The crucial role of temperature in high-velocity weakening of faults: Experiments on gouge using host blocks with different thermal conductivities

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ABSTRACT

We study the important role of temperature rise in the dynamic weakening of fault gouge at seismic slip rates by using host blocks composed of brass, stainless steel, titanium alloy, and gabbro with thermal conductivities (λ_h) of 123, 15, 5.8, and 3.25 W/m/K, respectively. Our experiments are performed mostly on fault gouge collected from the Longmenshan fault, Sichuan, China, consisting primarily of illite and quartz. High-velocity weakening of gouge becomes more pronounced as λ_h decreases because the temperature in the gouge increases. Microstructure observations reveal welded slip-zone material and more compact slip surfaces for the gouge deformed with low-λ_h host blocks, which is probably caused by a sintering process indicative of higher temperatures. These conclusions are supported by temperature calculation performed using the finite-element method. The observed differences in frictional behaviors, deformation microstructures, and calculated temperature demonstrate that temperature rise driven by frictional heating is essential in causing dynamic weakening of gouge at seismic velocities. We show that our data are in good agreement with the flash-heating model, though thermochemical pressurization may also be important. Some of our experiments, where nanoparticles are present but show negligible weakening, demonstrate that the presence of nanoparticles alone is not sufficient to cause dynamic weakening of faults.

INTRODUCTION

Understanding the mechanisms that cause faults to weaken at seismic slip rates is fundamental to understanding earthquake propagation and slip (Rice, 2006). Based on theoretical analyses and high-velocity friction experiments, a variety of coseismic weakening mechanisms have been proposed. Weakening mechanisms controlled by temperature rise include melt lubrication, thermal and/or thermochemical pressurization, and flash heating (Di Toro et al., 2011; Niemeijer et al., 2012; Tullis, 2015). Gel lubrication or a tribochemical effect (Goldsby and Tullis, 2002) may require a lower temperature rise because weakening starts at much lower slip rates, whereas powder or nanoparticle lubrication (Han et al., 2010; Reches and Lockner, 2010) does not seem to require an elevated temperature.

To understand the importance of these weakening mechanisms in crustal faults, temperature should be considered as a key variable in experimental studies. However, it is not easy to control temperature conditions in high-velocity friction experiments because temperature is closely coupled with slip rate, normal and shear stress, and conduction of heat out of the sample assembly. Furthermore, conflating the effects of temperature and those of velocity may lead to confusion between temperature weakening and rate weakening (Noda et al., 2011), which limits our ability to formulate and extrapolate an integrated low- to high-velocity frictional law applicable to earthquake simulations. There are large differences between metals and rocks in the characteristic velocities for the onset of weakening and dramatic weakening, i.e., ~1 mm/s and 1 m/s, respectively, for rocks (Di Toro et al., 2011), as compared to ~1 m/s and 100 m/s, respectively, for metals (Lim et al., 1989). These differences may provide some hints to the dominant weakening mechanisms of rocks and metals.

To isolate the effect of temperature, we produced host blocks with thermal conductivities ranging from 3.25 to 123 W/m/K at room temperature (brass, stainless steel, titanium alloy, and gabbro, respectively). Using this approach, we are able to produce different temperature conditions in friction experiments performed on the same gouge material under the same slip rates and normal stresses. This paper reports a diverse range of behaviors that can be correlated with temperature rise in the gouge. The results have important implications for the operation of flash heating, thermochemical pressurization, and powder lubrication, which were previously recognized to be important weakening mechanisms in gouge experiments (Niemeijer et al., 2012).

MATERIALS AND METHODS

The high-velocity friction experiments were performed on a low- to high-velocity rotary shear apparatus at the Institute of Geology, China Earthquake Administration (Beijing; Ma et al., 2014). The sample assembly includes a gouge layer, two cylindrical host blocks, and a Teflon sleeve fitting tightly around the blocks (Fig. 1A). The four kinds of host blocks used are composed of brass (UNS C28000), stainless steel (AISI 316), titanium alloy (Ti-alloy, Ti90Al6V4, Goodfellow Cambridge Ltd., UK), and Shanxi gabbro, with thermal conductivities (λ_h) of 123, 15, 5.8, and 3.25 W/m/K at room temperature (Cverna, 2002), respectively. Most tests were done using a fault gouge collected from the Longmenshan fault zone, which hosted the A.D. 2008 Wenchuan earthquake (Sichuan, China). The mineral composition of the gouge is illite (47%), quartz (41%), smectite (3%), kaolinite (3%), chlorite (2%), and other minerals (hereafter referred to as illite-quartz gouge). In addition, we performed four experiments using simulated quartz gouge prepared from commercial pure quartz grains. The air-dried gouges were disaggregated and sieved to obtain a grain-size fraction of <150 µm. For each experiment, 2.5 g of gouge was placed between host blocks with a layer thickness of ~1.2 mm. The sliding surfaces of all the host blocks were roughened with 80# SiC powders. The slip rate, V, used in the experiments was either a constant value ranging from 0.1 to 2.1 m/s throughout the runs, or a constant value of 1.9 m/s for ~6.4 s followed by a linear slow deceleration with time over 24 s (hereafter referred to as standard constant-velocity tests and slow deceleration tests, respectively). All experiments were performed under a normal stress σ_n of 1.0 MPa and at room humidity.

RESULTS

Mechanical Data

In Figure 1, we present the evolution of the friction coefficient with displacement for eight experiments on the illite-quartz gouge (Figs. 1B and 1C) and four comparative experiments on the pure quartz gouge (Fig. 1D) at constant V of 1.0 or 2.1 m/s (corrected for Teflon friction in

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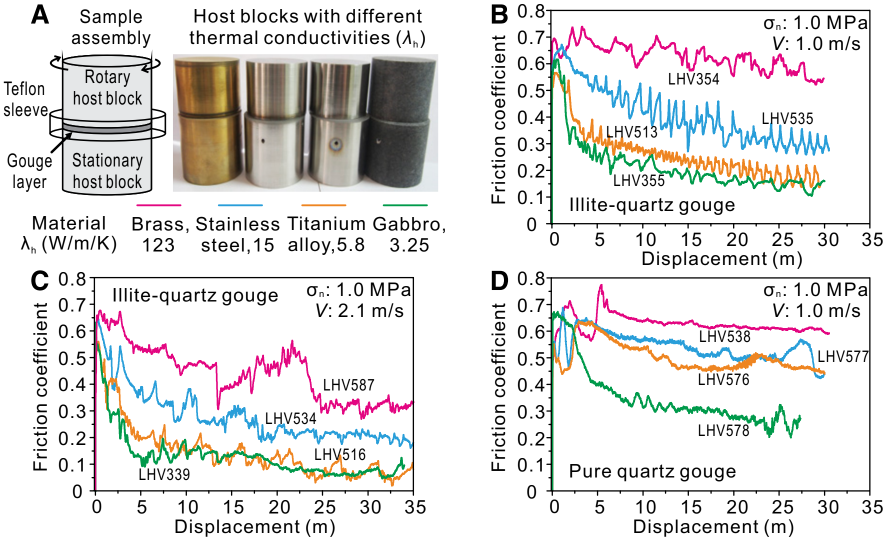

Figure 1. A: Schematic diagram of sample assembly for gouge experiments and photographs of (from left to right) brass, stainless steel, titanium alloy, and gabbro host blocks. B–D: Friction coefficient versus displacement curves for illite-quartz–rich gouge (47% illite, 41% quartz; B,C) and pure quartz gouge (D). Experiments were performed at normal stress σ_n of 1.0 MPa and slip rates *V* of 1.0 or 2.1 m/s under room humidity (run numbers are denoted by the alphanumeric labels next to the curves). Curves are shown with different colors corresponding to materials of host blocks, as shown in A.

all presented data, as specified in the GSA Data Repository[1]). For both of the gouges and both velocities, there is a clear trend showing that the amount of weakening (i.e., the drop in friction) increases with decreasing λ_h of host blocks. Note that fault gouges sheared with brass host blocks maintain fairly high friction at seismic slip rates. A relatively high steady-state friction coefficient (μ_{ss}) and a large slip weakening distance (D_w) are observed even for slip rates as high as 2.1 m/s (Fig. 1C). The Ti-alloy has a λ_h fairly close to that of gabbro, leading to similar frictional behavior (at least for the illite-quartz gouge). Compared with the illite-quartz gouge, the pure quartz gouge weakens more gradually, with larger values of D_w and μ_{ss} in the tests using stainless steel, Ti-alloy, and gabbro host blocks (see Figs. 1B and 1D).

To better understand the velocity dependence of gouge friction at typical seismic slip rates, we extend the slip rates to relatively low values of 0.1–0.5 m/s for standard constant-velocity experiments and also perform several slow deceleration tests. For the constant-velocity tests performed at $V = 0.5$ m/s, μ_{ss} decreases with the λ_h of host blocks (Fig. DR1 in the Data Repository), in good agreement with the observations shown in Figure 1. At $V = 0.3$ m/s, μ_{ss} has a narrower range and finally converges to a value of 0.74–0.77 at $V = 0.1$ m/s (Fig. DR1). The results of the slow deceleration tests conducted with metal host blocks are shown in Figure 2A. For all experiments, dynamic weakening is observed during sliding at $V = 1.9$ m/s and the initial stage of deceleration, with strength recovery occurring in the latter stages of deceleration (note the good reproducibility of experiments from the two performed with Ti-alloy host blocks). With decreasing λ_h of the host blocks, the fault gouge weakens more dramatically and strengthens more sharply upon deceleration. In all of the tests, the gouge thickness reduces sharply at the onset of the experiments due to initial compaction, then increases due to dilation, and finally decreases slightly near the end of the deceleration (Fig. 2B). Interestingly, the dilation tends to be faster and more significant with decreasing λ_h of host blocks.

We plot μ_{ss} from the constant *V* experiments (filled circles) and the evolution of friction with decelerating slip rate of the slow deceleration tests (lines) together in Figure 2C (see the summary of mechanical data in Table DR1 in the Data Repository). These two types of data are, for the most part, in agreement (except for the decelerating-slip data of the two tests with Ti-alloy host blocks at $V < 0.2$ m/s [dashed lines] probably due to residual temperature and material changes), suggesting that friction during the slow deceleration is close to the steady-state value. The compiled data clearly show that the relationship between μ_{ss} and *V* at $V > 0.1$ m/s is affected by the λ_h of host blocks, which suggests that temperature rise plays a key role in controlling the apparent velocity weakening at seismic slip rates.

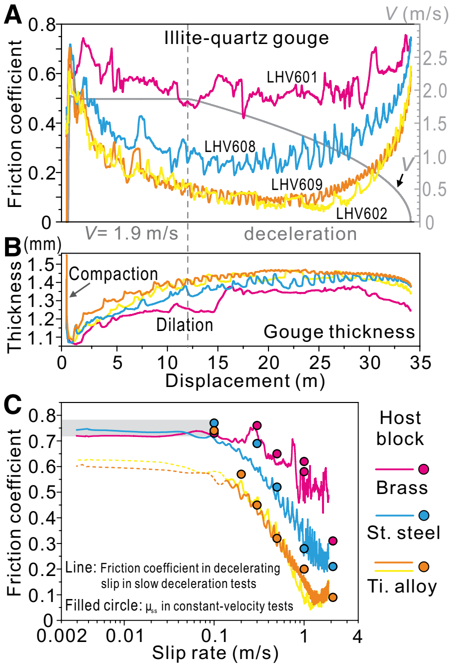

Figure 2. A,B: Evolution of friction coefficient and gouge thickness with displacement in experiments conducted with brass, stainless steel, and titanium alloy host blocks, with slip history consisting of constant slip rate *V* of 1.9 m/s followed by linear deceleration with time. C: Apparent velocity dependence of illite-quartz gouge friction compiled from standard constant-velocity tests (Figs. 1B and 1C; Fig. DR1 [see footnote 1]; μ_{ss} is steady-state friction coefficient) and decelerating slip portions of the slow deceleration tests (Fig. 2A).

Microstructures

Back-scattered electron images of the illite-quartz gouge deformed with brass and gabbro host blocks are presented as two extremes in Figures 3A–3B and Figures 3C–3D, respectively. In both cases, two highly deformed units with dramatic grain-size reduction are observed adjacent to rotary and stationary host blocks (see Figs. 3A and 3C; the SEM images of entire thin sections are shown in Fig. DR3). The internal structures of slip zones at the sub-micron scale are characterized by individual ultrafine grains or grain-like structures in the case of brass host blocks (Fig. 3B), but in the case of gabbro host blocks, the deformed quartz and illite in the slip zone show a welded structure probably due to the sintering process (Fig. 3D; Togo and Shimamoto, 2012), implying that the local temperature must have been high.

Secondary electron photos of slip surfaces were taken to observe the existence and distribution of nanoparticles. Shiny slip surfaces of the illite-quartz gouge sheared with brass (Fig. 3E) and Ti-alloy (Fig. 3F) host blocks were chosen as examples. Slickensides are observed in all cases, but the slip surface tends to be smoother and more compact (less porous) with the Ti-alloy host block compared to the brass block.

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[1] GSA Data Repository item 2016015, summary of experiments, supplementary experimental data, temperature calculation, supplementary information on microstructures, and details of fits to experimental data, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

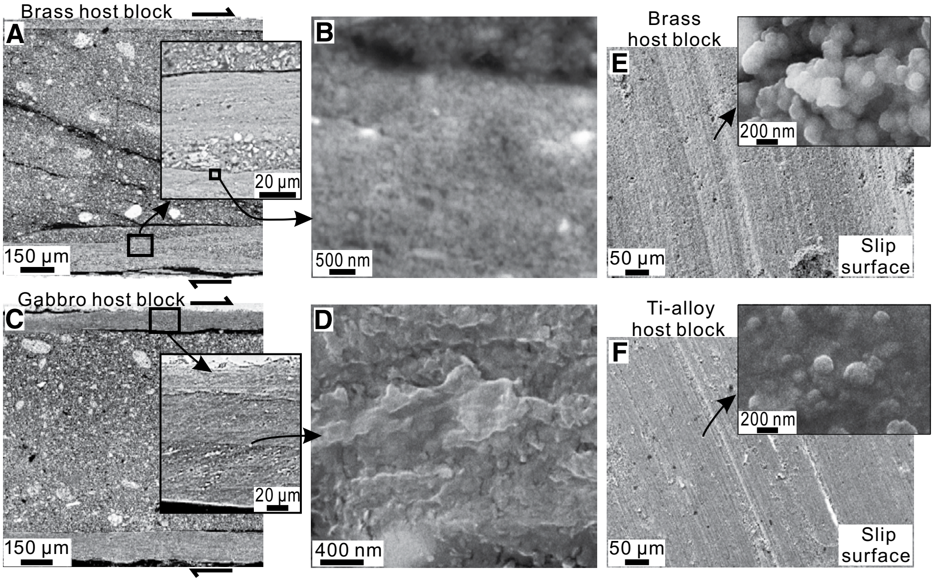

Figure 3. Microstructures of illite-quartz gouge deformed at slip rate of 1.0 m/s and normal stress of 1.0 MPa. A–D: Back-scattered electron images of gouge sheared with brass (A,B; run LHV596) and gabbro (C,D; run LHV355) host blocks. E,F: Secondary electron images of slip surfaces generated in tests conducted with brass (E; run LHV354) and titanium alloy (F; run LHV513) host blocks at micron and nanometer scales.

Two close-up images of the slip surfaces show the presence of ultrafine particles widely distributed on both of the slip surfaces; these particles are roughly round in shape and tens to hundreds of nanometers in size.

Temperature Evolution

We calculated the temperature changes in the gouge layers during our experiments with the COMSOL Multiphysics software (see details in the Data Repository). Figure 4A shows the evolution of the volume-averaged temperature of the outer-half slip zone in standard constant-velocity experiments on the illite-quartz gouge with four kinds of host blocks at $V = 1.0$ m/s (the tests shown in Fig. 1B). Differences in the calculated temperature between experiments clearly illustrate the effect of the thermal conductivity of the host blocks on bulk temperature rise in the slip zones, causing a difference of up to 150 °C for the given normal stress and slip velocity.

DISCUSSION AND CONCLUSIONS

The observed frictional behaviors, microstructures, and calculated temperatures suggest that bulk temperature rise strongly influences dynamic weakening of the illite-quartz and pure quartz gouges at seismic velocities. We thus rule out the possibility of powder lubrication because it is considered to weaken faults by particle rolling (Han et al., 2011), which operates without frictional heating, although the formation of nanoparticles may be assisted by thermally activated reactions. In our experiments with brass host blocks, although nanoparticles are widely distributed on the slip surfaces (e.g., Fig. 3E), the measured friction is fairly high (Fig. 1). These results demonstrate that the presence of nanoparticles is not sufficient for dynamic weakening of faults.

For the illite-quartz gouge, thermochemical pressurization is a possible weakening mechanism that could explain the observed behaviors. The gabbro and metal host blocks sandwiching the gouge layer are almost impermeable, and the kinetics of the dehydroxylation reaction of illite can be enhanced by shear-induced reduction of activation energy as well as by frictional heating (Hirono et al., 2013). Compared to the results of the pure quartz gouge, the effectiveness of thermochemical pressurization in the illite-quartz gouge tests is supported by the observation of water that wets host blocks after some experiments, and by the lower μ_{ss} and the smaller D_w under the same experimental conditions. The negative correlation between the dilation of the illite-quartz gouge and the λ_h of the host blocks (Fig. 2B) also could be important evidence suggesting differences in pore pressure due to different temperature increases.

However, comparing our illite-quartz and pure quartz gouge data with existing models suggests that the dominant weakening mechanism in our experiments is most likely to be flash heating. The classic model of flash heating relies on the temperature at highly stressed frictional asperities. Using a simple model for contact temperature, Rice (2006) and Beeler et al. (2008) balanced the fraction of time a contact spends in the weakened and unweakened states to predict the macroscopic friction coefficient:

$$f(V) = \left[\left(f_0 - f_w \right) \frac{V_w}{V} + f_w \right], \qquad (1)$$

where V_w is the characteristic weakening velocity, $f(V)$ is the friction coefficient for $V > V_w$, f_0 and f_w are the friction coefficients at low slip rates and in the weakened state, respectively. The characteristic weakening velocity V_w is proportional to (T_w

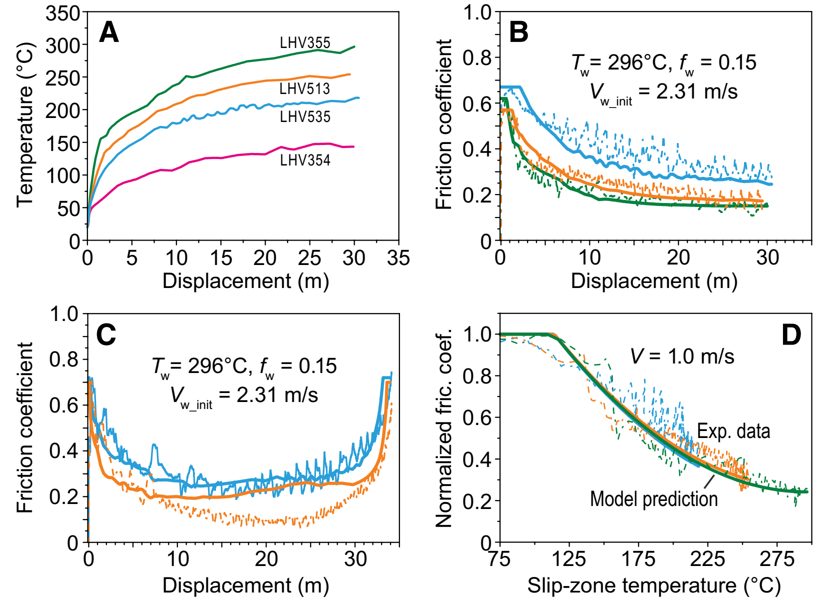

Figure 4. A: Comparison of volume-averaged temperature of outer-half slip zone against displacement for four experiments, as shown in Figure 1B. B,C: Comparison of measured friction data (dashed lines; selected from Figs. 1B and 2A) and predicted friction evolutions (bold solid lines) using updated flash-heating model (Platt et al., 2014). D: Normalized post-peak friction coefficient f/f_0 versus calculated slip-zone temperature T_f (for tests shown in B). T_w, f_w, and V_{w_init} denote the fitted weakening temperature, residual friction coefficient, and initial weakening velocity, respectively. Colors of lines denote different host blocks following Figures 1 and 2.

– $T_f)^2$ (Rice, 2006), where T_w is the weakening temperature and T_f is the temperature of the fault surface. Recent work by Nielsen et al. (2013) and Platt et al. (2014) suggests that while flash heating is controlled by a critical slip rate, temperature effects could also be important because V_w decreases dramatically as T_f increases. Taking the slip-zone temperature calculated in the previous section as T_f, we can fit our frictional data of experiments showing dramatic slip weakening with three independent fitting parameters, which are T_w, f_w, and the initial weakening velocity V_{w_init} (Platt et al., 2014; see details in the Data Repository). Figures 4B and 4C show representative fits to five experiments on the illite-quartz gouge. The fits are in reasonably good agreement with the measured friction data, yielding T_w = 296 °C, V_{w_init} = 2.31 m/s, and f_w = 0.15 for the illite-quartz gouge. The T_w of 296 °C probably represents the temperature for strength reduction of illite due to the dehydroxylation reaction (see more information about the results of the quartz gouge and discussion on the uncertainties of the data fitting in the Data Repository). Our results suggest that thermochemical effects may first become important at highly stressed frictional contacts, leading to significant weakening long before the reaction produces elevated pore pressures. The V_{w_init} values for gouges here are approximately 10 times those observed for bare rock surfaces (Goldsby and Tullis, 2011), in good agreement with models that assume that the effective weakening velocity for flash heating in gouge is equal to the number of contacts between which deformation is shared, multiplied by the weakening velocity for sliding of bare surfaces (Beeler et al., 2008; Platt et al., 2014). In Figure 4D, the normalized post-peak friction coefficient f/f_0 was plotted against the calculated slip-zone temperature T_f for the three tests shown in Figure 4B. All the curves of the experimental data and model predictions almost overlap although the thermal histories of the three tests are different, suggesting that the flash-heating model that considers the change in T_f (Platt et al., 2014) can explain our experimental data well.

Our experimental and fitting results are in accord with those reported by Proctor et al. (2014), where varying normal stresses were applied in the experiments and the differences in dynamic weakening were interpreted using a flash-heating model that considers the role of T_f. However, Passelègue et al. (2014) demonstrated that V_w of quartzite, granite, and gabbro increases slightly if the rocks are heated to a high temperature before friction experiments, which seems to contradict our conclusion that raising the fault temperature decreases V_w. One important difference between their experiments and ours is the method of increasing T_f. In Passelègue et al. (2014), T_f is elevated before experiments and changes negligibly during sliding, while in our experiments, T_f starts at room temperature and increases sharply due to frictional heating. If some contact properties such as contact size require time to reach a new equilibrium, then it is unsurprising that the time scale over which the temperature change occurs strongly influences the results. Furthermore, Passelègue et al. (2014) chose a much larger weakening temperature than that inferred from our data, suppressing the direct dependence on T_f studied here. Our results suggest that a sharp temperature rise on the fault surface during earthquakes can significantly promote the effectiveness of flash heating, although it may be statically suppressed with increasing depth in natural fault zones (Passelègue et al., 2014).

Our study highlights the important role temperature plays in dynamic weakening and shows how this can be controlled by using a range of materials for making host blocks. The use of high thermally conductive metal host blocks in gouge experiments will give rise to unrealistic temperature distributions within the gouges, and thus be unsuccessful in simulating the high temperatures attained during seismic slip in natural fault zones. Ti-alloy, with a thermal conductivity almost as low as those of rocks, is a good material for making specimen assemblies for friction experiments at high normal stresses under fluid-rich environments. Moreover, our results demonstrate that the presence of nanoparticles is not sufficient to produce dynamic weakening of faults.

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