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Experimental constraints on energy partitioning during stick–slip and stable sliding within analog fault gouge

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ABSTRACT

The lack of substantial frictional heat anomalies across major fault zones has been a key observation suggesting that faults support low shear stress during slip. Some studies have suggested that the lack of large thermal anomalies across faults may be a result of considerably less energy going to frictional heat than generally thought and that a large fraction of energy is dissipated by other processes such as the creation of new surface area. We evaluate this hypothesis through the analysis of laboratory shear experiments for both stick–slip (seismic) and stably sliding (aseismic) analog fault gouges. These experiments differ from previous laboratory studies in that they 1) provide independent constraints on frictional heat generation and energy consumed generating new surface area, 2) cover a broader range of shear stresses (2–20 MPa) than most previous studies, and 3) evaluate both stick–slip and stable sliding within granular material. Based on the analysis of high-precision temperature measurements and comparisons with numerical model simulations >90% of the total energy appears to go to frictional heat generation (E_H) for all of our experiments. We also show based on grain size analysis that ~1% of total work is consumed generating new surface area (E_{SA}). These results are consistent with assumptions allowing frictional resistance to be inferred from thermal data. Furthermore, we observe no resolvable difference in the fraction of energy going to fracturing or frictional heat between stick–slip and stable sliding experiments.

1. Introduction

Thermal data have played an important role in evaluating the mechanics of earthquakes and faulting. The lack of large frictional heat anomalies across major fault zones in regional heat flow data or in borehole temperature profiles that intersect faults after large earthquakes has been one of the primary observations suggesting that many faults support low shear stress during slip, considerably less than expected by laboratory-derived friction laws and hydrostatic pore pressure (e.g., Brune et al., 1969; Lachenbruch and Sass, 1980; Wang et al., 1995; Kano et al., 2006; Tanaka et al., 2006). An important assumption in interpreting frictional resistance during slip from thermal observations is that nearly all of the dissipated energy during fault slip goes to frictional heat generation (e.g., Brune et al., 1969; Lachenbruch and Sass, 1980). Fig. 1A illustrates how work during slip is partitioned to elastic radiation (e.g., seismic waves) and dissipated energy during an unstable stick–slip event. Fig. 1B shows how work is partitioned during stable aseismic creep.

Total work during slip is defined by the sum of the work due to shear and the sum of work due to slip-induced dilation or compaction. This is expressed by Eq. (1),

$$W = A\int_0^D \tau d\delta + A\int_0^L \sigma_n dw = A\bar{\tau}D + A\bar{\sigma}_n L \quad (1)$$

where A is the fault surface area, $\bar{\tau}$ and $\bar{\sigma}_n$ are the displacement-averaged shear stress and normal stress along a plane parallel to the direction of slip, D is the total displacement, and L is the absolute change in thickness due to compaction or dilation during slip. The total work during slip is balanced by dissipated energy E_f and radiated energy E_a. Elastic radiated energy E_a is related to the stress drop during unstable stick–slip sliding and the apparent stress τ_a which can be determined seismologically. Elastic radiated energy is generally considered to account for <6% of the total work during slip (McGarr, 1999), whereas dissipated energy E_f is thought to account for ~95% of the total work (e.g., Lachenbruch and Sass, 1980; Lockner and Okubo, 1983). Dissipated energy includes both frictional heat and fracture energy, which can include work done by chemical processes, compaction, and grain rolling, in addition to the energy consumed making new surface area through rock fracture and grain breakage.

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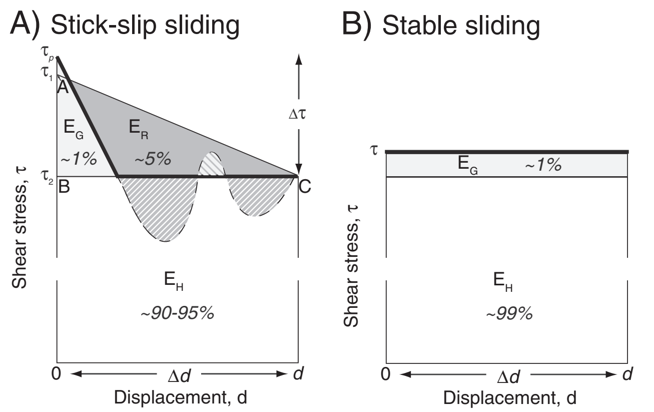

Fig. 1. Total work per unit fault area during stick–slip (A) and creep (B). Bold line represents the fault strength during slip. For panel A the bold fault strength curve is based on a simple slip-weakening model (Andrews, 1976) and the dashed curve illustrates more complex strength evolution that includes weakening and healing. The initial, peak and final stresses are denoted by τ_1, τ_p, and τ_2, respectively (Ben-Zion, 2003; Kanamori and Rivera, 2006). For both panels, the area beneath the fault strength curve represents dissipated energy, consisting of frictional heat E_H, and fracture energy E_G. E_G involves energy associated with new surface area E_{SA} and may also include additional energy consumed by dilation, grain rolling and other grain interactions. The difference in total and dissipated energy is released as elastic radiation E_R. The triangle marked by points A–B–C in panel (A) represents the energy defined by Eq. (3) as $E_{\Delta\tau}$.

Dissipated energy E_f is a function of the displacement-averaged frictional resistance along the fault during slip $\overline{\tau}_f$ and cannot be directly determined seismologically, although it is a critical parameter in controlling the mechanics of fault slip.

Some studies have argued that the lack of thermal anomalies across major fault zones may not necessarily imply that the average frictional resistance and shear stress during slip has been low. Rather they suggest that the fraction of dissipated energy going to frictional heat (i.e., the thermal efficiency) may be considerably less than ~90–95% of the total work and that the missing heat energy is partitioned to other processes (e.g., Brown, 1998; Wilson et al., 2005). For example, the grain size distribution of some natural fault gouges have been interpreted to suggest that the creation of new surface area through grain breakage may amount to as much as 50% or more of the total work during slip rather than ~1% as is more commonly thought (Wilson et al., 2005). This interpretation, although controversial (e.g., Chester et al., 2005; Rockwell et al., 2009; Wechsler et al., in press), has been used to suggest that considerably less energy goes to frictional heat generation and may thus explain the lack of large frictional heat anomalies across major fault zones without the need for low shear stress during slip. Understanding how energy during slip is partitioned between frictional heat, seismic radiation, and the generation of new surface area and other processes is important not only for characterizing fault strength, but also for our general understanding of the mechanics of earthquakes and faulting and for assessing seismic hazard.

Although laboratory experiments may be an effective way to put constraints on the energy budget of fault slip, few experimental studies within the geosciences literature have tried to directly constrain the amount of frictional heat generation during slip (Lockner and Okubo, 1983; Yoshioka, 1985; Blanpied et al., 1998; Brown, 1998; Mair and Marone, 2000) or the amount of energy consumed in generating new surface area (e.g., Engelder et al., 1975; Yoshioka, 1986). The few experimental studies of thermal efficiency (i.e. the fraction of total work during slip that is spent generating frictional heat) have generally been performed on granite slabs and the detrital material generated during the experiment (Lockner and Okubo, 1983; Yoshioka, 1985; Brown, 1998) or on stably sliding granular material (Lockner and Okubo, 1983; Mair and Marone, 2000). The results of these experiments have generally supported estimates of >90–95% of the total work during slip going to frictional heat generation.

Some experimental results of frictional heat generation during stick–slip (earthquake-like) sliding of granite slabs, however, have also suggested that thermal efficiency may be less than conventionally thought (Yoshioka, 1985; Brown, 1998). The results of Brown, 1998 reveal a significantly large difference in the rate of temperature rise, a proxy for frictional heat generation rate, between stick–slip and stable sliding experiments, suggesting a thermal efficiency ~50% for stick–slip failure rather than >90% interpreted for stable sliding under similar stress conditions. Brown, 1998 argues that the discrepancy between stick–slip and stable sliding systems is not a result of pulsed versus continuous heat generation, rate and state friction, or thermal pressurization. The study presumed that the generation of new surface area through grain size reduction was negligible, based on the small amount of detrital material between the layers after each experiment, although this was not directly verified through analysis. The abnormal thermal efficiency in these experiments only occurs at normal stresses >~7 MPa, and thus may explain why this behavior was not seen in similar experiments by Lockner and Okubo, 1983 which were conducted at normal stresses <3.45 MPa. Similar interpretations of low thermal efficiency have also been determined within laboratory experiments of slip between granite slabs that exhibit chaotic stick–slip behavior and stress drops that are very large in both total magnitude (~20 MPa) and in relation to the average background stress (Yoshioka, 1985). These results appear to be largely a function of an absence of abundant gouge/detrital material within the slip zone during the experiment.

In contrast with experiments on granite slabs, large earthquakes are generally hosted within mature fault zones that have well-established gouge zones that support slip (e.g., Scholz, 2002). Results of numerical models of shear within granular gouge material have suggested that grain interactions including bouncing and rolling of grains may have a significant influence in reducing thermal efficiency (Mora and Place, 1998), although the models do not include the effects of grain size reduction in either consuming energy or restricting rolling of grains. Experiments of shear heating for stably sliding (aseismic) gouge material do not reveal low thermal efficiency (Mair and Marone, 2000).

Here we evaluate the partitioning of energy during slip through the analysis of laboratory shear experiments within analog fault gouge for both stick–slip (seismic) and stable (aseismic) sliding (Table 1). These experiments are particularly relevant in that 1) they were designed such that constraints on both the amount of frictional heat generation and energy consumed in making new surface area can be independently determined, 2) the sliding behavior for each material used is consistently similar between experiments, 3) they cover a greater range and magnitude of stress conditions than most previous experiments of frictional heat generation during stick–slip sliding, and 4) they cover both stick–slip and stable styles of sliding within analog fault gouge, whereas previous laboratory studies of thermal efficiency have been performed on granite slabs and the detrital material generated during the experiment or on only stably sliding granular material (Lockner and Okubo, 1983; Yoshioka, 1985; Brown, 1998; Mair and Marone, 2000).

The objective of this study is to test the hypothesis that the generation of new surface area through grain breakage during stick–slip sliding within fault gouge accounts for a significantly large portion of the total energy budget during slip and thus reduces the amount of energy partitioned to frictional heat. Fundamental questions we seek to address include: 1) Does frictional heat consistently account for ~90% or more of the total slip energy budget for a range of different stress conditions? 2) Is the generation of new surface area through grain breakage a large, yet overlooked, component of the energy budget? 3) Is there a significant difference in the partitioning of