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Thermal Weakening in Large Seismic Slips and Effects on Rupture Dynamics

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Recent reports related to theme of this project:

Abercrombie, R. E., and J. R. Rice, "Can observations of earthquake scaling constrain slip weakening?", *Geophys. J. Int.,* in press, 2005. http://esag.harvard.edu/rice/212_AbercrombieRice_toGJI04.pdf

Rice, J. R., C. G. Sammis and R. Parsons, "Off-fault secondary failures induced by a dynamic slip pulse", submitted to *Bull. Seismol. Soc. Amer.,* in press, 2004 or 2005 (this item is also listed for our other SCEC project). http://esag.harvard.edu/rice/211_RiceSammisPars_BSSA04.pdf

Lapusta, N., and J. R. Rice, "Low-heat and low-stress fault operation in earthquake models of statically strong but dynamically weak faults", *EOS Trans. Amer. Geophys. Union*, vol. 84, no. 46, Fall Meet. Suppl., Abstract S51B-02, 2003.

Rice, J. R., "Earthquake fracture energies and weakening of faults by thermal pressurization of pore fluid", *EOS Trans. Amer. Geophys. Union*, vol. 84, no. 46, Fall Meet. Suppl., Abstract S41G-01, 2003.

Rempel, A. W., J. R. Rice and L. M. Jacques, "Fault zone drainage, heating and melting during earthquake slip", *EOS Trans. Amer. Geophys. Union*, vol. 84, no. 46, Fall Meet. Suppl., Abstract S42C-0183, 2003.

Rice, J. R., and M. Cocco, "Seismic fault rheology and earthquake dynamics", Background Paper for 95th Dahlem Workshop (Berlin, January 2005), on "Dynamics of Fault Zones", for publication by MIT Press, submitted November 2004. http://esag.harvard.edu/rice/RiceCocco_toDahlemWrkshp04.pdf

Lapusta, N., and J. R. Rice, "Earthquake sequences on rate and state faults with strong dynamic weakening", *EOS Trans. Amer. Geophys. Union*, Fall Meet. Suppl., to appear, 2004.

Uenishi, K., and J. R. Rice, "Three-dimensional rupture instability on a slip-weakening fault under heterogeneous loading", *EOS Trans. Amer. Geophys. Union*, Fall Meet. Suppl., to appear, 2004.

Rice, J. R., "Heating and weakening of faults during seismic slip", manuscript in progress, 2004; for related presentation (at December 2004 Hubbert Quorum), available on web, see http://esag.harvard.edu/rice/Hubbert_Quorum_Dec04_therm.ppt

Progress

The recent work has addressed the possibility that primary physical mechanisms of strength loss on mature faults during seismic slip are thermal, and are due to

(1) *flash heating at microscopic friction-asperity contacts*

and to

(2) *thermal pressurization of pore fluids within the ultracataclastic fault core.*

These are now addressed in turn.

(1) *Flash heating and weakening of micro-asperity contacts:* Shear strength τ_c at the microscopic friction-asperity contacts is very high (estimated to be of order 0.1 x shear modulus μ) at contacts in typical rock systems, and thus when forced to shear, they generate intense but highly localized heating during their limited lifetime, which is of order D/V (here D is the slip needed to renew the asperity contact population, and V is slip rate). If slip is fast enough, the significantly heated zone is just a thin (relative to contact diameter) region adjoining the contact. The contact's shear strength is diminished by temperature increase, but because the affected zone is thin, the capacity of the contact to support normal stress, and also the net area of contact, are not much affected. Thus the friction coefficient reduces with slip rate V. An elementary first model (Rice, 1999) considers contacts of uniform size D, hence lifetime D/V, and assumes that their shear strength remains at the low-temperature value τ_c until temperature has reached a

weakening value T_w, above which shear strength is taken to be zero. (Their temperature rise is estimated from a simple one-dimensional heat conduction analysis, with heating rate $\tau_c V$ per unit area at the sliding contact interface. The modeling thus identifies a critical slip rate V_w, such that there is no weakening if $V < V_w$, but strong weakening if $V > V_w$. That is, the friction coefficient f (precisely, a *steady state* friction coefficient at slip rate V), which has the value f_o at low slip rates, is given in this simple model by

$$f = f_o \text{ if } V < V_w \,, \quad f = f_o \frac{V_w}{V} \text{ if } V > V_w \,; \quad \text{here } V_w = \left(\frac{\pi\alpha}{D}\right)\left[\frac{\rho c\left(T_w - T_f\right)}{\tau_c}\right]^2$$

where α is thermal diffusivity, ρc is heat capacity per unit volume and T_f is the average temperature of the fault surface; T_f increases gradually due to the heat streaming in at the sliding contacts. [Beeler and Tullis (2003) assume that some low contact strength is retained at $T > T_w$ and modify the latter to $f = f_w + f_o V_w / V$ where $f_w < f_o$.] Tullis and Goldsby (2003) and Rice (1999) have estimated V_w to range from 0.1 to 0.5 m/s, when it is recognized that $\tau_c \sim 0.1\mu$. Since the average slip rate in an earthquake is thought, from seismic slip inversions (Heaton, 1990) to be of order 1 m/s, the theoretical expectation is that f is reduced significantly from its low speed value f_o during seismic slip. Laboratory experiments imposing rapid slip (Tsutsumi and Shimamoto, 1997; Hirose and Shimamoto, 2004; Tullis and Goldsby, 2003; Prakash, 2004) are indeed consistent which such an anticipated friction reduction at higher V. The results suggest the possibility that f of order 0.2 to 0.3 may prevail at average seismic slip rates for rocks whose normal f is of order 0.6 to 0.7. The weakened f implies a slower heating rate, i.e., that more slip is needed to achieve a given temperature change. When combined with the next thermal weakening mechanism, that leads to effective values of the slip-weakening parameter D_c (see later) which may reach a size ~0.2 m (Rice, 2004).

(2) ***Thermal pressurization of pore fluid:*** This mechanism (Sibson, 1973; Lachenbruch, 1980; Mase and Smith, 1985, 1987) assumes that fluids (water, typically) are present within the fault gouge which shears, and that the shear strength τ during seismic slip can still be represented by the classical effective stress law $\tau = f(\sigma_n - p)$, where σ_n is normal stress and p is pore pressure. Frictional heating then would cause the fluid, if it was unconstrained, rather than caged by the densely packed solid particles, to expand in volume much more than would the solid cage. Thus, unless shear-induced dilatancy of the gouge cage overwhelms the thermal expansion effect, or unless the gouge is highly permeable, a pressure increase must be induced in the pore fluid. Since σ_n typically remains constant during slip, that means that strength τ is reduced, ultimately towards zero, as shear heating continues to raise temperature so that p approaches σ. Calculations done in our recent work have evaluated this mechanism using permeability and poroelastic properties based on properties of the Median Tectonic Line fault (Wibberley, 2002; Wibberley and Shimamoto, 2003), Nojima fault (Lockner et al, 2000). Here is discussed the case of slip on a mathematical plane in a porous fluid-saturated material, an idealization that is appropriate when the zone of a shear is thin compared to transport distances during the event. Such seems well justified by the recent studies of the Punchbowl fault (Chester and Chester, 1998; Chester et al., 2003; Chester and Goldsby, 2003); there, a 1 mm thick zone experiences high shear but the most intense shear is actually localized over thicknesses of order 0.1 mm

within it. That localized shear takes place within a finely granulated (ultracataclastic) fault core of 10s to 100s mm thickness.

The analysis for slip at speed V on the fault plane $y = 0$ (zero thickness shear zone) in a poroelastic solid under constant normal stress σ_n is as follows: With standard simplifications of the equations of energy and fluid mass conservation, the fluid pore pressure p and temperature T satisfy:

$$\text{In } |y| > 0 \,, \quad \frac{\partial T}{\partial t} = \alpha_{th} \frac{\partial^2 T}{\partial y^2} \quad \text{and} \quad \frac{\partial p}{\partial t} - \Lambda \frac{\partial T}{\partial t} = \alpha_{hy} \frac{\partial^2 p}{\partial y^2} \,,$$

$$\text{with conditions on } \; y = 0^{\pm} \,, \quad -\rho c \alpha_{th} \frac{\partial T}{\partial y} = \pm \frac{1}{2} f(\sigma_n - p) V \quad \text{and} \quad \frac{\partial p}{\partial y} = 0 \,.$$

Here α_{th} and α_{hy} are the respective thermal and hydraulic diffusivities, Λ is the value of dp/dT under undrained conditions, and ρc is the specific heat per unit mass. These can be solved for the case of constant V and f, and when the solution is written in terms of slip δ (= Vt), the p and T on the fault plane $y = 0$ are (Rice, 2004)

$$p - p_o = (\sigma_n - p_o)\left[1 - \exp\left(\frac{\delta}{L^*}\right)\operatorname{erfc}\left(\sqrt{\frac{\delta}{L^*}}\right)\right] \,, \quad T - T_o = \left(1 + \sqrt{\frac{\alpha_{hy}}{\alpha_{th}}}\right)\frac{p - p_o}{\Lambda} \,,$$

$$\text{where} \quad L^* = \frac{4}{f^2}\left(\frac{\rho c}{\Lambda}\right)^2 \frac{\left(\sqrt{\alpha_{hy}} + \sqrt{\alpha_{th}}\right)^2}{V} \,,$$

and where p_o and T_o are the initial values; T_o would be the ambient temperature but, if we sensibly assume that the onset of shear should be associated with some inelastic dilatancy of material near the fault zone, inducing a sudden suction in it (Segall and Rice, 1995), then p_o should be assumed to be reduced from the ambient value by that suction. The shear stress transmitted across the fault plane is thus predicted to be

$$\tau = f(\sigma_n - p) = f(\sigma_n - p_o)\exp\left(\frac{\delta}{L^*}\right)\operatorname{erfc}\left(\sqrt{\frac{\delta}{L^*}}\right) \qquad (1).$$

This shows continued weakening at an ever-decreasing rate over a very broad range of size scales, as shown in Figure 1. How large is L^*? Lachenbruch (1980) gives $\rho c \approx 2.7$ MPa/ºC and $\alpha_{th} \approx 1.0$ mm^2/s. Supplementing his data set by results from Wibberley (2002) and Wibberley and Shimamoto (2003) for gouge from the central slip zone of the Median Tectonic Line at 130 MPa effective confining stress (≈ effective overburden at 7 km depth, for hydrostatic pore pressure), with porosity 0.04 (Wibberley, private communication, 2003), gives $\Lambda \approx 0.8$ MPa/ºC and $\alpha_{hy} \approx 1.8$ mm^2/s, using a permeability of 10^{-20} m^2 from their data. That gives, with $V = 1$ m/s and $f = 0.25$ to allow for flash heating, $L^* = 4$ mm. That estimate directly uses lab data on relatively undisturbed samples, whereas in the natural situation there may be initial dilatant deformation and damage near the rupture front (e.g., Poliakov et al., 2002) at the start of shear. As guesses as to how such effects might change parameters, a tenfold greater permeability, 10^{-19} m^2, and doubled pressure-expansivity of the pore space (making $\Lambda \approx 0.5$ MPa/ºC and $\alpha_{hy} \approx 12$ mm^2/s), would instead give $L^* = 33$ mm. Thus the upper right panel in Figure 1 could correspond to a maximum slip ($\delta / L^* = 1$) between 4 and perhaps 30 mm, and the lower right

panel to maximum slip ($\delta / L^* = 100$) between 0.4 and 3 m. It is interesting that the multiscale nature of the slip-weakening shown in figure 1 is similar in character to what Abercrombie and Rice (2004; their Figure 9) inferred by their analysis of seismic data.

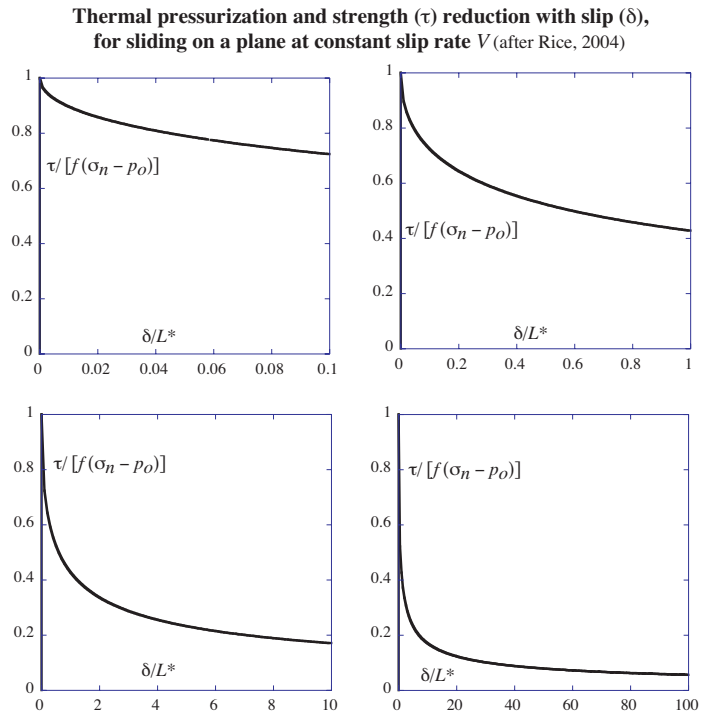


Figure 1: Multiscale nature of slip-weakening implied by thermal pressurization.

The substantial weakening by thermal pressurization, together with the fact that f is much lower than static friction due to flash heating, means that, despite the extreme localization of shear, strength loss over all but deeper portions of crustal seismogenic zones is generally too rapid for melting to take place. That seems consistent with conclusions that fault zone pseudotachylytes of tectonic earthquake origin have generally formed deep in the seismogenic zone.

The fracture energy G associated with an event with slip δ may be calculated from a slip-weakening function $\tau = \tau(\delta)$ by $G = G(\delta) = \int_0^{\delta} [\tau(\delta') - \tau(\delta)] d\delta'$, that definition (Abercrombie and Rice, 2004) generalizes Palmer and Rice (1973) to forms of $\tau(\delta)$ for which weakening continues at an ever-decreasing rate to slips greater than that in the event. Then, for the above $\tau(\delta)$, there results (Rice, 2004)

$$G(\delta) = f(\sigma_n - p_o) L^* \left[\exp\left(\frac{\delta}{L^*}\right) \operatorname{erfc}\left(\sqrt{\frac{\delta}{L^*}}\right)\left(1 - \frac{\delta}{L^*}\right) - 1 + 2\sqrt{\frac{\delta}{\pi L^*}} \right]$$

That is plotted as the solid lines in Figure 2 (Rice, 2004), for the low and high poromechanical estimates of L^* above, using $V = 1$ m/s, $f = 0.25$ as an approximate representation of flash heating (Hirose and Shimamoto, 2004; Prakash, 2004; Tullis and Goldsby, 2003), and $\sigma_n - p_o$ = 126 MPa (initial effective overburden at 7 km depth, a representative centroidal depth for slip during crustal events). Seismic data assembled recently by Abercrombie and Rice (2004) and, for the seven large events of Heaton (1990), by Rice et al. (2004) is also shown there. The seismic

data and theoretical modeling have many uncertainties, but the rough coincidence does lend credibility to the concept that flash heating together with thermal pressurization of pore fluid may be dominant processes in fault weakening during earthquakes.

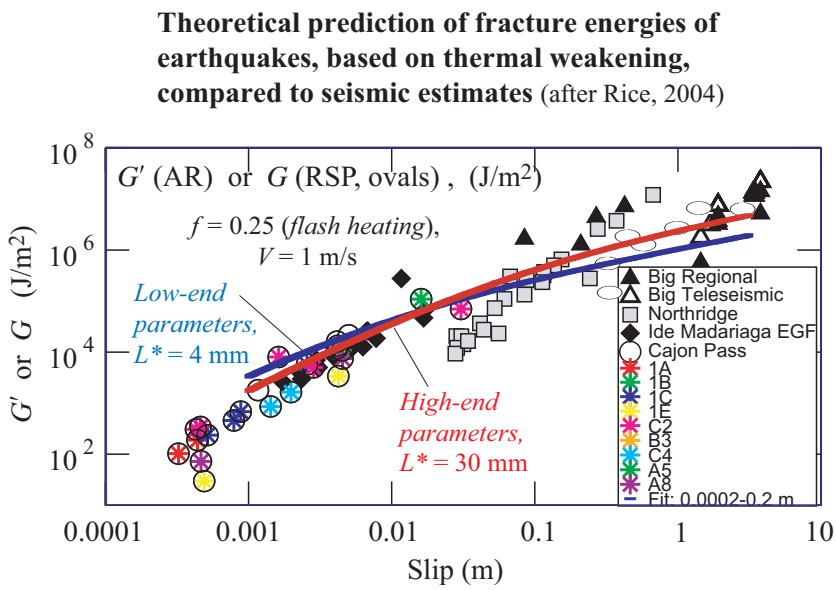
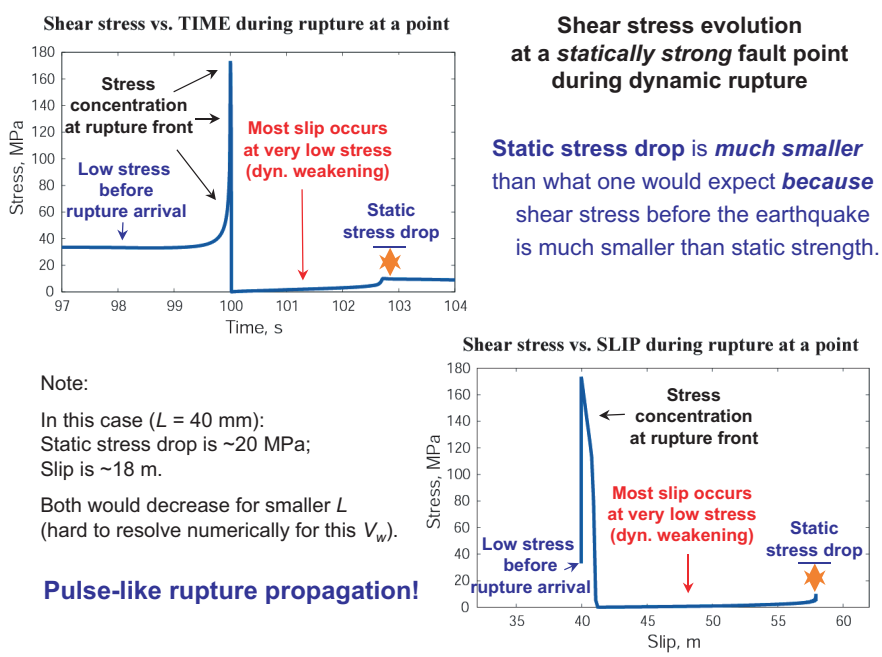


Figure 2: Theoretical prediction of G compared to seismic estimates

Related rupture dynamics studies: Work in progress, separately with Nadia Lapusta at Caltech (Lapusta and Rice, 2003, 2004) and graduate research assistant Harsha Bhat at Harvard is attempting to understand the consequences of laws of the type described, embodying extreme rate weakening (the flash heating effect on f) and weakening with accumulated slip (due to the ongoing thermally induced rise of pore pressure), for rupture dynamics. The figure below, from the Lapusta and Rice poster at the Annual Meeting, illustrates some of the physical and computational issues involved.