of frictional healing ranges from ~.01 for eta =1 to ~.075 for eta=0. Data from Westerly granite experiments (red circles) correlate well with data from previous work in quartz poweder (black squares from Karner and Marone ,2001] and F110 experiments I conducted (yellow triangles).

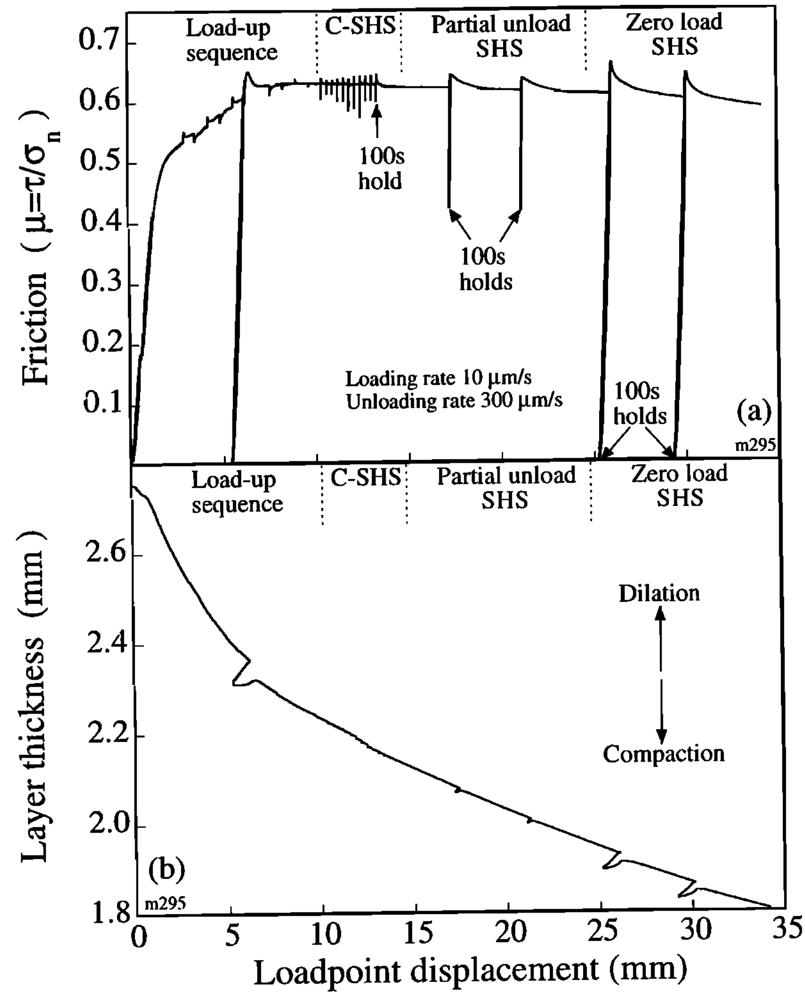


Figure 4. Data from one experiment involving holds at different shear loads. (a) Friction is the ratio of measured shear and normal stress and is plotted against load point displacement. Base level sliding friction decreases slightly with slip. Data show a set of CSHS tests with hold times of 10, 100, 1000, and 10000 s. The last three hold cycles of the series were of 100 s duration. For comparison, the next two hold cycles (100 s) were performed at a reduced shear load ($\mu_{hold} \sim 0.4$), and the last two hold cycles involved complete removal of shear load. Peak static yield strength increases as τ_{hold} decreases. (b) Layer thickness data are shown for the same experiment shown in Figure 4a. Layers thin with increasing shear displacement. Layer thickness variations are larger for holds with lower levels of τ_{hold}.

definition of "static" friction. The difference between static friction and prehold sliding friction is taken as a measure of restrengthening ($\Delta\mu$, which we refer to as healing).

Healing and layer thickness data for a series of CSHS tests are shown in Figure 3. For simulated fault gouge, $\Delta\mu$ increases with hold time and is in the range 0.005-0.015 for times (t_h) of 1-100 s (e.g., Figures 3a and 3b). Healing rates, $\beta = \Delta\mu/\Delta\log_{10} t_h$, are typically between 0.003 and 0.02 (e.g., Figure 3b). Layer compaction for holds is also observed to increase with $\log_{10} t_h$ (e.g., Figure 3c). Gouge layer thinning, coupled with continued sample creep during holds, indicates that shear enhanced compaction may be a key mechanism responsible for healing and time-dependent restrengthening of fault gouge. However, healing in these tests involves both time- and slip-dependent processes, making it difficult to separate their effects (see *Beeler et al.* [1994] for a novel way to achieve this for CSHS tests). Thus it is important to design laboratory experiments to isolate the effects of time and slip.

2.2.2. Reduced load slide-hold-slide tests. To investigate time-dependent processes, we performed experiments using a technique similar to that of the CSHS tests described above. Gouge layers were sheared at a reference loading rate that was interrupted for specified periods of time (holds). Our experiments differ from CSHS tests in that shear load was rapidly reduced prior to initiating holds [e.g., *Nakatani and Mochizuki*, 1996; *Karner and Marone*, 1998; *Nakatani*, 1998; *Olsen et al.*, 1998](see Figures 4-6). In this way, shear creep of the sample is limited or does not occur at all during holds. Shear load was decreased by retracting the loading piston at a fast rate (up to 300 μm/s) using displacement feedback servocontrol, together with a comparator circuit to stop unloading at a preset shear stress level. Complete removal of shear load occurred within 2.5-3 s for the stiffness, loading conditions, and sample dimensions of our tests. Holds were timed from the point when the reduced shear load (τ_{hold}) was reached, to the time that reloading began.

Data from numerous trial experiments indicated that the frictional response following hold cycles was strongly dependent on sample slip history. Thus the data reported here were obtained from experiments with identical slip histories, including the initial loading sequence to ~10 mm displacement (as seen in