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Frictional weakening and shear heating induced thermal pressurization during earthquakes

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Fault strength, $\tau = f(\sigma - p)$ depends on f the friction coefficient, and effective normal stress, where σ is fault normal stress, and p is pore-fluid pressure. Much attention over the last 20 years has focussed on rate and state friction [e.g., *Ruina,* 1983; Dieterich, 1992] where the weakening occurs through changes in f. Theoretical analyses show that frictional weakening is crucial to the nucleation of unstable fault slip [Dieterich, 1992]. At the same time it has long been recognized that thermal weakening may play an important role in earthquake slip [*Sibson,* 1973; Lachenbruch, 1980; Mase and Smith, 1987; Andrews, 2002; Rice, 2006]. Frictional heating causes thermal expansion of pore-fluids which, if diffusion and dilatancy are limited, leads to an increase in pore-pressure and therefore a reduction in effective normal stress $(\sigma - p)$. *Lapusta and Rice* [2004] showed that shear heating may allow rupture propagation at low overall stress, even though the fault strength is compatible with normal coefficients of friction and ambient hydrostatic pore pressure. Stress concentrations at the rupture front are sufficient to initiate slip, yet the average stress doing work against fault slip is low, consistent with the absence of a thermal anomaly along the San Andreas fault.

Weakening due to thermal pressurization is limited by thermal diffusion (thermal diffusivity is well constrained for rock), pore-pressure diffusion (dependent on permeability, which varies widely for rocks), and dilatancy. Some workers have suggested that thermal effects are not important for earthquakes smaller than roughly magnitude 3 to 4 [*Andrews*, 2002; *Kanamori and Heaton*, 2000]. However, Segall and Rice [2006] suggest that thermal pressurization becomes the dominant weakening mechanism during the nucleation phase, well before seismic waves are radiated. Recent field and drill core observations indicate that mature strike-slip faults have a thin (< 1 mm) shear zone on which slip is concentrated, embedded within a narrow (~ 0.1 m) fault core with permeability of order 10^{-21} to 10^{-19}m^2 at effective stresses appropriate for earthquake nucleation [*Wibberley,* 2002; *Lockner et al,* 1999], surrounded by rock of variable but higher permeability. Segall and Rice [2006] showed that these permeabilities are sufficiently low that thermal pressurization overwhelms frictional weakening at slip speeds that are well below elastodynamic rates.

This suggest a paradigm in which frictional weakening controls quasi-static nucleation, but thermal weakening controls fault strength during dynamic earthquake slip. Thermal pressurization can also be mitigated by dilatancy, which acts to increase effective stress and can stabilize slip [Segall and Rice, 1995]. This then leads to the proposition that the difference between slow and fast slip may be whether or not dilatant strengthening stabilizes the rupture before thermal weakening mechanisms have a chance to weaken the fault (Segall and Rubin, 2007).

Laboratory results show that the frictional resistance depends on the instantaneous slip speed v and the past sliding history, which can be characterized by an internal state variable θ,

$$\tau = f(\sigma - p) = (\sigma - p)[f_0 + a \log \frac{v}{v_0} + b \log \frac{\theta v_0}{d_c}] \tag{1}$$

[*Ruina*, 1983]. The state is sometimes interpreted as the average asperity contact lifetime, and evolves over a characteristic displacement d_c. The proper mathematical description of state evolution has not been fully resolved (and may not be fully described by any simple analytical form), although two forms in wide use are

$$\frac{d\theta}{dt} = 1 - \frac{\theta v}{d_c} \quad \text{or} \quad \frac{d\theta}{dt} = -\frac{\theta v}{d_c} \ln\left(\frac{\theta v}{d_c}\right). \tag{2}$$

The first exhibits healing in stationary contact and is thus referred to as the "aging" law. In the second form friction changes only with slip ($\dot{\theta}$ vanishes when $v = 0$), so that it is referred to as the "slip law".

We employ the "radiation damping" approximation of inertial effects [Rice, 1993] such that the momentum balance becomes

$$\frac{\mu}{2\pi(1-\nu)} \int_{-\infty}^{\infty} \frac{\partial\delta/\partial\xi}{\xi - x} d\xi - f(v,\theta)(\sigma - p) = \frac{\mu}{2v_s} v \tag{3}$$

where the first term on left represents the elastic stress due to gradients in slip δ, (μ is the shear modulus), and the second is the frictional resistance. *Lapusta et al* [2000] show this "quasi-dynamic" formulation leads to a reasonable representation of dynamic slip, although maximum slip speeds and propagation rates are under-predicted relative to the full elastodynamic results.

Ruina [1983] showed that a spring-slider system is linearly unstable if the spring stiffness is less than a critical value $k_{crit} = (\sigma - p^{\infty})(b - a)/d_c$. In an elastic continuum, the effective stiffness of a slip patch decreases with increasing dimension of the slipping zone. This leads to a critical nucleation dimension, often referred to as h^*; to within a constant of order unity

$$h^* = \frac{d_c \mu/(1-\nu)}{(\sigma - p^{\infty})(b-a)}. \tag{4}$$

Dieterich (1992) followed by Rubin and Ampuero (2005; 2007) have studied slip nucleation on drained, isothermal faults in two dimensional elastic media. Rubin and Ampuero (2005), find that for the aging law and $a/b < 0.4$, nucleation takes the form of a fixed-length crack, with half-length $L_d \equiv 1.377 * \mu d_c/b(\sigma - p^{\infty})$. For $0.4 < a/b < 1$ slip first nucleates with half-length L_d, but then expands quasi-statically. For the slip-law the effective fracture energy cannot balance the increasing energy release rate, and quasi-static crack-like solutions fail to exist. Numerical simulations instead show that slip-law nucleation occurs as a single-sided slip pulse.

To investigate the role of dilatancy and shear heating in slow slip events we consider coupled friction, elasticity, dilatancy, along with heat, and pore-fluid flow. Neglecting transport parallel to the fault, and assuming that the thickness of the actively deforming zone is small,

$$\frac{\partial T}{\partial t} = c_{th} \frac{\partial^2 T}{\partial y^2} \qquad \left.\frac{\partial T}{\partial y}\right|_{y=0} = -\frac{\tau v}{2c\rho c_{th}} \tag{5}$$

[e.g., Rice, 2006], where c is specific heat capacity and c_{th} is thermal diffusivity. The boundary condition balances the rate of heat production on the fault plane, $y = 0$, with conduction away from the fault. Similarly, pore pressure satisfies

$$\frac{\partial p}{\partial t} = \frac{1}{\eta\beta\phi} \frac{\partial}{\partial y}\left(\kappa \frac{\partial p}{\partial y}\right) + \Lambda \frac{\partial T}{\partial t} - \frac{1}{\beta}\frac{d\phi}{dt} \qquad \left.\frac{\partial p}{\partial y}\right|_{y=0} = 0 \tag{6}$$

where Λ is a thermal coupling parameter, dependent on the ratio of thermal expansivity to compressibility, η is fluid viscosity, β compressibility of the fluid and pores, κ is permeability, ϕ is porosity, and $d\phi/dt$ the inelastic change in porosity [Rice, 2006; Segall and Rice, 2006]. Note that temperature changes and dilatancy act as a fluid pressure sources and sinks, respectively. For spatially uniform permeability, the transport term can be written in terms of the hydraulic diffusivity $c_{hy} = \kappa/\eta\phi\beta$.

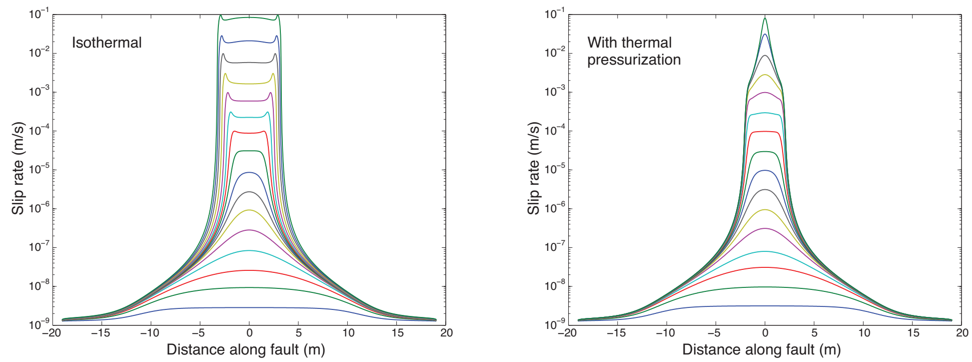

Figure 1: Slip-rate profiles at different snapshots in time comparing isothermal case (left) with thermal pressurization (right). Aging law, $a/b = 0.8, a = 0.015, d_c = 100\mu$m, and $\sigma - p^{\infty} = 140$ MPa. $c_{hyd} = 8 \times 10^{-6}$ m^2/s.

We have investigated earthquake nucleation including the effects of thermal pressurization, but excluding dilatancy (Schmitt et al, 2007). These computations were done by modeling thermal diffusion using finite difference methods. If the thermal and fluid transport properties are spatially uniform, we take advantage of an analytical result from Rice [2006], which uniquely relates the temperature and pore pressure on the fault

$$T(0,t) - T_0 = \left(1 + \sqrt{\frac{c_{hy}}{c_{th}}}\right) \frac{p(0,t) - p_0}{\Lambda}. \tag{7}$$

This eliminates the need to compute pore pressure using finite difference, and leads to a factor of two decrease in computation time. This shortcut is not available when the properties (e.g., permeability) vary with distance from the fault, if dilatancy is included, or if the shear zone has finite thickness.

A significant part of our effort in developing the two-dimensional code has been to make the finite difference computations as efficient as possible. With order 10^3 to 10^4 grid points on the fault, and order 10^2 points in the finite difference grid perpendicular to the fault, the number of variables becomes quite large. A substantial savings is found by adapting the finite difference mesh to the rate of heat generation on the fault. When the fault slips slowly the mesh must extend an appropriate distance from the fault in order to capture the induced temperature changes. As slip accelerates the rate of heat production increases, and the temperature gradients adjacent to the fault steepen, necessitating a finer mesh near the fault. At the same time the temperature far from the fault does not change significantly during the short period of fast slip. We implement a remeshing scheme that tracks the leading order term neglected in the finite difference approximation to the second derivative of the temperature. When this term is no longer negligible we refine the mesh. The temperature is interpolated onto the refined mesh in such a way that both the temperature on the fault $T(y = 0, t)$ and its time derivative $\dot{T}$ are continuous in time.

Figure 1 compares results for the aging law with and without the effects of thermal pressurization. Slip initially nucleates in a zone of length $2L_d$. In the isothermal case the nucleation zone expands quasi-statically with nearly constant stress in the interior of the crack, as found by Rubin and Ampuero (2005). With thermal pressurization included however, the velocity distribution begins to diverge from the isothermal solution at slip speeds of $\sim 10^{-4}$ m/s, and rather than spreading, the nucleation zone contracts. The rate of heat-production increases as the center of the fault accelerates, leading to thermal pressurization and additional weakening.

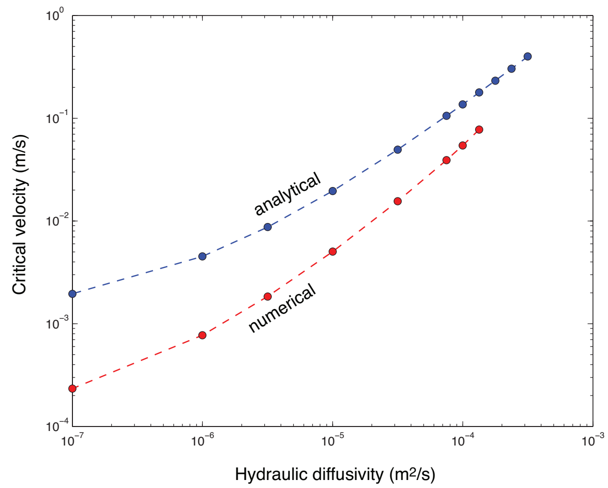

Figure 2: Comparison of analytical (8) and numerical estimates of v_{crit}, the critical slip speed beyond which thermal pressurization dominates over frictional weakening. $d_c = 100\mu$m, $\sigma - p^{\infty} = 140$ MPa, and $a/b = 0.8$.

Segall and Rice [2006] defined a critical velocity v_{crit} as the slip speed at which $-f_0 \partial p/\partial t$, the rate of thermal weakening, exceeds the rate of frictional weakening $\partial f/\partial t(\sigma - p^{\infty})$. For a planar fault bounding uniform half-spaces, the rate of thermal pressurization was computed with aging law friction and spring-slider elasticity, neglecting the feedback between pore-pressure and fault strength (the latter valid only early in the nucleation process), leading to a critical velocity

$$v_{crit} = \frac{1}{\pi d_c} \left[\frac{4(b-a)\rho c_v (\sqrt{c_{th}} + \sqrt{c_{hyd}})}{\mu_0^2 \Lambda} \right]^2 . \tag{8}$$

Figure 2 compares the numerically estimated v_{crit} with that determined by (8) over a wide range of hydraulic diffusivities. Note first that thermal pressurization becomes the dominant weakening mechanism well before the fault reaches seismic slip rates for $c_{hyd} < 10^{-4}$. For parameters and effective normal stress chosen (see caption) v_{crit} is less than 1 mm/s for c_{hyd} of 1 mm^2/s. While the analytical approximation overestimates v_{crit}, it does predict the dependence on c_{hyd} reasonably accurately.

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