Characterizing the Distribution of Temperature and Normal Stress on Flash Heated Granite Surfaces at Seismic Slip Rates

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Abstract At seismic slip rates, flash-weakening can significantly reduce the coefficient of friction, and the magnitude of weakening increases with surface temperature. To quantify the distribution of flash temperature, high-speed double-direct shear experiments were conducted on Westerly granite blocks using velocity steps from 1 mm/s to 900 mm/s at 9 MPa normal stress. We employed a high-speed infrared camera to measure surface temperatures on the moving block during sliding, and utilized a novel sliding-surface geometry to control the mm-scale contact history. Following the initial weakening upon the velocity step, the blocks slide at a constant coefficient of friction. Surface temperatures are inhomogeneously distributed across the sliding surface, and increase with displacement. To determine the local normal stress distribution at the mm-scale, we combine a one-dimensional thermal model with conventional flash-weakening models that incorporate a surface temperature-dependence informed by the controlled, mm-scale contact history. Early contacts experience local normal stress exceeding 40 times the applied normal stress. As sliding progresses, the local normal stress at the hottest contacts decreases as contact area increases, leading to local normal stresses ranging from 2 to 6 times the applied normal stress on most contacts by 30 mm of slip. Increases in surface temperature, which would decrease the coefficient of friction, are buffered by wear processes that increase contact area and decrease the local normal stress. Treatments of flash heating are advanced by incorporating improved characterization of the state of the sliding surface at the mm and larger scales during sliding.

1. Introduction

Identifying and characterizing processes of frictional weakening during seismic slip is important to understand earthquake source physics and advance dynamic rupture modeling (e.g., Kanamori & Heaton, 2000; Lui & Lapusta, 2018; Noda & Lapusta, 2013; Perry et al., 2020; Rice, 2006). Several processes for dynamic weakening are proposed to govern fault friction during seismic slip (see Tullis, 2015, for summary), and rock-friction experiment studies have documented dramatic reductions in friction as sliding velocities approach seismic slip rates for a wide range of materials (e.g., Badt et al., 2020; Brantut et al., 2008, 2010; Di Toro et al., 2004, 2011; De Paola et al., 2008, 2011; French et al., 2014; Goldsby & Tullis, 2011; Han et al., 2007, 2010; Hirose & Shimamoto, 2005; Kitajima et al., 2010; Proctor et al., 2014; Reches & Lockner, 2010; Rubino et al., 2017; Tsutsumi & Shimamoto, 1997; Violay et al., 2013; Yao et al., 2016a, 2016b). Dynamic weakening due to flash heating is one of the first weakening mechanisms expected to activate during seismic slip along localized zones or discrete fault surfaces, particularly in dry rocks before frictional melting occurs, and is considered a potentially important weakening mechanism (Beeler et al., 2008; Goldsby & Tullis, 2011; Rice, 2006).

The velocity dependent behavior of the coefficient of friction at high slip rates has long been a concern in engineering applications for unlubricated metals, leading to the development of the flash-heating and -weakening models (e.g., Archard, 1959; Bowden & Tabor, 1954; Lim & Ashby, 1987; Lim et al., 1989; Molinarl et al., 1999), that subsequently were applied to geologic materials to describe steady-state flash-weakening friction in rock (Beeler et al., 2008; Hirose & Shimamoto, 2005; Noda, 2008; Rice, 2006). Flash heating occurs at microscopic asperities that support the macroscopic load over a true contact area significantly less than the apparent contact area. During high velocity sliding, frictional heat is generated at asperity contacts resulting in locally elevated surface temperatures. Conventional models of flash-weakening recognize that...
above a critical velocity, microscopic asperity contact interfaces are heated sufficiently to degrade contact shear strength and reduce friction (Beeler et al., 2008; Rice, 2006; Sleep, 2019). High-velocity friction experiments conducted on rock, with both bare rock-on-rock surfaces and gouge layers, produce mechanical results and microstructural observations consistent with expectations of flash heating and weakening at the microscopic asperity scale (e.g., Beeler et al., 2008; Faulkner et al., 2011; Goldsby & Tullis, 2011; Kohli et al., 2011; gre et al., 2016; Proctor et al., 2014; Yuan & Prakash, 2008). The experiments, however, also often document transient friction during the acceleration and deceleration phase, and hysteresis in friction, which is not fully described by the conventional, steady-state model for flash-weakening (Beeler et al., 2008; Goldsby & Tullis, 2011; Proctor et al., 2014).

The critical velocity for flash-weakening, \( V_w \), is a function of material properties, the microscopic asperity contact dimension, and the macroscopic surface temperature, which may evolve with slip. An increase in surface temperature decreases \( V_w \), reducing the macroscopic coefficient of sliding friction (\( \mu \)) (Elbanna & Carlson, 2014; Yao et al., 2016a, 2016b). The evolution of friction is therefore dependent on the temperature history at asperity-contacts as well as at macroscopic scale (Proctor et al., 2014). Models incorporating a single asperity contact dimension and a uniform surface temperature produce hysteresis and transient friction, but do not fully describe the experimental observations of hysteresis, particularly during deceleration (Proctor et al., 2014; Saber, 2017). The transient friction also may reflect evolving characteristics of contact populations due to wear, plowing and degree of localization, as well as local changes in surface temperature and normal stress with slip (e.g., Beeler et al., 2008; Boneh et al., 2013, 2014; Dieterich & Kilgore, 1994; Hirose et al., 2012; Power et al., 1988; Proctor et al., 2014; Reches & Lockner, 2010; Violay et al., 2013; Wang & Scholz, 1994).

Using high-speed infrared (IR) thermography, Saber (2017) documents the spatial variation in flash temperature during sliding on smooth-ground surfaces of Westerly Granite as a function of displacement \( (d) \) up to 35 mm, sliding velocity \( (V) \) from 0.1 to 0.9 m/s, and macroscopic normal stress \( (\sigma_n) \) from 1 to 20 MPa. Thermographs show that the temperature of the surface is inhomogeneous, with localized flash-temperatures up to ~500°C that appear as linear arrays of ~2 mm diameter hot-spots aligned parallel to the sliding direction. Saber (2017) inferred that the hot spots represent mm-scale asperity contacts that carry, on average, a local normal stress \( (\sigma_l) \) that is approximately five times the applied \( \sigma_n \). These hot spots comprise ~21% of the macroscopic sliding surface area. On the basis of thermo-mechanical models that incorporate the surface temperature and frictional weakening observations, the transient and steady-state frictional weakening behaviors can be explained by the combined effect of flash-weakening at microscopic asperity contacts and the increase in local surface temperature \( (T_l) \) of the encompassing mm-scale contacts (Saber, 2017). Although this conclusion is consistent with the conventional flash-weakening model, it is qualified by the uncertainty of the assumption that the mm-scale, flash-heated contacts remain in contact and carry an elevated \( \sigma_l \) throughout the 35 mm of high-speed sliding.

Here we develop techniques to address the uncertainty of contact history during sliding by using samples with two scales of roughness: a conventional ground-flat surface with micrometer-scale roughness, and machined grooves to control the mm-scale contact roughness. The grooved geometry results in a series of flat-topped ridges on the sample block interface that controls the mm-scale contact history during sliding. With known life-times \( (LT) \) and rest-times \( (RT) \) of mm-scale ridge contacts we remove assumptions regarding mm-scale contact history and heat generation rate, and we can accurately model flash heating history and better determine the \( \sigma_l \) distribution on mm-scale contacts assuming the conventional flash-weakening model. We also document \( \sigma_l \) distributions in the context of changing surface conditions with slip. Finally, we establish a framework and basis for testing the ability of the conventional flash-weakening friction model to reproduce observed transient friction behaviors and to understand microscopic-scale processes of flash-weakening in future works.

2. Materials and Methods

2.1. Velocity-Step Experiments Using a High-Speed Biaxial Apparatus

Twelve double-direct shear (DDS) friction experiments were conducted on Westerly granite samples using a High-Speed Biaxial apparatus (HSB) outfitted with a high-speed IR camera. The HSB employs a hydraulic
direction. are 13 mm long parallel to, and 16 mm long perpendicular to the slip thermographs of the sliding surface (shown in yellow) of the moving-block from contact with the stationary block sliding surface. The rectangular plated mirror and is captured by the high-speed IR camera as it emerges block positioned below the stationary block, which reflects off of a gold-sliding, represented by yellow arrows, is through a window in the support light path configuration. The light emitted from the moving block during Figure 1. Double direct shear sample arrangement and infrared (IR) light path configuration. The light emitted from the moving block during sliding, represented by yellow arrows, is through a window in the support block positioned below the stationary block sliding surface. The rectangular thermographs of the sliding surface (shown in yellow) of the moving-block are 13 mm long parallel to, and 16 mm long perpendicular to the slip direction.

cylinder accompanied by a gas accumulator to apply a constant $\sigma_n$ across the sliding surface interface of each block during experiments. A pneumatic actuator equipped with a hydraulic damper was used to achieve velocity steps (VS) from quasi-static sliding rates to sliding rates up to 1 m/s, within 2 mm of $d$. After reaching the target velocity ($V_t$), constant-velocity sliding (within ±10% of the $V_t$) is maintained for up to 3.5 cm of $d$ (see Saber et al., 2014, 2016 for a full description of the HSB).

For all experiments, sliding was initiated at a sliding velocity, $V$, of 1 mm/s for approximately 5 mm of $d$, followed by a VS to 900 mm/s. Constant, high-velocity sliding was maintained for the remaining ~30 mm of high-velocity displacement ($d_{HV}$) until the pneumatic actuator hit a mechanical stop and velocity dropped to 0. Experiments were conducted at room temperature and humidity, with forces and $d$ measured at the sample throughout the acceleration, constant $V$, and deceleration phases of sliding. Shear force was measured via a load cell at the contact of the pneumatic actuator rod and the granite moving block, accurate to within 0.03%. Normal force was measured via a load cell in contact with one side block accurate to within 0.03%. Velocity of the piston rod was measured at the sample via a displacement transducer accurate to within 0.03% of span, or ~10 µm in our experiments. All measurements were recorded at a sampling rate of 25 kHz using a custom data acquisition software developed in LabVIEW™. Post-processing removed high frequency noise and determined $\mu$, $\sigma_n$, and $V$ as a function of $d$ (see Supplementary Information for description of filtering procedure).

2.2. Sliding Surface Preparation

The DDS configuration comprises three rectangular blocks: one moving, central block, and two stationary, side blocks (Figure 1). Assembled, the blocks generate two sliding surfaces, with each block interface area measuring 38.76 cm². All faces of the sample blocks were ground square and flat with a #60 grit precision grinding wheel to a root mean squared roughness of ~10⁻² mm. To compensate for torque generated on the sliding interfaces inherent to the DDS configuration (Dieterich & Linker, 1992), and to minimize variation in $\sigma_n$ along the surface during sliding, the bottom of each stationary block was ground such that the sliding surface is tilted 0.3° away from the surface of the moving block at unloaded conditions. The 0.3° angle was determined through trial and error by static loading with pressure sensitive film along the sliding interface and by achieving uniform wear on the sliding interfaces during high-speed sliding tests.

To dictate sliding histories of mm-scale contacts, we ground a series of grooves on the sliding surfaces (Figure 2). Each groove is 50 µm deep, 3.175 mm wide, and spaced 3.175 mm apart on the sliding surface. The grooved pattern generates a series of flat-topped ridges, that correspond to the original ground-flat surfaces. The ridges on the stationary blocks are oriented 22.5° clockwise from the sliding direction (i.e., from the long axis of each block) and those on the moving blocks are oriented 22.5° counterclockwise from the sliding direction, such that ridges on the two blocks are symmetric about the sliding direction. This geometry ensures that when the sliding surfaces of the stationary and moving blocks are placed together, the ridges generate a sliding interface comprised of uniformly distributed, diamond-shaped, flat, mm-scale contacts (Figures 1 and 2). Only ridges experience direct contact during sliding, establishing a contact $LT$ when a moving-block ridge opposes and is in contact with a stationary-block ridge. Contact $RT$ on a moving-block occurs when a moving-block ridge opposes a groove on the stationary block. Note that the diamond-shape contacts migrate along the ridges during slip such that all points on ridges experience periods of contact and no-contact. The grinding geometry ensures that a maximum total mm-scale contact area of 9.69 cm², equal to 25% of the total block interface area, exists at any time during at all stages of sliding. The mm-scale, diamond-shaped contacts are 8.3 and 3.4 mm parallel and perpendicular to the sliding direction, respectively.
During sliding, a point on the ridge of the moving block undergoes alternating periods of $LT$ and $RT$ every 8.3 mm of sliding; neighboring points will do the same but will be out of phase because of the ridge orientation relative to the sliding direction. Given the maximum $d_{mv}$ of 30 mm, points on moving block ridges (except those at the very top and bottom of the moving central-block) undergo a maximum of 1.8 total $LT$-$RT$ cycles at high speed. The same $LT$-$RT$ cycling applies to points on the ridges of the stationary blocks as well. The repeated pattern of the grooved surface geometry thus allows for precise determinations of the $LT$ and $RT$ history for points on the moving block during high-speed sliding. The exceptions arise for the ridges at the top and the bottom of the moving center-block, that necessarily make or break contact with the stationary block ridges, as the top of the moving block moves into contact with the stationary block after slip begins, and emerges from the base of the stationary blocks during sliding. The points on the ridges of the moving center-block that move in or out of contact relative to the ends of the stationary blocks experience the same $LT$-$RT$ cycling, but necessarily will undergo a total number of cycles less than 1.8 total $LT$-$RT$ cycles. This detail is critical to the interpretation of the IR images of surface temperature because the thermographs are captured from the moving block as it emerges from the base of the stationary block.

A detailed understanding of the sliding history of points on the ridges, and a basis for analysis of local temperature and modeling, is facilitated by identifying a minimum model area of a ridge on the moving block. The minimum model area is located in the imaged area of the moving block (Figure 3), and discretized into 544 1 mm$^2$ elements that have a unique $LT$-$RT$ sliding history.

2.3. High-Speed Infrared Imaging of Sliding Surfaces

Prior to conducting experiments, freshly machined sample blocks were run-in for 70 mm of $d$ (equivalent to two high-speed sliding runs) to generate a thin layer of wear product on the sliding surface, remove any grinding features, and generate a self-organized roughness. Between successive experiments, sliding surfaces were brushed lightly with a soft camel hair brush to remove loose, disaggregated gouge from the sliding interfaces, but leaving intact, compacted, thin layers of gouge on the ridge tops. Due to erosion of the ridges by wear during sliding, after a maximum of six consecutive experiments the sliding surfaces of the blocks were re-ground completely (surface and grooves) and then run-in before re-commencing experimentation. Two sets of blocks were utilized: one set for experiments 290–295 and a second set for experiments 373–386.

A high-speed IR camera was positioned to capture thermographs of the sliding surface of the moving block as it emerged from contact with a stationary block, via a window in the supporting steel block and a mirror to reflect the IR light to the camera (Figure 1). The thermographs cover an area of the sliding surface on the moving-block that is 13 mm parallel to the sliding direction and 16 mm perpendicular to the sliding direction (Figures 2 and 3), at a frame rate of 300 Hz and a resolution of 50 µm. During the high-speed sliding portion of each experiment, a sequence of approximately 10 thermographs were captured that collectively cover a 30 mm by 16 mm area, equivalent to about 12%, of the sliding surface of the moving block. To record the cooling history of the sliding surface, up to 40 additional thermographs were captured at 300 Hz. The IR camera is equipped with a neutral density filter, and is capable of measurements over several pre-set, calibrated temperature ranges. To robustly characterize the temperature distribution of the sliding surface, four temperature ranges were utilized in multiple repeat experiments: 55°C–100°C, 80°C–200°C, 100°C–300°C, and 200°C–600°C. We subsequently characterized the distributions of $T_i$ across the overlapping temperature ranges.

![Image of sliding surface geometry](image-url)
ranges for all captured thermographs to remove the effects of fixed temperature ranges, and isolate trends in $T_i$ distributions as a function of $d$.

3. Results

3.1. Mechanical Response

Mechanical results from a representative experiment (#295) show the $V$, $\sigma_n$, and $\mu$ as a function of $d$ (Figure 4). Audible stick-slip events occurred in all experiments during the initial low-velocity sliding prior to the velocity step. The events are represented by small drops in $\mu$ accompanied by small increases in the sliding velocity. Initial $d$ and $\mu$ values for all 12 experiments are reported in Table 1. After initiating the VS, the $V$ of 900 mm/s is accomplished within 1.5–2 mm of $d$. The $V$ and $\sigma_n$ are then maintained within ±10% of their target magnitudes for the remainder of high velocity sliding. The $\mu$ reduces by approximately 50% from the quasi-static value to a dynamic friction coefficient, $\mu_d$, within approximately 3 mm of $d$ following the VS, or in other words, within approximately 1 mm of $d_{hv}$. Following this initial weakening, relatively constant $\mu_d$ is maintained for the remainder of high-velocity sliding. The average value of $\mu_d$ in all experiments is 0.32, reproducible to within 8% of the average.

Comparisons of our DDS VS experiments employing the grooved sliding surface to Saber’s (2017) experiments, run at equivalent conditions but using ground-flat with rock on rock surfaces, show good agreement of the absolute frictional strength and the magnitude of dynamic weakening (Figure 4c). The agreement is not surprising in that our grooved surfaces were engineered to have an instantaneous contact area that is 25% of the total apparent surface area, and to match Saber (2017) interpretation that the true mm-scale contact area is about 25% for conventional planar, ground surfaces.

3.2. Thermography

Multiple experiments were conducted at the same $\sigma_n$ and VS history for each of the four temperature sensing ranges of the $IR$ camera to ensure reproducibility. We produced a large data set of surface temperature ranges for all captured thermographs to remove the effects of fixed temperature ranges, and isolate trends in $T_i$ distributions as a function of $d$. 

Figure 3. Starting contact condition of the macroscopic sliding surface on the moving block with the $IR$ imaged area identified by a blue box, and a minimum model area outlined with a black dashed line. The model area comprises 544 discrete 1 mm$^2$ elements, with each element having a different phase and total number of cycles. The $LT$-$RT$ cycle histories for selected elements are indicated to the right of the enlarged model area, with the first to last stage of the sequence labeled left-to-right. Note that the imaged area for each experiment contains approximately two complete model areas. Consistent with Figure 2, the gray shading represents the grooves in the moving block, the light-red shading represents the grooves in the stationary block, and the view of the interface is looking through the stationary block towards the moving block.
measurements over the full spectrum of elevated $T_i$ during all stages of sliding and cooling. A total of 117 thermographs were captured from all 12 experiments to measure an area (∼243 cm²) equivalent to 6 times the total apparent area of the sliding surface for both sliding and cooling conditions.

Thermograph dimensions were used in combination with the total $d$ measured during high-velocity sliding (Table 1) to calculate $d$ and $d_{hv}$ at the time of capture for all thermographs. The top boundary of each thermograph records the points of the moving block surface when they emerge from the stationary block. The top boundary of the first thermograph that is captured following the end of high-velocity sliding represents the full ∼30 mm of $d_{hv}$. At a 300 Hz sampling rate, and with approximately 0.9 mm of slip per millisecond during HV sliding, thermographs are taken every 3 mm of slip, each capturing 13 mm of the surface in the sliding direction. As a result, individual thermal features on the moving-block surface are recorded in 3–4 sequential, overlapping thermographs allowing clear tracking of the temperature distributions. Beginning with the first thermograph captured after the end of sliding and working backwards, the range of vertical $d$ and $d_{hv}$ captured in each thermograph were mapped using hot spot tracking and known thermograph dimensions for each experiment. Composite thermographs, constructed by stitching together the top ∼3 mm of each individual, successive thermograph, show the macroscopic surface temperature on the moving block measured within 3 ms of emergence from the stationary block.

Example thermographs for three representative experiments, captured using three of the four temperature ranges employed, are shown in Figure 5. The recorded temperature across the sliding surface is not homogeneous, and the spatial distribution of high and low temperature patches are different on neighboring ridges. High temperature regions typically develop as equidimensional hot spots at the mm-scale or less. Higher surface temperature spots generally are associated with contacts that experience 20 mm or more of $d_{hv}$, and more than one LT-RT cycle with an LT occurring just prior to emergence, for example, LT-RT-LT.

The surface temperature distribution at different stages of high-speed sliding for a representative experiment, imaged using the 100°C–300°C camera range, shows that the surface area was heated to above 100°C and peak temperatures increased as a function of $d_{hv}$ (Figure 6a). The surface temperature distribution above 55°C following ∼30 mm of $d_{hv}$ is determined from four representative experiments, each imaged using a different camera temperature range. The four distributions show similarity in the overall distribution of temperature, and good agreement in pixel (area) counts where the four distributions overlap (Figure 6b). Surface temperatures below 55°C are not captured, however 100% of the total ridge area is found to exceed 55°C for the last stages of sliding. After ∼30 mm of $d_{hv}$, the complete temperature distribution for the ridge area that emerged ranges from 60°C to over 360°C. The distribution is highly skewed, with a mode, median and mean of 66.5°C, 91.5°C, and 107°C, respectively. The surface area at temperatures above the median and mean comprise 23% (i.e., about half of the ridge area) and 15%, respectively, of the total apparent area (i.e., ridges and grooves) imaged.

Hot spots develop in equal numbers at the leading, center, and trailing edge of ridges. High temperature hot spots (∼200°C) are typically elongate in the direction of slip and are typically 2–4 mm long parallel to slip
and 1–2 mm long perpendicular slip (Figure 5b), while the highest temperature hot spots (∼300°C) are more equant and are typically 1 mm or less in diameter (Figure 5c). Temperature gradients at hot spots are very large, typically with the highest to lowest temperature spanning only ∼1 mm. Thermographs of different experiments conducted on the same set of moving and stationary blocks in non-consecutive experiments show similar, repeated patterns of mm-scale, hot-spot occurrences (Regions 1–3 in Figures 5b and 5c).

4. Thermal Modeling

Our experiments document an overall increase in surface temperature as a function of $d_{hv}$, and significant inhomogeneity in surface temperatures, even for locations on different ridges that experienced the same $LT-RT$ sliding history (e.g., Figure 5a). Given that the local heating rate is proportional to $V$, $\sigma_l$, and the local coefficient of friction ($\mu_l$), the mm-scale hot spots documented in this work must reflect high-load bearing contacts that develop during sliding. The observation that similar hot spot distributions persist in repeat experiments indicates that mm-scale contacts supporting high loads appear to be long-lived, and persist over several repeat experiments. At constant sliding velocity the heating rate is proportional to $\sigma_l$, but the proportionality likely depends on flash temperature due to the dependence of $\mu_l$ on $T_l$. Additionally, heat flow into the contact substrate depends on both time and the temperature gradient, suggesting that the relationship between the observed $T_l$, $\sigma_l$, and $\mu_l$ is not a simple proportionality.

Here, we develop a method to use observed temperature distributions and known mm-scale contact history of the machined surfaces to determine $\sigma_l$ and $\mu_l$. With a $\sigma_n$ of 9 MPa applied over the total apparent block-contact area, a uniform distribution of normal stress on the contacting flat-topped ridges would imply an average $\sigma_l$ of four times $\sigma_n$, or 36 MPa, on all the diamond-shaped ridge contact locations. Using a 1-D thermal model that incorporates the known sliding history of the grooved geometry and the functional dependence of contact friction on surface temperature described in the conventional flash-weakening model, we examine the actual mm-scale distribution of $\sigma_l$ and $\mu_l$ on the ridges of the sliding surface. With the inclusion of the flash-weakening model, we assume that mm-scale contacts are comprised of micrometer contacts that control the frictional behavior during sliding as described in conventional steady-state flash-weakening models. At sliding velocities of 900 mm/s, the time required for heat to penetrate a depth equal to the contact length of 8.3 mm is much greater than the time in which the heat source is applied,
satisfying the speed criterion for a fast-moving heat source (Archard, 1959). Sideways heat flow can thus be neglected, and the diffusion of heat can be considered a 1-D conductive process.

4.1. One-Dimensional Thermal Modeling With Surface Temperature Dependent Friction

Our grooved geometry ensures that during sliding, points on ridges undergo repeating cycles of LT and RT, but are out of phase and differ in total number of cycles with neighboring ridge locations. Additionally, each ridge experiences the same sliding history. For modeling purposes, we use the minimum model area that covers 35 mm of dhv, equal to the total maximum d in each experiment. Each of the 544 discrete model elements undergoes the same LT-RT cycle, but with different phase and number of cycles before emerging from contact with the stationary block. The sliding history of each model element is precisely calculated, and incorporated into models of surface temperature for experiments.

At seismic sliding rates, velocities are sufficiently high that the heat penetration depth during a contact LT is small compared to the overall contact length (∼0.152 mm penetration depth during 8.3 mm LT), and thus

Figure 5. Representative composite thermographs showing the measured macroscopic surface temperature on the moving block within 3.3 ms of exposure from contact with the stationary block for three temperature ranges: (a) Experiment 295 at 100°C–300°C; (b) Experiment 383 at 80°C–200°C; (c) Experiment 385 at 200°C–400°C. The images represent the view through the window of the support block towards the moving block before being reflected by the gold mirror. High-velocity displacements from the time the target velocity was reached following the velocity steps (VS), prior to emergence from contact with the stationary block, are shown on the left margin of each thermograph. Location of similar hot-spot patterns on ridges in repeat experiments are identified by outlined regions 1, 2, and 3 in Figures 5b and 5c. Three elements (a), (b), and (c), each of which experienced the same sliding history, are identified with black arrows in Figure 5a for modeling purposes.
heat conduction can be idealized as a 1-D process (Archard, 1959). To model surface temperature at the element scale, we employ a 1-D heat conduction equation (e.g., Carslaw & Jaeger, 1959; Proctor et al., 2014) incorporating thermal properties of Westerly granite at room temperature and known LT-RT history for each discrete element of the model. The $T_l$ is calculated using

$$T_l = T_0 + \frac{Q}{2\rho c_p} \frac{1}{\pi \alpha_{th} (t - t')} dt'$$

(1)

where $T_0$ is the ambient, initial surface temperature (20 °C), $t$ is time, $Q$ is the heat generation rate, $\rho$ is the density, $c_p$ is the specific heat capacity, and $\alpha_{th}$ is the thermal diffusivity. A density of 2700 kg m$^{-3}$ is assumed, and the specific heat capacity and thermal diffusivity used for Westerly granite are 800 J kg$^{-1}$K$^{-1}$ and 1.25 $\times$ 10$^{-6}$ m$^2$s$^{-1}$, respectively (Goldsby & Tullis, 2011). The local heat generation rate at the model element scale (i.e., 1 mm$^2$) is defined by

$$Q_l = \begin{cases} 0 & \text{during } RT \\ \sigma_{ij} V & \text{during } LT \end{cases}$$

(2)
In forward models of a particular element, the $\sigma_l$ may be assumed in order to compare with observations. The average, high-velocity values for $V$ and $\sigma_n$ are calculated from the mechanical results, and for modeling purposes are assumed to remain constant during sliding.

In the flash-weakening model, $\sigma_l$ at the mm-scale results from the aggregated true microscopic contact area and shear-strength of micrometer-scale asperity contact junctions within the modeled element. These micrometer-scale contacts are assumed to be two orders of magnitude smaller than macroscopic counterparts and have proportionally shorter life-times and rest times; they support local stresses in the GPa range over a true area of contact much smaller than the macroscopic contact area in our experiments. Micrometer-scale contact junction strength depends primarily on sliding velocity, but also on the local (mm-scale) surface temperature. For the case of homogeneous surface temperature, $\mu_l$ also is homogeneous. In the case of inhomogeneous surface temperature, as documented in the experiments herein, $\mu_l$ is inhomogeneous at the scale of the discrete model element. To incorporate temperature dependent friction into our model, we calculate $\mu_l$ from $V_w$ for each time step according to the flash-weakening relation (Rice, 2006), given by

$$\mu_l = (\mu_0 - \mu_w) \frac{V_w}{V} + \mu_w$$  \quad (3)$$

where $\mu_0$ is the quasi-static friction coefficient and $\mu_w$ is the fully weakened friction coefficient. $V_w$ is the weakening velocity above which flash-weakening will occur, defined by

$$V_w = C(T_w - T_b)^2$$  \quad (4)$$

where $C$ is a single constant representing all micrometer-scale contact junctions and material properties. For this analysis, we assume $C$ is equal to $2.58 \times 10^{-7}$ m s$^{-1}$C$^{-2}$ and $T_w$ is the breakdown temperature of 900°C, both of which are taken from Rice (2006) and largely consistent with values for Westerly Granite used by others (e.g., Goldsby & Tullis, 2011).

We use a $\mu_0$ of 0.735, obtained from averaging the mechanical results from all experiments during quasi-static sliding. We use a value for $\mu_w$ of 0.215. The fully weakened friction coefficient was obtained by first determining the macroscopic temperature distribution from experiment #377 at three time steps during HV sliding. Surface temperatures at each time step were separated into 8 $T_l$ bins (24 bins in total) and the local ridge-area percent values ($A_l$) were calculated for each bin. Using Equations 3 and 4, we calculated $\mu_l$ and $V_w$ for each bin. We then summed the products of $\mu_l$ and $A_l$ for each bin to calculate the macroscopic friction $\mu$ at each time step. The mechanical results from experiment #377 were then compared with the modeled $\mu$ to determine the best-fitting $\mu_w$.

The heat generation rates during low velocity sliding are $\sim 3$ orders of magnitude lower than rates during high velocity sliding. Models incorporating Equations 1 and 2 show no increase in macroscopic surface temperature above ambient temperature of 20°C when the sliding velocity is 1 mm/s. These results do not include effects of sideways heat flow; incorporation of 2D heat conduction would likely increase the rate of heat loss. Subsequently, local surface temperature is assumed to remain at ambient temperature during quasi-static sliding. During high-velocity sliding, $T_l$ is calculated over 300 discrete time steps for each element of the model area. During each time step, the weakening velocity and friction coefficient are calculated using Equations 4 and 3 for the current $T_l$. The heat generation rate is then calculated using Equation 2, and then $T_l$ for the next time step is calculated using Equation 1.

4.2. Changes in Surface Temperatures Reflecting Variations in Local Normal Stress

The model shows surface temperature increases during $LT$ and decreases during $RT$, and an overall net increase in surface temperature as a function of $d_{HV}$, consistent with expectations (Figure 7). For illustration of model fits to temperature observations, including cooling history after sliding, we show model results for measured temperature in experiment 295 at three locations, a, b, and c, identified in Figure 5a. Each modeled location is on adjacent ridges but in the same position within the minimum model area, and thus share the exact same $LT$-$RT$ history and are in phase and cycle with each other. The measured temperature of each location is different at the time of emergence, measuring 310°C, 191°C, and 138°C for a, b, and c,
respectively. Such large variances in temperature clearly indicate a difference in \( \sigma_l \), \( \mu_l \), or both for the three identical elements. Examining the \( \mu_l \) and \( Q_l \) history for each modeled element, we see that as temperature increases during LT, \( \mu_l \) and \( Q_l \) both decrease. The effect is magnified as \( \sigma_l \) is increased. During RT, \( \mu_l \) increases and \( Q_l \) drops to zero. A forward model assuming a constant \( \sigma_l \) equal to 4.3 times \( \sigma_n \) generates the observed temperature of 138°C at location a upon emergence. The higher temperature of 191°C observed at location b is predicted by a model with a constant \( \sigma_l \) equal to 6.5 times \( \sigma_n \). Both model curves agree well with measured temperatures during cooling, suggesting the 1-D heat conduction and constant normal stress assumptions are reasonable. For element c, the model predicts a constant \( \sigma_l \) equal to 12 times the macroscopic normal stress to achieve a temperature at emergence of 310°C, however the measured temperatures vary from model predictions for cooling.

To address the mismatch of model and observation for some cooling records, we consider relaxing the assumption of a constant \( \sigma_l \). We model cases of increasing and decreasing \( \sigma_l \) with \( \text{dhv} \), keeping the total amount of heat generated constant between each model and equal to the total amount of heat generated in the corresponding constant \( \sigma_l \) model. For the example location c, temperatures during cooling show good agreement with model predictions for a decreasing \( \sigma_l \), while variation in surface temperature during sliding between all models is small with a difference of 24°C at the end of both LT (Figures 7b and 7c). In this decreasing \( \sigma_l \) model, \( \sigma_l \) at the element decays from 12.6 to 6.8 times \( \sigma_n \), with the initial \( \sigma_l \) in the model only slightly greater than the constant \( \sigma_l \) model with the same amount of generated heat and a constant \( \sigma_l \) of 12 times \( \sigma_n \). The thermal model captures the behavior of low and intermediate \( \sigma_l \) locations well, and the assumption of constant \( \sigma_l \) appears valid. For high stress locations, the constant \( \sigma_l \) assumption is less consistent with temperature histories during cooling, but nevertheless serves as an acceptable maximum value for \( \sigma_l \).

Assuming temperature dependent friction and constant normal stress, we model surface temperature at the center of each element of the entire model area using the 1-D thermal model with Equations 1 and 2. Surface temperatures are determined for 15 normal stress magnitudes ranging from 1 to 40 times the \( \sigma_n \) to produce 15 synthetic thermographs of the entire imaged area for each experiment. To generate synthetic thermographs, all pixels are assigned to a model element, and pixel temperature is determined based...
on the model outputs for the element and the displacement history for each pixel. The synthetic thermographs apply to a particular experiment by matching ridge geometry and element sliding history. The synthetic thermographs for each modeled $\sigma_l$ are compared to the captured thermographs of the experiment and used as a basis to contour $\sigma_l$. As a representative example, the composite thermograph from Experiment 290 is contoured for $\sigma_l$ over the $d_{hv}$ range of 10 to 32.2 mm (Figure 8). As expected, locally high-temperature spots correlate with high $\sigma_l$. Note that lower $T_l$ at small $d_{hv}$ can indicate a higher $\sigma_l$ than a higher $T_l$ at large $d_{hv}$. In Experiment 290, the hot spots at $d_{hv}$ less than 15 mm are characterized by very high $\sigma_l$ that can exceed 24 times $\sigma_n$ (Figure 8b). As sliding progresses, the area heated to greater than 100°C increases, and by the latest stages of sliding areas with $\sigma_l$ as low as 2 times $\sigma_n$ can be defined. At the latest stages of sliding, the highest temperature spots support $\sigma_l$ that are half that at the highest $T_l$ in early $d_{hv}$ stages. Overall, the load-bearing mm-scale contacts identified by hot spots appear to evolve with progressive slip, from fewer contacts supporting higher $\sigma_l$ to more numerous contacts supporting lower $\sigma_l$. The temperature gradients at mm-scale contacts are relatively constant during all phases of the experiment; however, early stage contacts are narrower with $\sigma_l$ gradients almost two times greater than for late stage contacts (Figures 8b and 8c).

5. Discussion

5.1. Evolution of Normal Stress With Displacement

The combined area of thermographs used for calculating the $\sigma_l$ equals 1.5 times the area of the stationary block, and thus can be used to determine the $\sigma_l$ distribution for the entire sliding interface for $d_{hv}$. We characterize the distribution of $\sigma_l$ by determining the fractional area supporting 15 ranges of $\sigma_l$ by counting the total number of pixels within a set range of normal stress and dividing by the total number of pixels within the known ridge area in each thermograph. Ranges of $\sigma_l$ in contoured thermographs can be separated into three categories: partially imaged ranges with some contacts at temperatures below the lowest measurable temperature, fully imaged ranges with all contacts at temperatures within the measurable range, and partially imaged ranges with some contacts at temperatures above the highest measurable temperature. In analysis to characterize changes in $\sigma_l$ as a function of $d_{hv}$, we use area percent values from fully imaged normal stress ranges only, that is, regions bounded everywhere in a thermograph by closed contours or open contours terminating at image boundaries or ridge boundaries only. This reduces error associated with under-estimating the area percent of ranges with surface temperature above or below the measured limits. Plots of area percent for a particular normal stress range as a function of $d_{hv}$ show approximately linear trends, so simple linear-regression analysis was performed for each $\sigma_l$ range (Figure 9). The 15 ranges of $\sigma_l$ were binned into six master ranges to show the changes in $\sigma_l$ distribution with $d_{hv}$ during high-velocity sliding.

Overall, the $\sigma_l$ distribution evolves with $d_{hv}$ (Figure 10). In the early stages of slip, the ridge contact area is dominated by $\sigma_l$ exceeding 6 times $\sigma_n$. With high-velocity slip, the proportion of high normal-stress contacts decreases, and after $30$ mm of high velocity sliding, low normal-stress contacts dominate. The thermal modeling indicates that contacts supporting $\sigma_l$ less than the $\sigma_n$ will not reach temperatures of $55$°C for small to moderate $d_{hv}$, and thus are not detectable with IR-camera temperature ranges employed. Linear regression results suggest that contacts with $\sigma_l$ equal to $\sigma_n$ are not significantly developed prior to $25$ mm of $d_{hv}$.
any case, the overall trend from high to low $\sigma_l$ implies that contacts with lower $\sigma_l$ will continue to develop at even larger $dhv$.

At the initiation of slip, only 16% of the total interface area, representing 64% of the total ridge area, is in contact and supporting the total normal load. The early contacts are characterized by $\sigma_l$ exceeding 40 times $\sigma_n$ at some hot spots, with most contacts supporting $\sigma_l$ in the range of 6–20 times $\sigma_n$. As sliding continues the total mm-scale contact area increases, and $\sigma_l$ at the locally hottest (i.e., highest normal stress) mm-scale spots decrease. We attribute the increase in contact area and decrease in $\sigma_l$ at hot spots to wear and ploughing of high normal stresses mm-scale asperities during the early stages of high-velocity sliding. Following 35 mm of $dhv$, 100% of the ridge area is in contact, and 88% of the total ridge area supports $\sigma_l$ less than 6 times $\sigma_n$, with most contacts supporting $\sigma_l$ greater than 2 times $\sigma_n$. This distribution is consistently reproduced in experiments even as contacts are reset between successive experiments via surface separation, brushing off of loose wear product, and reassembly of the DDS blocks.

5.2. Significance for Flash-Weakening Model

The use of grooved sliding surfaces with known $LT$-$RT$ sliding histories for mm-scale contacts, coupled with thermal imaging of the sliding surfaces in real-time allows us to determine the distribution of $\sigma_l$ by accounting for the surface-temperature dependence of flash-weakening as described in the flash-weakening model. The accuracy of the determination, however, is subject to knowledge of micrometer-scale material properties such as the strength, weakening temperature, and dimensions of nanometer- and micrometer-scale contacts, and the thickness of the sliding zone. The values of micrometer-scale material properties we used, taken from Rice (2006) and Goldsby and Tullis (2011), are thought to be reasonable for granite rock-on-rock experiments, but in detail there are many uncertainties. As an example, a number of experimental works have used the macroscopic flash-weakening behavior (frictional strength and weakening velocity) to determine weakening temperature and other $\mu$m-scale contact properties, but such work has suffered from the incomplete knowledge of surface temperature distribution (e.g., Chen & Rempel, 2014; Goldsby & Tullis, 2011; Passelègue et al., 2014; Rempel & Weaver, 2008; Tisato et al., 2012). We suggest that with knowledge of surface temperatures and of the $LT$ and $RT$ of mm-scale contacts, which effectively provide critical constraints on the thermal state of the surface, determinations of temperature and contact properties will be more robust. Our calculations of normal stress distribution in the last few millimeters of $HV$ sliding show greater stress concentration on mm-scale contacts than inferred by Saber (2017), primarily because of his uncertainty in the $LT$ of contacts for conventional flat-ground surfaces. Nonetheless, Saber (2017) showed that hysteretic friction behavior during acceleration and deceleration could be better matched by using the observed surface-temperature distribution in coupled thermomechanical models of flash-weakening. Experiments employing different velocity histories, different mm-scale contact $LT$ and $RT$, and thermal imaging show great promise in enhancing our ability to perform more complete tests of the flash-weakening model for rock-on-rock friction.

The mechanical behavior in the experiments herein show dramatic, essentially instantaneous weakening as expected for flash-weakening of $\mu$m-scale asperity junctions at slip rates of $\sim 1$ m/s. Interestingly though, the subsequent strength is relatively constant for the remainder of slip and does not decrease even though the average and peak surface temperatures increase with slip. This may be explained when considering the evolution of normal stress due to wear of mm-scale contact junctions inferred herein. The transition from a
relatively small number of high load contacts to more numerous low-load contacts as slip progresses, if acting alone, would lead to strengthening, but instead appears to approximately cancel the effect of the overall increase in surface temperature such that relatively constant strength ensues.

The significance of wear processes on flash-weakening are further reinforced by the observed distributions of hot spots. As the evolution of the temperature and normal stress distributions are to some extent repeated in experiments, we suggest that (a) the light brushing and removal of wear product between experiments does indeed reset the surface geometry, or that (b) hot spots reflect self-organization by ploughing and wear in a statistically repeatable fashion. That individual hot spots tend to form in the same locations in successive experiments suggests resetting of the starting rock-on-rock surface characteristics is the more likely explanation. It follows that there may be a geometric or mechanical control from the rock substrate rather than generation of ephemeral structures in the wear product layer. Research on wear processes and the formation of mm-scale contact asperities documented here will help characterize the controls of macroscopic contact processes for flash-weakening in natural fault slip-surfaces.

6. Conclusions

For frictional sliding on a rock-on-rock interface at seismic slip rates, we document an inhomogeneous distribution of temperature at the mm-scale during all phases of slip, with an overall increase in surface temperature with slip. We also document inhomogeneous \( \sigma \), with the greatest normal stress concentration at hot spots reflecting mm-scale asperity contact junctions. The normal stress distribution evolves with slip reflecting an increase in contact area by ploughing and wear. Current approaches in modeling flash heating and weakening generally assume flash-weakening of micrometer-scale contact junctions with a homogeneous surface temperature and normal stress at the mm and larger scale. Our results indicate that the conventional flash-weakening model should not only consider flash heating at the micrometer scale, but also inhomogeneous normal stress and temperature at mm and larger scale contacts encompassing the \( \mu \text{m} \)-scale asperity contacts undergoing flash-weakening. Incorporating mm-scale contact evolution into the flash weakening model may better constrain material and geometric parameters in flash-weakening constitutive relations. It also appears that to correctly describe transient weakening and strengthening associated

Figure 10. (a) Changes in area percent as a function of high-velocity displacement for 6 ranges of local normal stresses based on model results from all 12 experiments. Below displacements of \( \sim 15 \text{ mm} \), temperatures in the lowest range, with local normal stresses less than the macroscopic normal stress, are below 55°C and unresolvable with the imageable temperature of the IR camera. The black dashed line marks the boundary between resolvable and unresolvable local normal stresses. As a result of the grooves ground into the sliding surfaces, 75% of the total area-percent is necessarily out of contact such that local normal stress equals 0 MPa (distinguished by the dotted line). (b) Model predicted distribution of local normal stress factors after 10 mm of high-velocity sliding. (c) Model predicted distribution of local normal stress factors after 30 mm of high-velocity sliding. The distribution becomes less right-skewed as displacement increases, and as the mode and mean for the local normal stress factor decreases.
with flash heating, it will be important to treat the changes in the macroscopic state of the sliding surface associated with worn and gouge accumulation during slip.

Data Availability Statement
The data related to this work can be accessed via the Texas Data Repository (Barbery et al., 2020).

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