AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2013GL058374

Key Points:
- Experimental investigation of the effect of fault temperature on Flash heating
- Unexpected frictional behavior supported by theory adapted for high temperature
- Flash heating may play a second role in in the propagation of earthquake rupture

Supporting Information:
- Readme
- Figure S1

Correspondence to:
F. X. Passelègue,
passelegue@geologie.ens.fr

Citation:
Passelègue, F. X., D. L. Goldsby, and O. Fabbri (2014), The influence of ambient fault temperature on flash-heating phenomena, *Geophys. Res. Lett.*, *41*, doi:10.1002/2013GL058374.

Received 25 OCT 2013
Accepted 17 JAN 2014
Accepted article online 20 JAN 2014

The influence of ambient fault temperature on flash-heating phenomena

François X. Passelègue[1,2], David L. Goldsby[3], and Olivier Fabbri[2]

[1]CNRS UMR 8538, École Normale Supérieure, Paris, France, [2]UMR 6249, Université de Franche-Comté, Besançon, France, [3]Department of Geological Sciences, Brown University, Providence, Rhode Island, USA

Abstract Recent high-velocity friction experiments on room temperature rocks reveal a dramatic weakening caused by extreme frictional heating and thermal degradation of the strength of microscopic asperity contacts on a slip surface, i.e., "flash" heating. Here we explore the effects of elevated ambient fault temperature, up to that at the base of the Earth's seismogenic zone, on the flash-heating behavior of quartzite, Westerly granite, and India gabbro. The experiments demonstrate that elevated ambient fault temperature causes 1) an increase in the characteristic weakening velocity for flash heating, and 2) an increase in the friction coefficient at a given velocity above this characteristic weakening velocity. These unexpected results are reconciled with flash-heating theory when temperature-specific values of various material parameters are incorporated in existing constitutive descriptions of flash heating. Our results suggest that constitutive equations for flash heating can be extrapolated with confidence to the elevated ambient temperatures of the seismogenic zone.

1. Introduction

Within the past decade, numerous laboratory experiments have been conducted to investigate the frictional properties of crustal rocks at seismic slip rates [see *Di Toro et al.*, 2011 for a review]. A number of dynamic weakening mechanisms have been proposed to explain coseismic weakening of faults [*Brune et al.*, 1969; *Lachenbruch and Sass*, 1992], including thermal pressurization of pore fluids [*Sibson*, 1973; *Wibberley and Shimamoto*, 2005], elastohydrodynamic lubrication [*Brodsky and Kanamori*, 2001], powder lubrication [*Reches and Lockner*, 2010], thixotropic behavior of silica (or silicate) gels [*Goldsby and Tullis*, 2002; *Di Toro et al.*, 2004], acoustic fluidization [*Melosh*, 1996], melt lubrication [*Tsutsumi and Shimamoto*, 1997; *Hirose and Shimamoto*, 2005; *Di Toro et al.*, 2006], and flash heating [*O'Hara*, 2005; *Rice*, 2006; *Goldsby and Tullis*, 2011]. Although large earthquakes nucleate at depths where fault zone temperatures are generally in the range of 150 to 350°C [*Oleskevich et al.*, 1999], a few experimental studies have been directed at understanding the influence of ambient (nonfrictionally generated) fault surface temperature on the coseismic frictional behavior of rocks [*Noda et al.*, 2011].

Recent theoretical and experimental studies have highlighted the role of flash heating in earthquake mechanics [*Rice*, 2006; *Beeler et al.*, 2008; *Noda*, 2008; *Kohli et al.*, 2011; *Goldsby and Tullis*, 2011]. On a fault surface (or within a fault zone), the real area of contact is much smaller than the nominal area of contact, resulting in high stresses at asperity contacts [*Dieterich and Kilgore*, 1996] of order 10 GPa for typical crustal silicate rocks. The total heat input per unit area at an asperity contact during its lifetime is $Q = f_c \sigma_c V\theta$, where σ_c is the contact normal stress, f_c is the friction coefficient of the contact, V is the sliding rate, and θ is the contact lifetime ($\theta = D/V$, where D is the contact size). For laboratory experiments, values of D are in the range of 1 to 50 μm [*Dieterich and Kilgore*, 1996], yielding values of $\theta = 1$ to 50 μs, respectively, at a seismic slip rate of 1 m/s. The heat input at the contacts is large owing to the large contact stresses [*Logan and Teufel*, 1986]. A large input of heat over a short lifetime during high-speed sliding can lead to a dramatic increases in temperature, even melting, of contacts, and thus degradation in contact strength, manifest as low friction in a rock-friction experiment. An important feature of the flash-heating mechanism is that weakening occurs over characteristic sliding displacements on the order of the contact size, such that friction is nearly a pure function of the instantaneous slip rate. This constitutive behavior may have implications for the mode of dynamic rupture during earthquakes (i.e., whether rupture occurs as a slip pulse or is "crack-like." [*Noda et al.*, 2009; *Goldsby and Tullis*, 2011])

High-speed friction experiments conducted on samples at room temperature [*Goldsby and Tullis*, 2011; *Kohli et al.*, 2011] reveal behavior consistent with weakening due to flash heating [e.g., *Rice*, 2006], namely, a friction coefficient that is nearly a pure function of slip velocity and a 1/V dependence of friction on slip rate above a characteristic weakening velocity, V_w. A first-order hypothesis is that the increase of fault temperature with depth in the Earth, following a mean geothermal gradient of 30°C/km, facilitates weakening due to flash heating by reducing the value of V_w required to thermally weaken the already warm asperities. After *Rice* [2006],

$$V_w \propto (T_w - T_f)^2 \tag{1}$$

where T_w is the temperature required to severely thermally degrade the strength of asperities, and T_f is the ambient temperature of the fault surface. Assuming a value of $T_w = 1000$°C [*Goldsby and Tullis*, 2011], an increase in temperature from 25 to 300°C might be expected to result in a decrease in V_w by a factor of ~2, based on equation (1).

In this study, we test this hypothesis at temperatures, up to 350°C, that approximately span the range of those in the seismogenic zone, for several crustal rocks—quartzite, India gabbro, and Westerly granite. We demonstrate that increases in ambient temperature cause an increase in V_w, in contrast with the hypothesis based on equation (1). We reconcile the experimental results with existing flash-heating theory by employing temperature-specific values of various material parameters for the tested rocks in the theoretical expression for V_w.

2. Experimental Details

Friction experiments were conducted at ambient humidity in an Instron 1-atm compression/rotary-shear apparatus. The experimental setup consists of a stationary annulus of a given rock with inner and outer diameters of 44.0 and 54.0 mm, fixed with high-temperature epoxy (automotive muffler cement) into a steel sample grip, sliding against a rotating circular plate of the same rock, 10 to 25 mm in thickness, and ~150 mm in diameter, mechanically attached to a steel sample grip. Tests were conducted under a constant normal stress of 5 MPa. The sample ring and plate were each in thermally conductive contact with one of two resistively heated aluminum plates. Average temperatures of the sliding surface were monitored with thermocouples contacting the surfaces of the annulus and plate as closely as possible to the sliding surface and with a handheld infrared detector used to probe the temperature at various locations on the samples (Figure S1 of the supporting information).

3. Experimental Results and Comparison With Flash-Heating Theory

The friction coefficient during the low-velocity portion of the tests at room temperature obtains values of ~0.6 for quartzite, 0.8 for granite, and 0.9 for gabbro (Figure 1), consistent with the data from previous studies on quartz rocks [*Beeler and Tullis*, 1997; *Di Toro et al*., 2004], granite [*Spray*, 1993], and gabbro [*Tsutsumi and Shimamoto*, 1997] and nominally with Byerlee's law [*Byerlee*, 1978]. The minimum value of the friction coefficient is observed at the peak velocity (~0.36 m/s). As V decreases from its peak value, the friction coefficient increases accordingly, with the most rapid increase in friction occurring during the rapid deceleration near the end of each experiment. At the end of each test, as V approaches zero, the friction coefficient f reaches a value close to that measured at 10 μm/s at the beginning of the test. In effect, as shown in Figure 1, the friction trace is observed to be essentially a "mirror image" of the slip velocity trace above a characteristic sliding velocity, V_w. Above V_w~0.1 m/s, the experiments reveal a 1/V dependence of the friction coefficient on slip rate (Figures 1 and 2), consistent with previous studies on samples at room temperature [*Kohli et al*., 2011; *Goldsby and Tullis*, 2011].

Oscillations in friction observed during the experiments (Figure 1) are due to the interactions of the comparatively compliant sample assembly and apparatus and the extremely strong rate-weakening behavior of the sample due to flash heating [see *Kohli et al*., 2011 for a discussion]. To aid in the interpretation of the data, the data in Figure 1 have therefore been smoothed using a low-pass filter, a process that yields a faithful "average" of the data. The data obtained between the peak velocity and the end of the tests (hereafter termed the "deceleration data") from Figure 1 after smoothing are reported in Figure 2. The plots show variations of the friction coefficient with sliding velocity plotted on a logarithmic scale. The deceleration data (as opposed to the "acceleration data" acquired from the beginning of the step to high-speed sliding to the

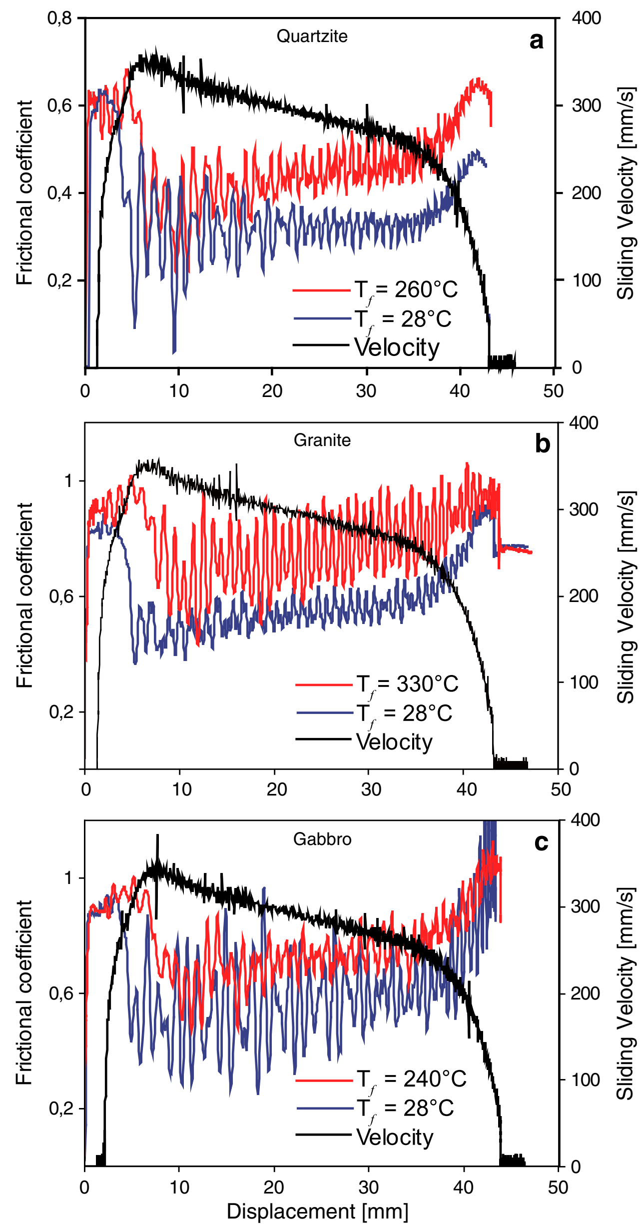

Figure 1. Effect of sliding velocity (black trace) on friction during experiments conducted at $T_f \approx 25$°C (blue trace) and $T_f \approx$ (indicated higher temperature) (red trace). Plots are for (a) quartzite, (b) granite, and (c) gabbro.

peak velocity) have been demonstrated to best represent the effects of flash heating on frictional behavior [*Kohli et al.*, 2011; *Goldsby and Tullis*, 2011]. The colored stars in Figures 2a–2c indicate the estimated value of V_w, whereas the colored circles indicate the value of the friction coefficient at the peak velocity, $V = 0.36$ m/s.

As shown in Figure 2, the increase in ambient fault surface temperature results in two prominent and unexpected effects: (1) the friction coefficient f at all slip rates increases with increasing temperature and (2) the weakening velocity V_w is shifted to higher slip rates with increasing temperature. For example, the value of f for quartzite at the peak velocity $V = 0.36$ m/s is equal to ~0.2 at room temperature and ~0.33 at 240°C (Figure 2a). For granite (Figure 2b), the friction coefficient at $V = 0.36$ m/s is 0.4 and 0.57 at temperatures of 25°C and 240°C, respectively, and for gabbro, 0.4 and 0.53 at temperatures of 25°C and 330°C, respectively (Figure 2c). Unlike the prediction deduced from flash-heating theory (equation (1)), the increase in ambient fault surface temperature leads to an increase in the value of V_w. Tests on gabbro yield the lowest value of V_w at room temperature,

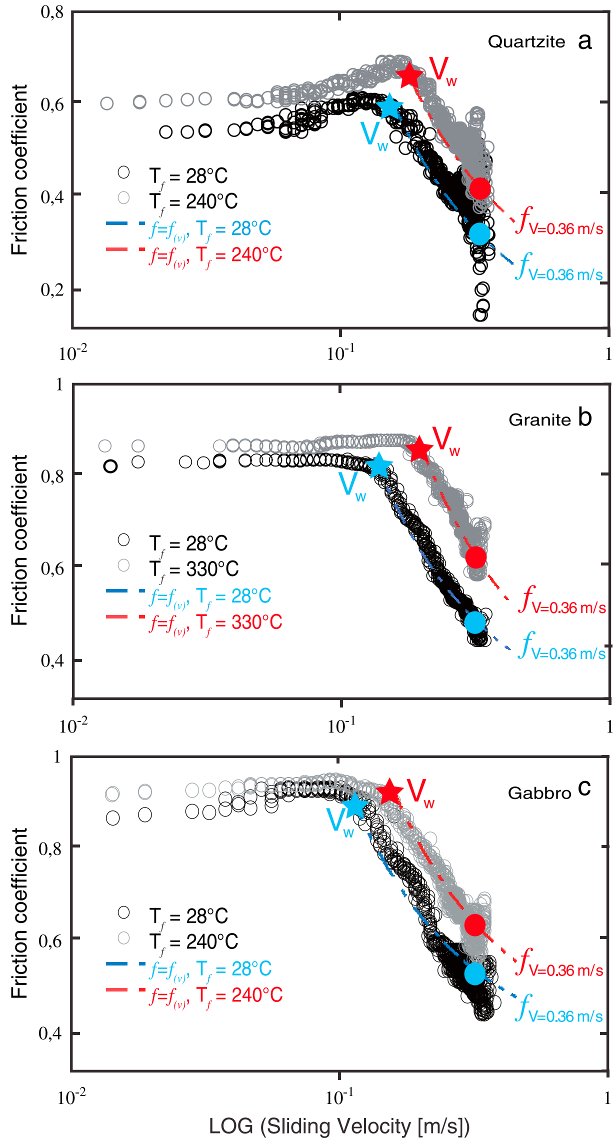

Figure 2. Friction coefficient measured during deceleration versus velocity. The black circles are the data measured during an experiment at $T_f \approx 25°C$ and the gray circles at $T_f \approx$ (elevated temperature). The data are compared to the theoretical relationship $f = f\ (V)$ for flash weakening (dashed lines) at $T_f \approx 25°C$ (blue dashed trace) and $T_f \approx$ elevated temperature (red dashed trace). The weakening velocity V_w and the weakened friction coefficient μ_w increase with the temperature of the sliding surface. Plots are for (a) quartzite, (b) granite, and (c) gabbro.

107 mm/s, followed by 129 mm/s for granite and 143 mm/s for quartzite (Figures 2a–2c). For the higher ambient temperature of the sliding surface (>240°C), the value of V_w increases to 147 mm/s for gabbro, 169 mm/s for granite, and 184 mm/s for quartzite (Figure 2), an average increase by ~30% for an increase in fault surface temperature from 25°C to 240°C (330°C for gabbro). In short, over the tested range of temperatures, the higher the fault surface temperature, the higher the velocity required to weaken the asperities and the lower the friction due to flash heating.

Despite the apparent discrepancy of the experimental results with our simple hypothesis based on equation (1), we find that the data compare very favorably with existing flash-heating theory [*Rice*, 2006] when variations with temperature of the relevant physical parameters in equation (2) are taken into account. In the Rice model, the shear strength τ_c of the asperity contact is assumed to be constant when $T < T_w$ and decrease dramatically for $T > T_w$, where T_w is the temperature at the onset of severe thermal weakening of contacts.

Table 1. Room Temperature Data Used in the Flash-Heating Model [after *Goldsby and Tullis*, 2011; *Rempel and Weaver*, 2008]

Parameters	Symbol	Units	Quartzite	Gabbro	Granite
Thermal diffusivity	α	$m^2 s^{-1}$	1.10^{-6}	$1.29.10^{-6}$	$1.25.10^{-6}$
Mass density	ρ	$kg\,m^{-3}$	2650	2590	2350
Heat capacity	C	$J\,kg^{-1}\,K^{-1}$	1082	975	900
Thermal conductivity	λ	$J\,s^{-1}\,m^{-1}\,K^{-1}$	5.7	3.29	2.64
Contact shear stress	τ_c	10^9 Pa	7.4	5	5.6
Asperities diameter	D	µm	10	15	4
Weakening temperature	T_w	°C	1600	1200	900
Static friction	f_s		0.62	0.85	0.82
Residual friction	f_w		0.1	0.2	0.2

Weakening due to flash heating occurs when the time θ_w required to raise the temperature of the contact to T_w is shorter than the contact lifetime, a condition met when $V > V_w$:

$$V_w = \frac{\pi\alpha}{D}\left[\frac{\rho C(T_w - T_f)}{\tau_c}\right]^2 \tag{2}$$

where α is the thermal diffusivity and ρC is the thermal capacity (where ρ is the rock density and C is the heat capacity). The normal stress borne by contacts is approximately equal to the indentation hardness (H) of the mineral(s) constituting the tested rocks, with $\tau_c = f\,H$. The values of the various parameters in equation (2) employed in the following sections are given in Table 1.

An estimate of the effect of flash heating on macroscopic friction for a given D is obtained by noting that, above V_w, a contact spends a fraction $\theta_w/\theta = V_w/V$ of its lifetime with its initially high strength τ_c and the remaining fraction with its strength in the weakened state, $\tau_{c,w}$. The macroscopic shear stress τ and the nominal normal stress σ satisfy $f = \tau/\sigma$, where f is the friction coefficient. The macroscopic friction as a function of the slip velocity for $V > V_w$ is given by [*Rice*, 2006]:

$$f = (f_o - f_w)\frac{V_w}{V} + f_w \tag{3}$$

where f_w is the friction coefficient in the weakened state.

To compare experimental data with the flash-heating theory, the physical parameters used in equations (2) and (3) must be appropriate for the initial ambient temperatures of the samples in our experiments. The thermal diffusivity $\alpha = \lambda/\rho C$, where the thermal conductivity λ and heat capacity C are given by the empirical equations of *Vosteen and Schellschmidt* [2003]. Even though these empirical equations were developed for rocks, not minerals, a good fit to experimental measurements on minerals as a function of temperature [e.g., *Clauser and Huenges*, 1995] is observed when comparing the empirical equations for rocks with data for minerals. Furthermore, because two of the tested rocks are polymineralic, it is difficult to assign specific thermal parameters to frictional contacts between different minerals. In addition to the variations of λ and C with temperature, the value of τ_c decreases with increasing T_f. Contact stresses as a function of T_f are estimated using polynomial fits to hardness data from microindentation experiments on silicate minerals (quartz and olivine) at elevated temperatures [*Evans*, 1984; *Evans and Goetze*, 1979]. Dynamic changes of the contact shear stress and other material properties due to the flash temperature rise [*Noda*, 2008] are neglected in our simple model.

Equation (2) can be used to estimate the evolution of V_w as a function of T_f (Figure 3) using the temperature-dependent material parameters described above. Increasing values of T_f then lead to increases in the values of V_w, in accord with our experimental observations. Figure 3 shows that this theoretical prediction agrees quantitatively with our experimental results.

4. Discussion and Conclusions

This study demonstrates that increasing fault surface temperature leads to (i) an increase of the friction coefficient at a given slip rate and (ii) an increase of the velocity required to induce severe weakening

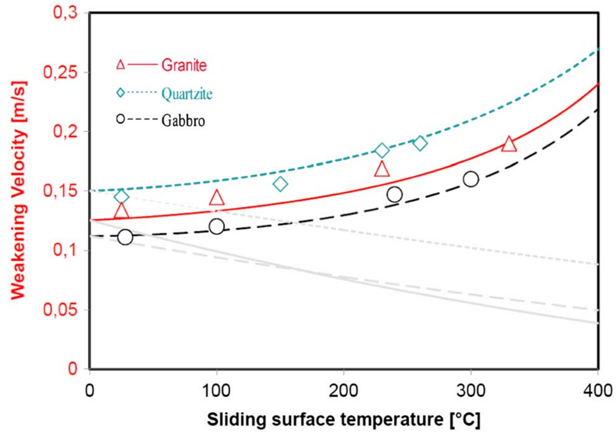

Figure 3. Influence of average fault surface temperature on the weakening velocity. Blue, black, and red lines and symbols represent, respectively, the theoretical estimations and experimental data for the weakening velocity for quartzite, gabbro, and granite. Gray dashed lines correspond to the theoretical predictions made without taking into account the influence of ambient fault temperature on the values of various physical parameters.

due to flash heating (i.e., an increase in V_w). Despite these somewhat unexpected results, our study demonstrates that flash-heating theory can be successively reconciled with experimental observations by adopting various physical parameters of the rocks as functions of the ambient fault temperature in calculations of V_w (Figures 2 and 3).

The "thermal strengthening" effect on flash-heating behavior can be explained as follows. The increase of the quasi-static friction coefficient (when $V_s << V_w$) with the fault surface temperature is explained by an increase in the real area of contact along the fault plane due to enhanced plastic deformation of asperities. When $V_s > V_w$, the temperature rise at sliding asperity contacts is a function of contact shear stress and can be estimated by the following equation [*Archard*, 1959; *Rice*, 2006]

$$\Delta T = \frac{\tau_c}{\rho C}\sqrt{\frac{rV}{2\pi\alpha}} + T_f \tag{4}$$

where r is the contact radius (=D/2). Figure 4a shows the results of an estimation of the flash temperature for quartzite using different slip rates and values of T_f between 0 and 500°C. As indicated by previous experiments

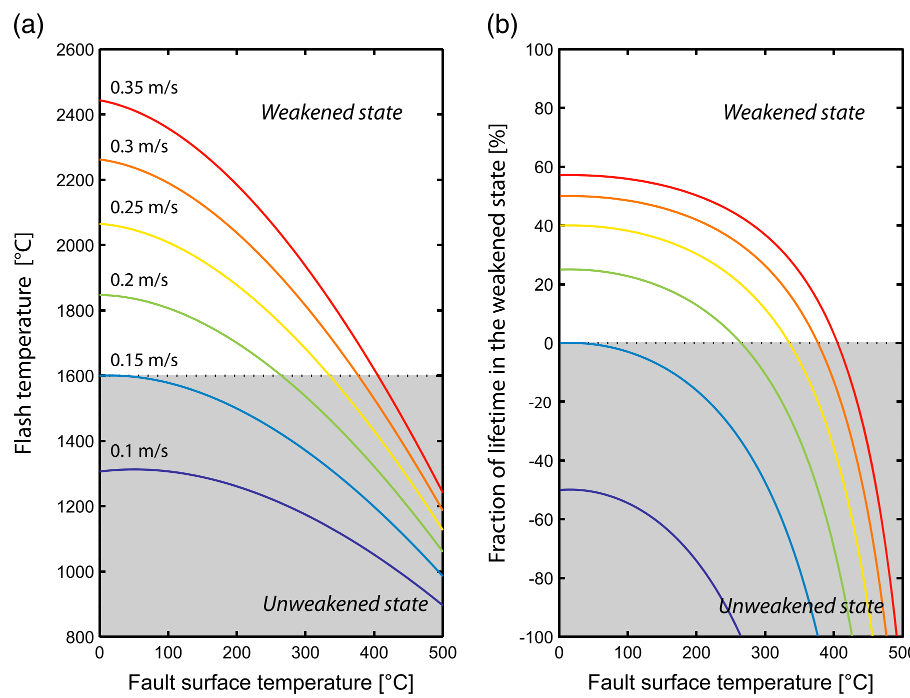

Figure 4. The influence of ambient fault surface temperature on flash-heating behavior. (a) Influence of fault surface temperature on the flash temperature of an asperity; estimates for quartzite for different indicated slip rates. (b) Influence of ambient fault surface temperature on the fraction of its lifetime an asperity spends in its weakened state; estimates for quartzite, for the same slip rates indicated in Figure 4a.

[*Goldsby and Tullis*, 2011; *Kohli et al.*, 2011], a strong dependence of flash temperature on sliding velocity is observed; the higher the sliding velocity, the higher the flash temperature. However, the flash temperature decreases continuously with the fault temperature for a given sliding velocity (Figure 4a). The flash temperatures attained when T_f is high are lower than when T_f is low, inducing a smaller degree of weakening at higher ambient temperatures for the same sliding velocity (Figures 2 and 4a).

However, the flash temperature cannot increase significantly above T_w (above the melting temperature, for example). The increase in friction (at a given sliding velocity) with ambient fault temperature when $V > V_w$ is not explained only by the decrease in flash temperature. The dramatic effect of flash heating on "macroscopic" friction (i.e., the friction coefficient measured in a rock-friction experiment) is a function of the fraction of its lifetime that an asperity spends in its weakened state; the larger the fraction in the weakened state (i.e., with $T_{asperities} > T_w$), the larger the effect on the macroscopic friction. The total contact lifetime of the asperities is $\theta = D/V$. The time θ_w necessary to reach T_w can be estimated by [*Rice*, 1999]

$$\theta_w = \frac{\pi\alpha}{V^2}\left[\frac{\rho C(T_w - T_f)}{\tau_c}\right]^2 \quad (5)$$

A "residual" lifetime of an asperity can be defined as the difference between θ and θ_w. Figure 4b shows the results for the same temperature and velocity conditions as for Figure 4a. If the residual lifetime is less than 0 (i.e., if the contact time θ is less than the time θ_w required to reach T_w), the contact temperature never reaches T_w, and weakening due to flash heating does not occur. The results presented in Figure 4b explain our experimental results—at a given sliding velocity, the residual lifetime decreases with increasing temperature because of the increase of θ_w. The macroscopic friction will thus be lower at room temperature than at higher temperatures (when $V > V_w$), as observed in the experiments.

This study demonstrates that increasing fault temperature with depth suppresses slightly the dramatic effects of flash-heating during seismic slip. The deeper the seismic rupture, the higher the velocity required to induce weakening due to flash heating and the less the weakening will be at a given velocity. In addition, the dramatic effects of flash heating on faults in nature may be moderated by (i) distributed shearing of a gouge layer, reducing the contact-scale slip rate and thus the flash temperature, thereby increasing V_w [*Noda*, 2008; *Goldsby and Tullis*, 2011] and/or (ii) the increase of ambient fault temperature, causing an increase in V_w and f_w. A larger value of f_w at 300°C (0.33 for quartzite, for example) compared to the value at 25°C (0.1–0.2) will increase the likelihood that flash heating will transition to bulk-melting behavior [*McKenzie and Brune*, 1972; *Sibson*, 1975; *Hirose and Shimamoto*, 2005; *Di Toro et al.*, 2006]. Similarly, flash heating at elevated T_f may give way to thermal pressurization of pore fluids [*Sibson*, 1973; *Wibberley and Shimamoto*, 2005] in shorter sliding distances than would be predicted on the basis of experiments conducted at room temperature [*Beeler*, 2006; *Rempel*, 2006].

Acknowledgments
Travel expenses were funded by the UMR CNRS 6249 (Chrono-Environnement) Laboratory. F.X.P. thanks Alexandre Schubnel and Lucas Pimienta for fruitful discussions. Support for DLG is gratefully acknowledged from the U.S. Geological Survey–National Earthquake Hazards Reduction Program, Awards G11AP20196 and G11AP20196, and the Southern California Earthquake Center, from its National Science Foundation NSF Cooperative Agreement EAR-1033462 and U.S. Geological Survey Cooperative Agreement G12AC20038. The SCEC contribution number for this paper is 1907. This study benefited from comments by Terry Tullis, Nick Beeler, and Greg Hirth.

The Editor thanks Hiroyuki Noda and an anonymous reviewer for their assistance in evaluating this paper.

References

Archard, J. F. (1958/1959), The temperature of rubbing surfaces, *Wear*, *2*, 438–455.

Beeler, N. M. (2006), Inferring earthquake source properties from laboratory observations and the scope of lab contributions to source physics, in *Radiated Energy and the Physics of Faulting*, *Geophys. Monogr. Ser.*, vol. 170, edited by R. Abercrombie et al., pp. 99–119, AGU, Washington, D. C.

Beeler, N. M., and T. E. Tullis (1997), The roles of time and displacement in velocity-dependent volumetric strain of fault zones, *J. Geophys. Res.*, *102*, 22,595–22,609.

Beeler, N. M., T. E. Tullis, and D. L. Goldsby (2008), Constitutive relationships and physical basis of fault strength due to flash heating, *J. Geophys. Res.*, *113*, B01401, doi:10.1029/2007JB004988.

Brodsky, E. E., and H. Kanamori (2001), Elastohydrodynamic lubrication of faults, *J. Geophys. Res.*, *106*, 16,357–16,374.

Brune, J. N., T. L. Henyey, and R. F. Roy (1969), Heat flow, stress and rate of slip along the San Andreas Fault, California, *J. Geophys. Res.*, *74*, 3821–3827.

Byerlee, J. (1978), Friction of rocks, *Pure Appl. Geophys.*, *116*(4–5), 615–626.

Clauser, C., and E. Huenges (1995), Thermal conductivity of rocks and minerals, in *AGU Reference Shelf 3 Rock Physics and Phase Relations, A Handbook of Physical Constants*, edited by T. J. Ahrens, pp. 105–125, AGU, Washington, D. C.

Di Toro, G., D. L. Goldsby, and T. E. Tullis (2004), Friction falls towards zero in quartz rock as slip velocity approaches seismic rates, *Nature*, *427*(6973), 436–439.

Di Toro, G., T. Hirose, S. Nielsen, G. Pennacchioni, and T. Shimamoto (2006), Natural and experimental evidence of melt lubrification of faults during earthquakes, *Science*, *311*(5761), 647–649, doi:10.1126/science.1121012.

Di Toro, G., R. Han, T. Hirose, N. De Paola, S. Nielsen, K. Mizoguchi, F. Ferri, M. Cocco, and T. Shimamoto (2011), Fault lubrication during earthquakes, *Nature*, *471*(7339), 494, doi:10.1038/nature09838.

Dieterich, J. H., and B. D. Kilgore (1996), Imaging surface contacts: Power law contact distributions and contact stresses in quartz, calcite, glass and acrylic plastic, *Tectonophysics*, *256*, 219–239.

Evans, B. (1984), The effect of temperature and impurity content on indentation hardness of quartz, *J. Geophys. Res.*, *89*, 4213–422.

Evans, B., and C. Goetze (1979), The temperature variation of Hardness of olivine and its implication for polycrystalline yield stress, *J. Geophys. Res.*, *84*, 5505–5524.

Goldsby, D. L., and T. E. Tullis (2002), Low friction strength of quartz rocks at subseismic slip rates, *Geophys. Res. Lett.*, *29*, 1844, doi:10.1029/2002GL015240.

Goldsby, D. L., and T. E. Tullis (2011), Flash heating leads to low frictional strength of crustal rocks at earthquake slip rates, *Science*, *334*, 216–218, doi:10.1126/science.1207902.

Hirose, T., and T. Shimamoto (2005), Slip weakening distance of faults during friction melting as inferred from experimental and natural pseudotachylytes, *Bull. Seismol. Soc. Am.*, *95*, 1666–1673.

Kohli, A. H., D. L. Goldsby, G. Hirth, and T. E. Tullis (2011), Flash weakening of serpentinite at near-seismic slip rates, *J. Geophys. Res.*, *116*, B03202, doi:10.1029/2010JB007833.

Lachenbruch, A., and J. Sass (1992), Heat flow from Cajon Pass, fault strength, and tectonic implications, *J. Geophys. Res.*, *97*(B4), 4995–5015, doi:10.1029/91JB01506.

Logan, J. M., and L. W. Teufel (1986), The effect of normal stress on the real area of contact during frictional sliding in rocks, *Pure Appl. Geophys.*, *124*, 471–486.

McKenzie, D., and J. N. Brune (1972), Melting on fault planes during large earthquakes, *Geophys. J. R. Astron. Soc.*, *29*, 65–78.

Melosh, J. (1996), Dynamic weakening of faults by acoustic fluidization, *Nature*, *397*, 601–606.

Noda, H. (2008), Frictional constitutive law at intermediate slip rates accounting for flash heating and thermally activated slip process, *J. Geophys. Res.*, *113*, B09302, doi:10.1029/2007JB005406.

Noda, H., E. M. Dunham, and J. R. Rice (2009), Earthquake ruptures with thermal weakening and the operation of major faults at low overall stress levels, *J. Geophys. Res.*, *114*, B07302, doi:10.1029/2008JB006143.

Noda, H., K. Kanagawa, T. Hirose, and A. Inoue (2011), Friction experiments of dolerite at intermediate slip rates with controlled temperature: Rate weakening of temperature weakening?, *J. Geophys. Res.*, *116*, B07306, doi:10.1029/2010JB007945.

O'Hara, K. (2005), Evaluation of asperity-scale temperature effects during seismic slip, *J. Struct. Geol.*, *27*, 1892–1898.

Oleskevich, D. A., R. D. Hyndman, and K. Wang (1999), The updip and downdip limits to great subduction earthquakes: Thermal and structural models of Cascadia, south Alaska, SW Japan, and Chile, *J. Geophys. Res.*, *104*, 14,965–14,991.

Reches, Z., and D. A. Lockner (2010), Fault weakening and earthquake instability by powder lubrication, *Nature*, *467*, 452–456.

Rempel, A. W. (2006), The effects of flash-weakening and damage on the evolution of fault strength and temperature, in *Radiated Energy and the Physics of Faulting*, *Geophys. Monogr. Ser.*, vol. 170, edited by R. Abercrombie et al., pp. 263–270, AGU, Washington, D. C.

Rempel, A. W., and S. L. Weaver (2008), A model for flash weakening by asperity melting during high-speed earthquake slip, *J. Geophys. Res.*, *113*(B11), 1978–2012, doi:10.1029/2008JB005649.

Rice, J. R. (1999), Flash heating at asperity contacts and rate-dependent friction, *Eos Trans. AGU*, *80*, F681.

Rice, J. R. (2006), Heating and weakening of faults during earthquake slip, *J. Geophys. Res.*, *111*, B05311, doi:10.1029/2005JB004006.

Sibson, R. H. (1973), Interactions between temperature and pore-fluid pressure during earthquake faulting and a mechanism for partial or total stress relief, *Nature*, *243*(126), 66–68.

Sibson, R. H. (1975), Generation of pseudotachylyte by ancient seismic faulting, *Geophys. J. R. Astron. Soc.*, *43*, 775–794.

Spray, J. G. (1993), Viscosity determinations of some frictionly generated silicate melts: Implications for fault zone rheology at high strain rates, *J. Geophys. Res.*, *98*, 8053–8068.

Tsutsumi, A., and T. Shimamoto (1997), High-velocity friction properties of gabbro, *Geophys. Res. Lett.*, *24*, 699–702.

Vosteen, H.-D., and R. Schellschmidt (2003), Influence of temperature on thermal conductivity, thermal capacity and thermal diffusivity for different types of rock, *Phys. Chem. Earth, Parts A/B/C*, *28*, 499–509.

Wibberley, C. A. J., and T. Shimamoto (2005), Earthquake slip weakening and asperities explained by thermal pressurization, *Nature*, *436*, 689–692.