2006 SCEC Final Report
Frictional weakening and shear heating induced thermal pressurization during earthquakes

Paul Segall
Stanford University Geophysics Department

June 29, 2007

Earthquake nucleation and unstable fault slip requires a loss of frictional strength $\tau = \mu(\sigma - p)$ with slip or slip rate, where τ is shear strength, μ is friction coefficient, σ is fault normal stress and p is pore pressure. Friction μ is understood to vary with rate and slip history [*Ruina,* 1983]. Pore pressure varies with slip due to dilatancy and pore compaction. In addition, shear heating increases p and, if dilatancy and pore pressure diffusion are limited, will cause τ to decrease [*Sibson,* 1973; Lachenbruch, 1980]. There is still a great deal of uncertainty about the importance of these effects. *Kanamori and Heaton* [2000] stated that "A modest ΔT of 100-200 °C would likely increase the pore pressure enough to significantly reduce friction for earthquakes with M_w =3 to 4". *Andrews* [2002] estimates a transition from slip weakening to shear heating for events of M_w 3.5, assuming hydraulic diffusivities of 0.02 m^2/s.

We have studyied how frictional weakening, shear heating, and the flow of pore fluid and heat together govern the spatial and temporal evolution of fault slip. Field and drill core observations indicate that mature faults have a thin ($<$ 1 mm) shear zone on which slip is concentrated, embedded within a narrow ($\sim$ 0.1 m) fault core with permeability of order 10^{-21} to 10^{-19}m^2 [*Wibberly,* 2002; *Lockner et al,* 1999], surrounded by rock of variable but higher permeability. For these permeabilities fluid (and heat) flow is sufficiently rapid to suppress instability due to shear heating for faults that are frictionally stable [*Segall and Rice,* 2006]. For frictionally unstable faults, as slip rates increase the rate of pore pressure generation eventually exceeds the rate at which heat and pore pressure dissipate due to flow. At this point fault strength drops rapidly. Approximate analytical results suggest that this occurs at slip speeds of $\sim$ 1 mm/s, for typical parameters [Segall and Rice, 2006; see below]. *Rice* [2006] has recently shown that earthquake fracture energies estimated from seismic observables are consistent with shear heating induced thermal pressurization. These two results suggest a paradigm in which frictional weakening controls quasi-static nucleation, but thermal weakening processes control fault strength during dynamic earthquake slip.

Although shear heating alone can not nucleate slip, given permeabilities inferred from recent field and laboratory studies (Segall and Rice, 2006), thermal effects become increasingly important as the slip speed increases. Segall and Rice (2006) estimate the slip speed at which the rate of thermal weakening $-\mu\dot{p}$ exceeds the rate of frictional weakening $\dot{\mu}(\sigma - p)$ for a planar fault bounding uniform half-spaces. This leads to a critical velocity beyond which the fault is weakening faster due to thermal pressurization than by frictional processes,

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

For $d_c \sim 10 \rightarrow 100\mu$m and hydraulic diffusivity $c_{hyd} \sim 1 \rightarrow 10 \times 10^{-6} m^2/s$, $b - a = 4 \times 10^{-3}$, $\rho c_v/\Lambda \sim 1 \rightarrow 3$, we find v_{crit} of $.01 \rightarrow 10$ mm/s. Note that: a) this is at least an order of magnitude less than slip speeds during earthquakes, so that thermal pressurization effects should be important even for small earthquakes, and b) the time it takes the fault to accelerate from order 1 mm/s to seismic rates is of order d_c/v or less, which is $\sim 0.1s$ or less. This implies that time to failure and seismicity rate variations based on rate-state friction alone (e.g.*Dieterich* [1994]) are valid.

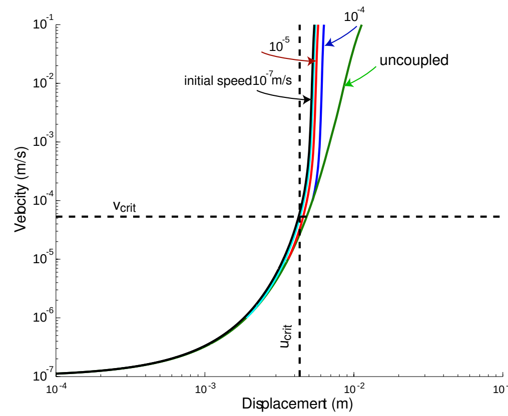

Figure 1: Slip speed and displacement for different initial velocities compared to the uncoupled (no pore-pressure feedback on strength) model. The coupled solutions diverge from the uncoupled result near v_{crit} given by (1). Note that these calculations use $d_c = 0.01$m so that they underestimate v_{crit} in nature.

We address the fully coupled diffusive, elastic, frictional system with fluid and heat transport limited to the fault perpendicular (y-) direction. For slip in the fault parallel (x-) direction, the governing equations are

$$\begin{aligned}
\frac{\partial T}{\partial t} &= c_h \frac{\partial^2 T}{\partial y^2} + \frac{\tau v}{\rho c_v h} \\
\frac{\partial p}{\partial t} &= \frac{1}{\nu\beta}\frac{\partial}{\partial y}\left(\kappa \frac{\partial p}{\partial y}\right) + \Lambda \frac{\partial T}{\partial t} \\
\tau &= (\sigma - p)[\mu_0 + a \log\frac{v}{v_0} + b \log\frac{\theta}{\theta_0}] = \tau^\infty + k(m)u - \frac{G}{2v_s}v \\
\frac{d\theta}{dt} &= 1 - \frac{\theta v}{d_c} \quad \text{or} \quad \frac{d\theta}{dt} = -\frac{\theta v}{d_c}\log\left(\frac{\theta v}{d_c}\right) \\
\phi &= \phi_0 - \varepsilon \ln \frac{v_0 \theta}{d_c}
\end{aligned} \tag{2}$$

where the variables are shear stress τ, slip u, slip velocity $v = \partial u/\partial t$, state θ, inelastic pore volume ϕ, pore pressure, p, and temperature T, and k is a wavenumber, m, dependent stiffness. The shear stress on the fault is the sum of three contributions, τ^{∞} is the loading stress, the stress interaction term $k(m)u$, and a "radiation damping" term, roughly accounting for dynamic effects.

We have adapted a finite difference scheme for the coupled pore-fluid and thermal transport equations. The time stepping is implemented through a Matlab ODE solver. We have made several advances that greatly improve solution efficiency while retaining sufficient numerical accuracy. During the "locked" interseismic phase, frictional heat production is balanced by conduction from the fault; it is therefore not necessary to compute the temperature and pore pressure fields. We initiate the finite difference calculations when the fault slip rate becomes some fraction of v_{crit} and assume a constant temperature gradient that balances the heat flux from the fault. Figure 1 demonstrates that starting the calculation at yet lower velocities does not alter the behavior. As the slip-rate increases the temperature increase becomes more localized near the fault. We keep track of the correction terms to the temperature and pore-pressure at the fault, and re-mesh to a finer grid when the corrections become significant. After the earthquake, as the temperature and pore- pressure gradients diminish, we revert to the coarser grid, until $|\mu\dot{p}|$ becomes small compared to $|\dot{\mu}(\sigma - p)|$, and the finite difference computation is suspended until the next earthquake nucleation. In this way we can compute the behavior over the full earthquake cycle. For uniform properties the pore-pressure on the fault is uniquely determined by the temperature on the fault (Rice, 2006) vastly speeding up the calculations.

Rice (2006) gives the solution for slip between two half- spaces with uniform properties, constant coefficient of friction μ_c and constant slip speed v_c. Full coupling of the thermal and pore pressure fields and friction, through the effective normal stress, is included. The frictional resistance on the fault depends only on displacement $D = \delta/L^*$ as

$$\tau = \mu_c(\sigma_n - p_0)\exp(D)\mathrm{erfc}(\sqrt{D}) \tag{3}$$

where the effective slip weakening distance L^* depends only on material parameters and slip speed

$$L^* = \frac{4}{\mu_c^2 v_c}\left(\frac{\rho c_p}{\Lambda}\right)^2 \left(\sqrt{c_{hy}} + \sqrt{c_{th}}\right)^2 \tag{4}$$

The associated temperature distribution is given by

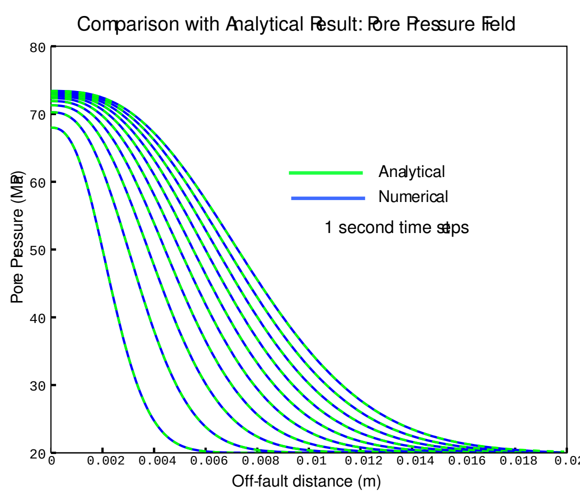

Figure 2: Comparison between numerical and analytical pore-pressure distribution for the case of constant friction coefficient and constant slip speed, equation (6).

$$T(y,t) - T_0 = \left(1 + \sqrt{\frac{c_{hy}}{c_{th}}}\right)\left(\frac{\sigma_n - p_0}{\Lambda}\right)\left[\mathrm{erfc}\left(\frac{Y}{2\sqrt{D}}\right) - \exp(Y + D)\mathrm{erfc}\left(\frac{Y}{2\sqrt{D}} + \sqrt{D}\right)\right] \tag{5}$$

where $Y = |y|/\sqrt{c_{th}L^*/v_c}$. The pore-pressure field is

$$\frac{p(y,t)-p_0}{\sigma_n - p_0} = \frac{\sqrt{c_{th}}+\sqrt{c_{hy}}}{c_{hy}-c_{th}}\left\{\sqrt{c_{hy}}\left[\mathrm{erfc}\left(\frac{Y'}{2\sqrt{D}}\right) - \exp(Y'+D)\mathrm{erfc}\left(\frac{Y'}{2\sqrt{D}}+\sqrt{D}\right)\right] - \sqrt{c_{th}}\left[\mathrm{erfc}\left(\frac{Y}{2\sqrt{D}}\right) - \exp(Y+D)\mathrm{erfc}\left(\frac{Y}{2\sqrt{D}}+\sqrt{D}\right)\right]\right\} \quad (6)$$

where $Y' = |y|/\sqrt{c_{hy}L^*/v_c}$.

We compare the numerical solution to Rice's (2006) analytical result for constant coefficient of friction and slip speed. The shear strength as a function of displacement (not shown) is in extremely good agreement except at very small displacement. Because the analytical result posits a step function in velocity, the fault weakens with infinite slope ($\partial\tau/\partial\delta$), which cannot be tracked numerically. The pore pressure distribution is also in excellent agreement with the analtyical result (Figure 2).

In Figure 3 we show the results for the fully coupled case. Elasticity is approximated by a single degree of freedom spring-slider system. The fault is initially sliding at a slip-rate of 10^{-7} m/s with initial stress sufficiently high that the fault accelerates toward instability. As the fault accelerates thermal pressurization becomes significant, increasing both the peak slip rate and coseismic slip substantially compared to the case when thermal feedback effects are neglected. Temperature increases (not shown) are limited to a few hundred degrees in the coupled case, but easily reach melting in the uncoupled case.

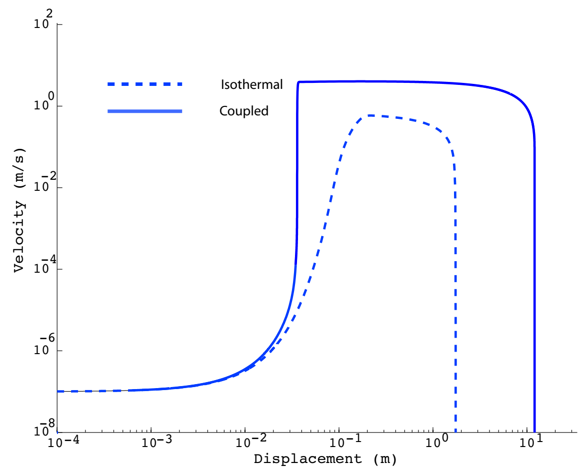

Figure 3: Solution for a single degree of freedom elastic system with thermal and pore pressure transport normal to the fault. Dashed line shows the uncoupled result, while solid line shows the fully coupled frictional result. Both calculations employ the radiation damping approximation.

SCEC Publications

Matsuzawa, T. and P. Segall, Numerical simulation of the transition from frictional weakening to thermal pressurization during earthquakes, Eos Trans. AGU, 87(52), Fall Meet. Suppl., Abstract S42A-01, 2006.

References

[1] Andrews, D.J., A fault constitutive relation accounting for thermal pressurization of pore fluid, *J. Geophys. Res. 107*, doi:10.1029/2002JB001942, 2002.

[2] Dieterich, J. H., A constitutive law for rate of earthquake production and its application to earthquake clustering, *J. Geophys. Res., 99*, 2601-2618, 1994.

[3] Kanamori, H., and T. H. Heaton, Microscopic and macroscopic physics of earthquakes, AGU Monograph Series, "Physics of Earthquakes", J. B. Rundle, D. L. Turcotte, and W. Klein, Eds., 147-163, 2000.

[4] Lachenbruch, A. H., Frictional heating, fluid pressure, and the resistance to fault motion, *J. Geophys. Res., 85*, 6097-6112, 1980.

[5] Lockner, D.A., H. Naka, H. tanaka, H. Ito and R. Ikeda, Permeability and strength of core samples from the Nojima Fault of the 1995 Kobe earthquake *in Proceedings of the International Workshop on the Nojima Fault core and Borehole Data Analysis, Tsukuba Japan, 22-23 November, 1999* edited by H.Ito, K. Fujjimoto, H. Tanaka, and D. Lockner, U.S. G.S. Open Filte Rep 00-129, 147-152, 1999.

[6] Rice, J.R., Heating and weakening of faults during earthquake slip, *J. Geophys. Res,*, 111, B05311, doi:10.1029/2005JB004006, 29 pages, 2006.

[7] Ruina, A., Slip instability and state variable friction laws, *J. Geophys. Res., 88,* 10,359-10,370, 1983.

[8] Segall, P. and J. R. Rice, Does shear heating of pore fluid contribute to earthquake nucleation? *J. Geophys. Res,* 111, , B09316, doi: 10.1029/2005JB004129, 17 pages, 2006.

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

[10] Wibberly A.J., Hydraulic diffusivity of fault gouges and implictions for thermal pressurization during seismic slip, *Earth Planets Space 54,* 1152-1171, 2002.