Earthquake nucleation with thermal pressurization: aging law and slip law

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INTRODUCTION

For decades, researchers have considered shear heating-induced thermal pressurization as a potential dynamic weakening mechanism during earthquakes. In this hypothesis, shear heating pressurizes the pore fluid faster than it can diffuse away, thereby reducing the effective normal stress on the fault.

Segall & Rice [JGR, 2006] suggested that thermal effects may become dominant during the quasi-static nucleation phase, which is usually modeled using isothermal rate- and state-dependent friction. Using the simple slip history predicted by "aging law" rate/state friction—along with reasonable estimates of heat and pore pressure transport parameters—they estimated that thermal pressurization dominates frictional weakening at slip rates in excess of 10^{-5} to 10^{-3} m/s.

In the last few years, we have explored that problem further by performing numerical simulations of earthquake nucleation using fully coupled elasticity, friction, and heat/fluid transport. We confirmed the *Segall-Rice* [2006] hypothesis and observed an interesting behavior in the nucleation zone—that the nucleation zone shrinks as slip accelerates.

Thermal pressurization is effectively a slip weakening mechanism that feeds back into itself, and therefore rapidly dominates in the center of an aging law nucleation zone, where the most slip occurs. This effect leads to dramatic along-strike localization of the nucleation zone at its midpoint (see **Figure 1**).

With the slip (logarithmic) friction evolution law, however, nucleation is pulse-like. That is, the fastest-slipping portion of the nucleation zone propagates unidirectionally, with velocity decaying behind [*Ampuero & Rubin*, JGR, 2008]. Under this regime, the relative importance of thermal pressurization is diminished since most of the frictional weakening occurs in locations with limited amounts of slip. In the present work, we explore in detail the effect of thermal pressurization on slip law earthquake nucleation.

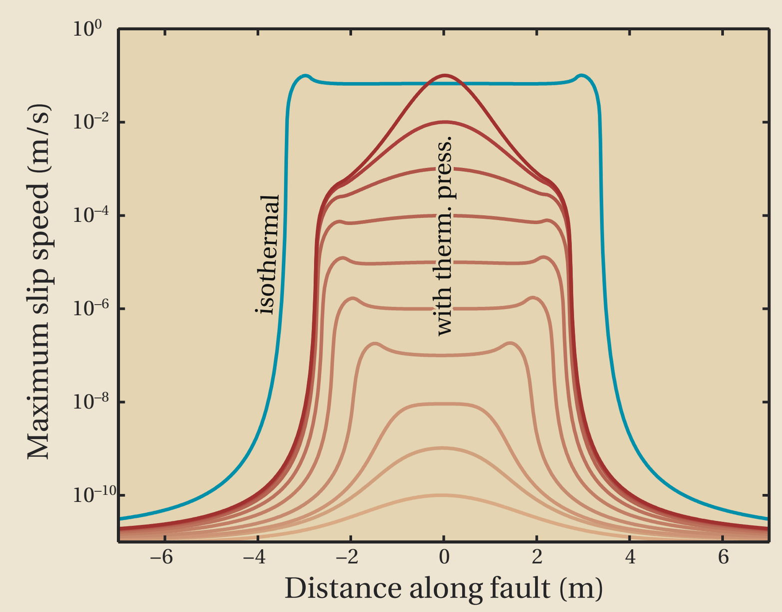
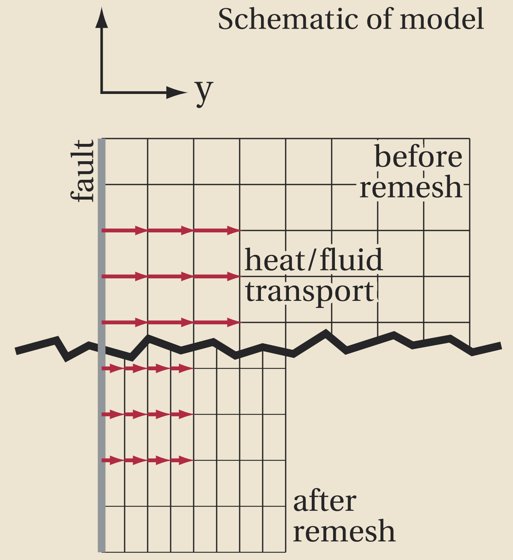


Figure 1. The effect of thermal pressurization on aging law nucleation. Lines are snapshots of slip speed on the fault. In red, snapshots for every 10-fold increase in v_{max} are shown for nucleation with thermal pressurization. The nucleation zone starts as a growing crack, then shrinks. For comparison, the isothermal profile for $v_{max} = 10^{-1}$ m/s is shown in blue; crack growth continues in this case.

Figure 2. Schematic of model



DESCRIPTION OF MODEL

- 2D finite difference diffusion grid.
- Shear heating included as a boundary condition (zero thickness shear zone).
- Diffusion away from fault only.
- Grid refinement as accuracy demands.
- Stress rate and slip rate related through a Hilbert transform in the Fourier domain.
- Driven by constant remote stress rate.
- Started below steady state ($v\theta/d_c < 1$), with a small span at slightly higher v to influence location of nucleation.

GOVERNING EQUATIONS

A. Shear stress on the fault

Elastic stress interaction:

$$\tau_{\text{el}}(x) = -\frac{G}{2\pi}\int_{-\infty}^{\infty}\frac{1}{x-\xi}\frac{\partial u}{\partial \xi}\,d\xi\,. \tag{1}$$

Radiation damping approximation [*Rice*, JGR, 1993]:

$$\tau_{\text{rad}} = \frac{G}{2v_s}v\,. \tag{2}$$

Rate- and state-dependent friction:

$$\tau_{\text{fric}} = \left[\mu_0 + a\ln\frac{v}{v_0} + b\ln\frac{\theta v_0}{d_c}\right]\sigma_{\text{eff}}\,, \tag{3}$$

with the slip state evolution law and *Linker-Dieterich* [JGR, 1992] effect (necessary because p changes):

$$\frac{d\theta}{dt} = -\frac{\theta v}{d_c}\ln\frac{\theta v}{d_c} - \frac{\alpha\theta}{b\sigma_{\text{eff}}}\frac{d\sigma_{\text{eff}}}{dt}\,. \tag{4}$$

Together, (1)–(4) form the equation of motion

$$\tau_{\text{el}} - \tau_{\text{fric}} - \tau_{\text{rad}} = 0\,. \tag{5}$$

We take the time derivative of (5) to form a system of coupled ODEs, which we numerically integrate to determine v, θ, p, and T.

B. Generation/transport of heat and pore pressure

Thermal diffusion and shear heating on the fault:

$$\frac{\partial T}{\partial t} = c_{\text{th}}\frac{\partial^2 T}{\partial y^2} \quad\text{and}\quad \left.\frac{\partial T}{\partial y}\right|_{y=0} = -\frac{\tau v}{2\rho c_v c_{\text{th}}}\,. \tag{6}$$

Pore pressure generation and transport:

$$\frac{\partial p}{\partial t} = c_{\text{hyd}}\frac{\partial^2 p}{\partial y^2} + \Lambda\frac{\partial T}{\partial t} \quad\text{with}\quad \Lambda = \frac{\Lambda_f - \Lambda_\phi}{\beta_f + \beta_\phi}\,. \tag{7}$$

GOVERNING EQUATIONS (CONTINUED)

If the thermal and hydraulic transport properties are uniform, then the pore pressure and temperature change on the fault are uniquely related through [*Rice*, JGR, 2006]

$$\Delta p(y=0) = \frac{\Lambda}{1+\sqrt{c_{\text{hyd}}/c_{\text{th}}}}\Delta T(y=0)\,. \tag{8}$$

C. When is thermal pressurization important?

The time derivative of (3) is

$$\frac{d\tau_{\text{fric}}}{dt} = \underbrace{\frac{d\mu}{dt}(\sigma - p_0)}_{\text{friction}} - \underbrace{\mu_0\frac{dp}{dt}}_{\text{thermal pressurization}}\,. \tag{9}$$

We define the critical velocity v_{crit} to be when the thermal pressurization term in (9) is larger than the friction term in the area of the fault that has undergone any sort of weakening.

Nominal parameters in this study

G	shear modulus	10 GPa
μ_0	nominal friction	0.6
v_s	s-wave velocity	3700 m/s
σ_{eff}	nominal eff. stress (σ–p_0)	140 MPa
α	coeff. of $\dot\sigma$ effect on θ	0.6
a	friction velocity effect	0.012
b	friction state effect	0.015
d_c	slip weakening distance	100 μm
c_{th}	thermal diffusivity	10^{-6} m^2/s
c_{hyd}	hydraulic diffusivity	10^{-6} m^2/s
ρc_v	density × heat capacity	2.86 MPa/°C
Λ	thermal coupling param.	0.8 MPa/°C
θ	frictional state	
v	slip speed	
T	temperature (change)	
p	pore pressure (change)	
σ	normal stress	
λ_f	pore fluid expansivity	
λ_ϕ	pore expansivity	
β_f	pore fluid compressibility	
β_ϕ	pore compressibility	

RESULTS

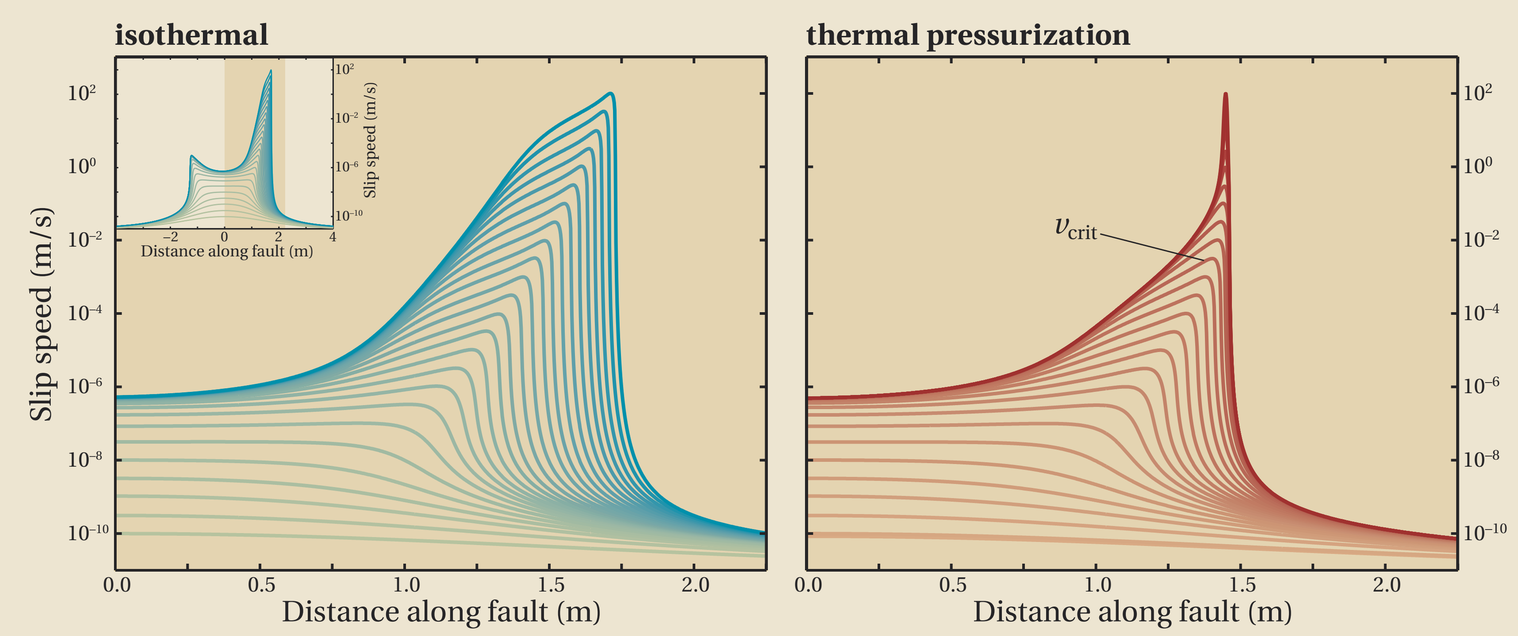
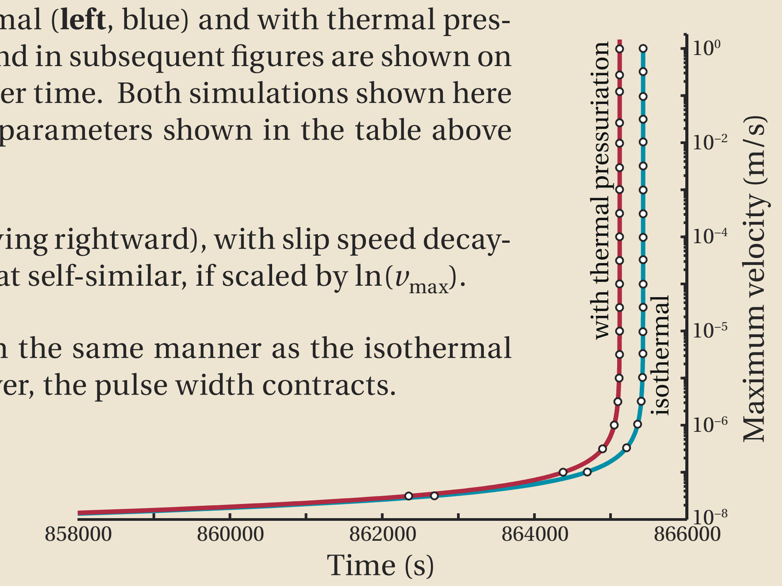


Figure 3. Comparison of slip law nucleation: isothermal (**left**, blue) and with thermal pressurization (**right**, red). The snapshots selected here and in subsequent figures are shown on the curve to the lower right. Bolder colors indicate later time. Both simulations shown here were started with identical initial conditions, using parameters shown in the table above (but with radiation damping turned off for clarity).

Isothermal slip law nucleation is pulse-like (here, moving rightward), with slip speed decaying behind the pulse tip. The pulse shape is somewhat self-similar, if scaled by $\ln(v_{max})$.

With thermal pressurization, nucleation starts out in the same manner as the isothermal case. After thermal pressurization dominates, however, the pulse width contracts.

In the slip speed-time curve at right, note that thermal pressurization has only slightly advanced the time of the earthquake.



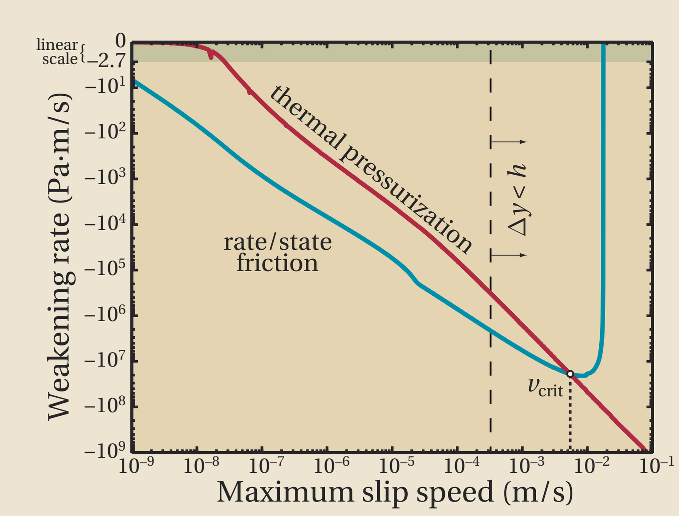


Figure 4. Critical velocity v_{crit}. The terms in eq. (9) are plotted against v_{max}. Rate/state friction dominates the weakening until $v_{\text{crit}} = 0.005$ m/s, at which point thermal pressurization becomes the dominant weakening term.

For $v_{\text{max}} > 0.02$ m/s, thermal pressurization becomes the *only* weakening term. Rate/state friction becomes strengthening because of the direct velocity strengthening effect (the a term in eq. [3]).

For $v_{\text{max}} > 3{\times}10^{-4}$ m/s, finite difference accuracy requires off-fault grid spacing smaller than the expected shear zone width of $h \approx 100$ μm, [*Rice*, JGR, 2006]. A finite-width shear heating source would be more appropriate.

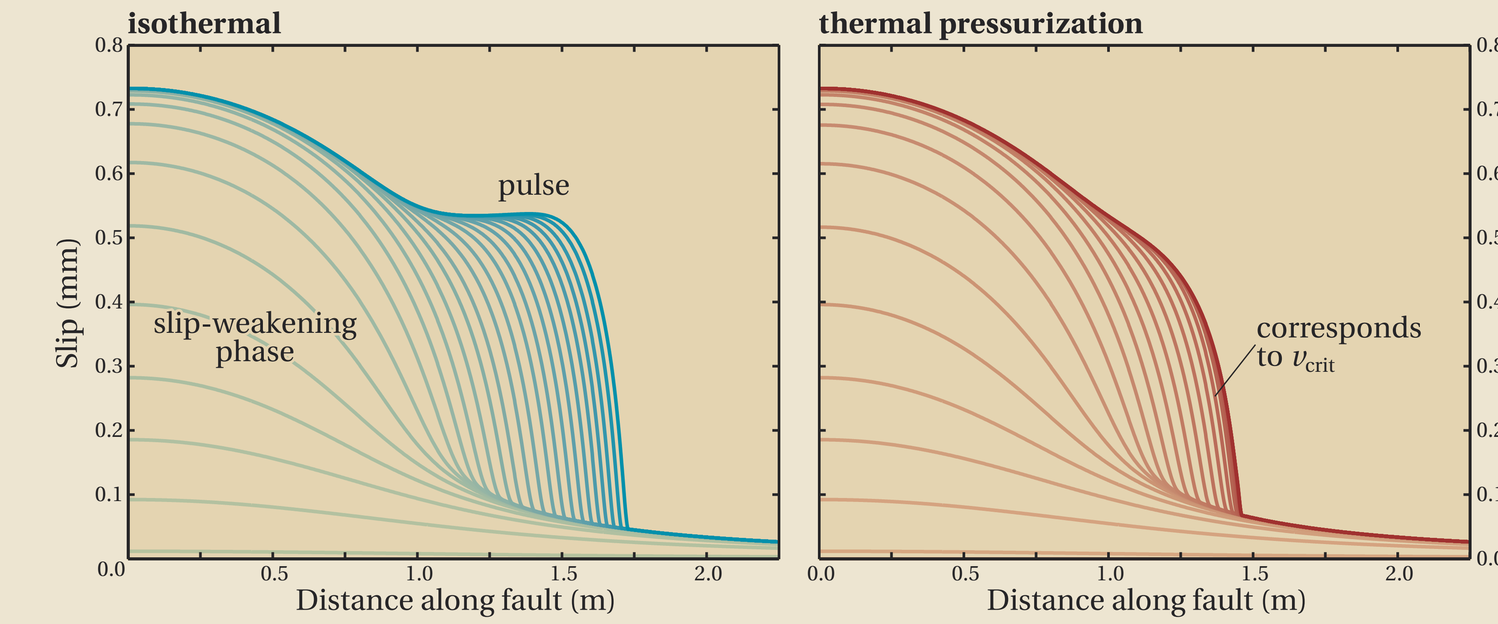


Figure 5. Cumulative slip; snapshots correspond to those shown in Figure 3. In isothermal nucleation, the initial slip-weakening phase is clearly followed by a propagating pulse. With thermal pressurization, the pulse starts in an identical manner. For $v_{\text{max}} > v_{\text{crit}}$, however, the pulse travels a shorter distance for corresponding values of v_{max}.

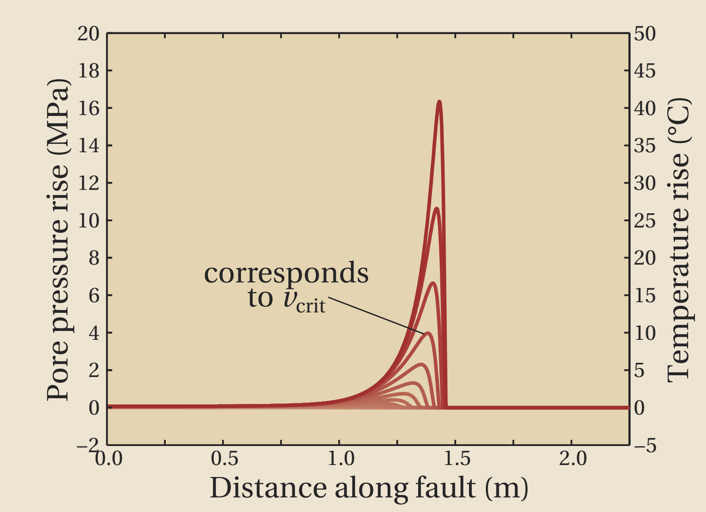
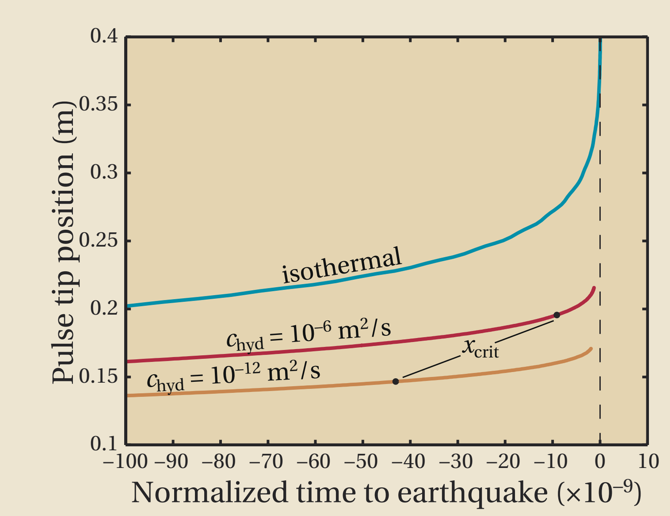


Figure 6. Snapshots of pore pressure rise on the fault, which are directly proportional to temperature. The temperature and pressure changes at v_{crit} are modest—10°C and 4 MPa (3% of nominal σ_{eff}), respectively. These values are 10× larger than $p(v_{\text{crit}})$ and $T(v_{\text{crit}})$ for the aging law.

Figure 7. Thermal pressurization does not affect the pulse propagation speed. Lines show pulse tip position x_{pulse} in the ~10 ms before frictional instability. Dots indicate the pulse tip position when $v_{\text{max}} = v_{\text{crit}}$, labeled as x_{crit}. The trajectory does not differ from the isothermal case.

We include an example with low c_{hyd} in order to maximize thermal pressurization. The offsets between the x_{pulse} lines are arbitrary and do not indicate a trend.



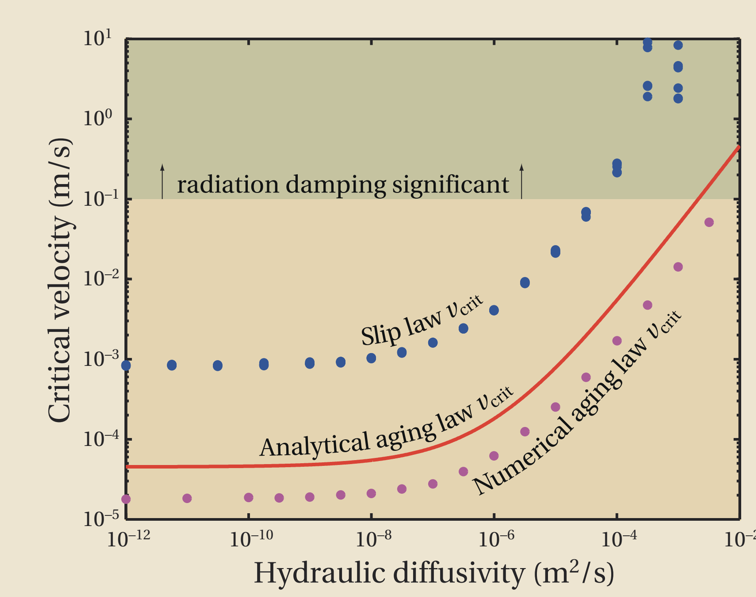


Figure 8. The effect of hydraulic diffusivity c_{hyd}—the least well-known parameter—on thermal pressurization. For the slip law with parameters used here, thermal pressurization dominates before seismic radiation for $c_{\text{hyd}} < 10^{-5}$ m^2/s. The values of slip law v_{crit} are consistently ~40 times greater than those for aging law nucleation. The analytical prediction of *Segall & Rice* [JGR, 2006] for the aging law is also shown.

CONCLUSIONS

- For reasonable values of material properties, thermal pressurization dominates frictional weakening before seismic radiation if
  $c_{\text{hyd}} \le 10^{-3}$ m^2/s for the aging law, or if
  $c_{\text{hyd}} \le 10^{-5}$ m^2/s for the slip law.
- Thermal pressurization is delayed with slip law friction compared with aging law friction.
- The width of the nucleation zone shrinks after thermal pressurization dominates. Both aging law "cracks" and slip law "pulses" shrink.
- In slip law nucleation, thermal pressurization causes the pulse to attain higher slip speeds over a shorter propagation distance, as compared to isothermal nucleation.
- Thermal pressurization does not affect slip law pulse propagation speeds.
- A finite-width shear zone is necessary to model thermal pressurization at high preseismic slip speeds.