Shear heating-induced thermal pressurization during earthquake nucleation

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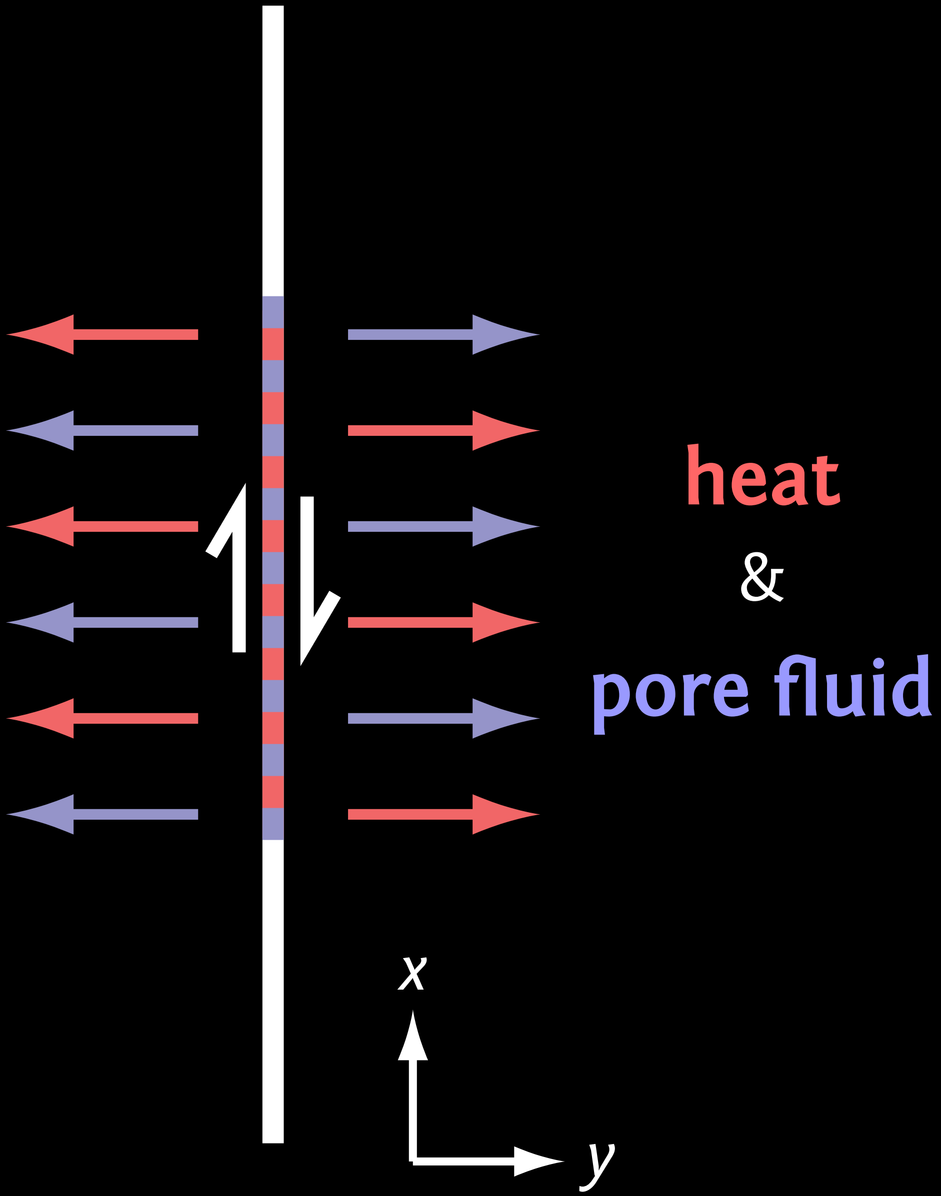
1. Shear heating-induced thermal pressurization can be dominant during earthquake nucleation, well before seismic slip.

2. Thermal pressurization restricts the expansion of the nucleation zone.

3. Finite thickness of the shear zone as well as the normal stress effect on state only slightly modify nucleation behavior.

Thermal pressurization

1. Frictional sliding generates heat.
2. Pore fluid expands more than rock.
3. Pore pressure increases if rate of heat production exceeds rate of fluid and heat transport.
4. Effective normal stress decreases, weakening the fault.



References: Sibson (1973); Lachenbruch (1980); Mase & Smith (1985, 1987); Lee & Delaney (1987); J. Andrews (2002); Noda & Shimamoto (2005); Wibberley & Shimamoto (2005); Rempel & Rice (2006); Rice (2006); Bizzari & Cocco (2006); Segall & Rice (2006).

Prior results

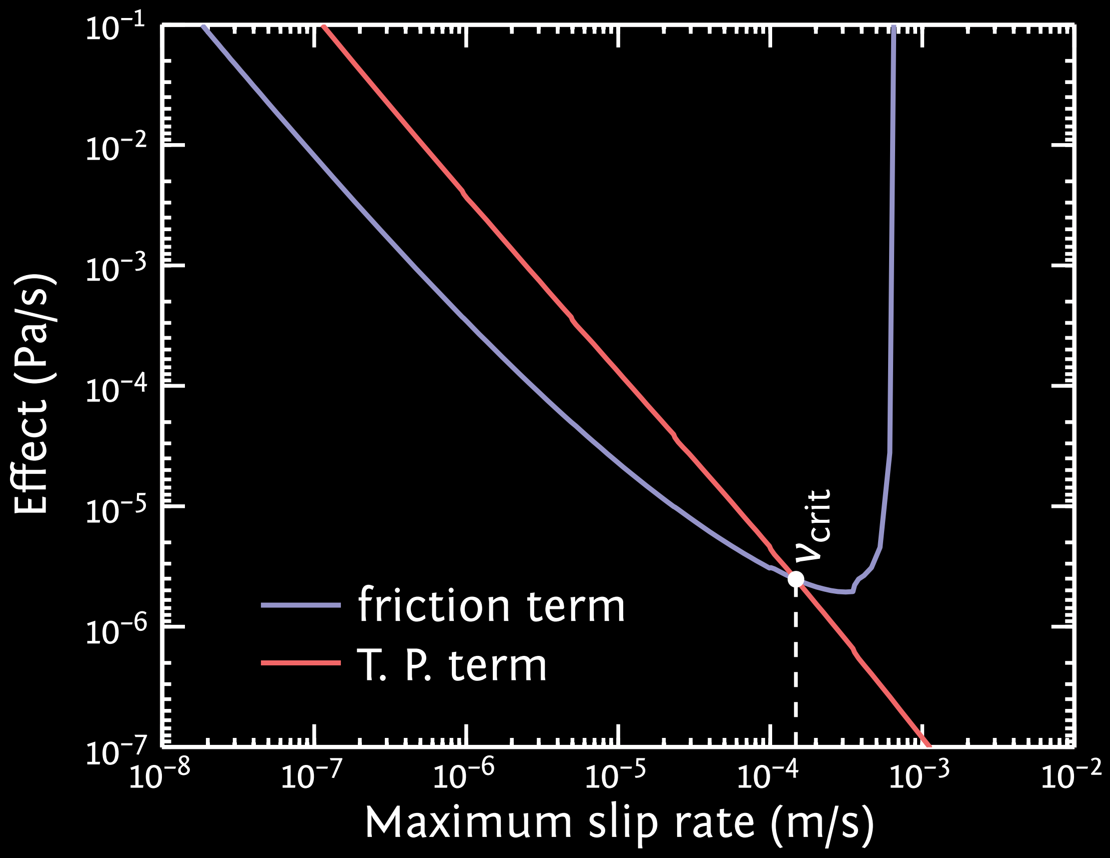
For planar faults with “standard” rate-state friction, thermal pressurization

- can become dominant during nucleation.
- restricts the growth of the nucleation zone.

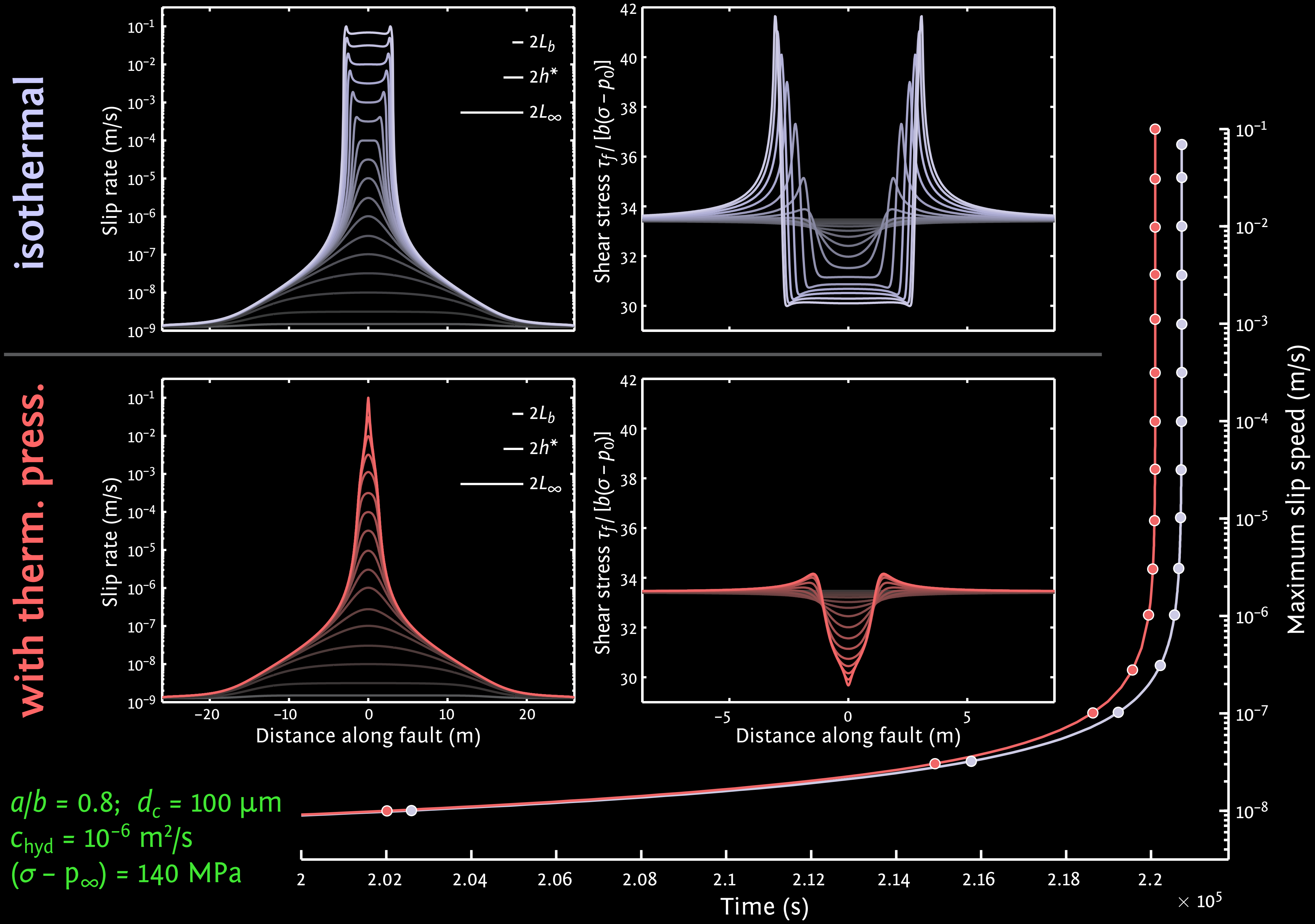
$$\frac{d\tau_{\text{fric}}}{dt} = \underbrace{\frac{d\mu}{dt}(\sigma - p_0)}_{\text{rate-state friction}} - \underbrace{\mu_0 \frac{dp}{dt}}_{\text{thermal pressurization}}$$

Parameters:

$a/b = 0.8$; $d_c = 100\ \mu\text{m}$;
$c_{\text{hyd}} = 10^{-6}\ \text{m}^2/\text{s}$
$(\sigma - p_\infty) = 140$ MPa



Prior results: comparison to isothermal aging law friction



$a/b = 0.8$; $d_c = 100\ \mu\mathrm{m}$

$c_{\mathrm{hyd}} = 10^{-6}\ \mathrm{m}^2/\mathrm{s}$

$(\sigma - p_\infty) = 140$ MPa

Open questions

It is surprising that the nucleation zone becomes a singularity. What physical effects might make the problem well-posed?

Will nucleation zone shrink or expand when these effects are included?

Some possible mechanisms

- The effect of variable normal stress on frictional state (*Linker & Dieterich*, 1992)
  - Delays the effect of pressurization on frictional resistance.
- Using a finite-width shear zone
  - Same work done over a wider zone produces less heat.

Governing equations

Quasi-dynamic equation of motion

$$\underbrace{-\frac{G}{2\pi}\int_{-\infty}^{\infty}\frac{1}{x-\xi}\frac{\partial u}{\partial \xi}\,d\xi}_{\text{elasticity}} - \underbrace{\left[\mu_0 + a\ln\frac{v}{v_0} + b\ln\frac{\theta v_0}{d_c}\right][\sigma - p(t)]}_{\text{friction}} - \underbrace{\frac{G}{2v_s}}_{\substack{\text{radiation}\\ \text{damping}}} v \;=\; 0$$

State evolution law: $\frac{d\theta}{dt} = 1 - \frac{\theta v}{d_c}$ (the “aging law”)

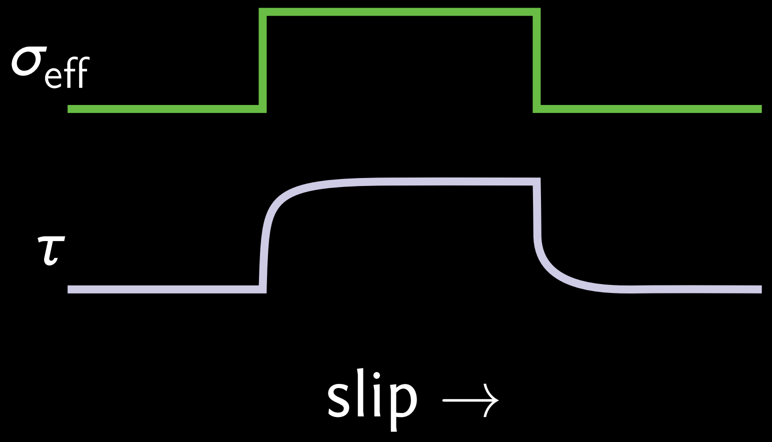
Thermal diffusion: $\frac{\partial T}{\partial t} = c_{\text{th}}\frac{\partial^2 T}{\partial y^2} + \frac{\tau}{\rho c_v}\frac{d\gamma(y)}{dt}$, with $\left.\frac{\partial T}{\partial y}\right|_{y=0} = 0$

Pore pressure diffusion: $\frac{\partial p}{\partial t} = c_{\text{hyd}}\frac{\partial^2 p}{\partial y^2} + \Lambda\frac{\partial T}{\partial t}$, with $\left.\frac{\partial p}{\partial y}\right|_{y=0} = 0$

Thermal pressurization factor: $\Lambda = \frac{\lambda_f - \lambda_\phi}{\beta_f + \beta_\phi}$ ≈ 1 MPa/°C

The effect of varying normal stress on friction

Following a change in normal stress, shear stress evolves to its new value (*Linker & Dieterich*, 1992).



Modified state evolution law:

$$\frac{d\theta}{dt} = 1 - \frac{\theta v}{d_c} - \frac{\alpha\theta}{b(\sigma - p)}\frac{d}{dt}(\sigma - p)$$

If $\alpha = \mu_0$, there is no instantaneous effect.

For thermal pressurization, this delays the weakening effect.

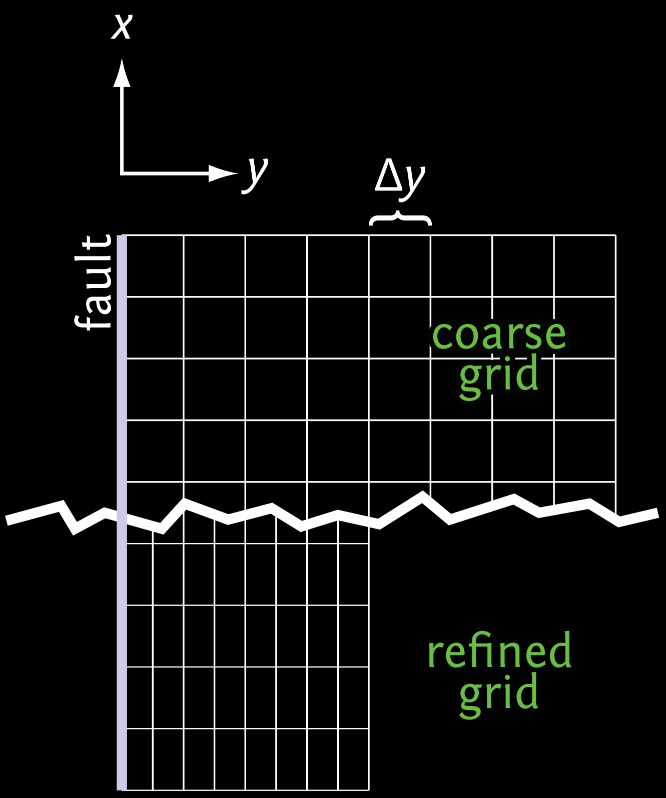
Numerical simulations

1D fault in a 2D elastic, diffusive medium.

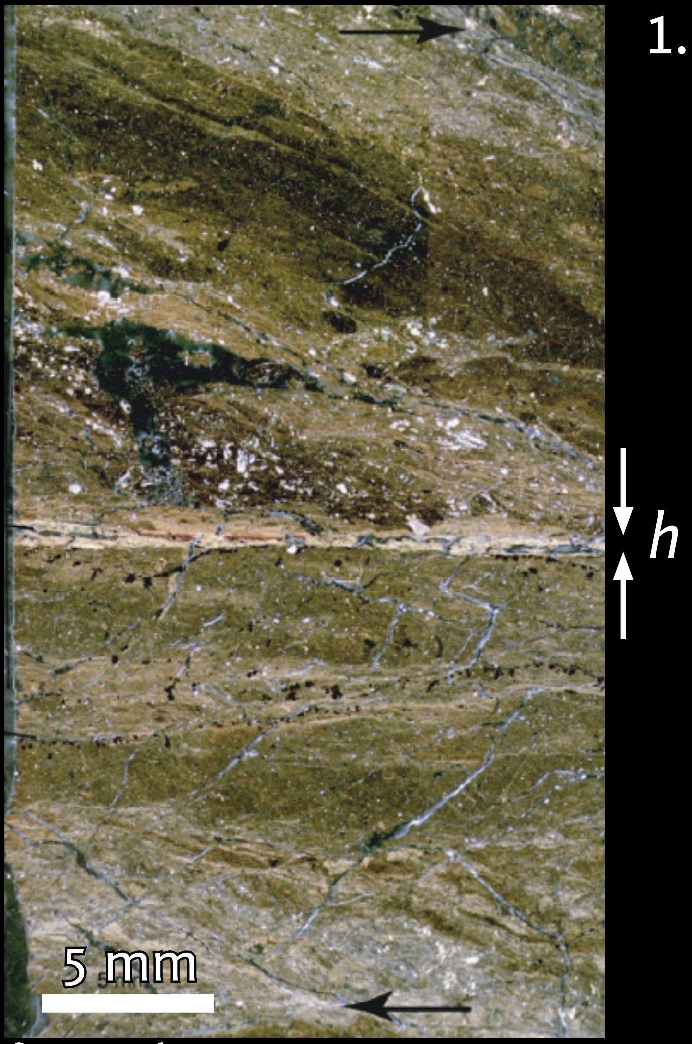
Finite difference thermal diffusion and pore pressure diffusion

Automatic grid refinement as accuracy demands.

Creep imposed at edge of fault; central region started with $d\theta/dt > 0$ to control where and when nucleation occurs.

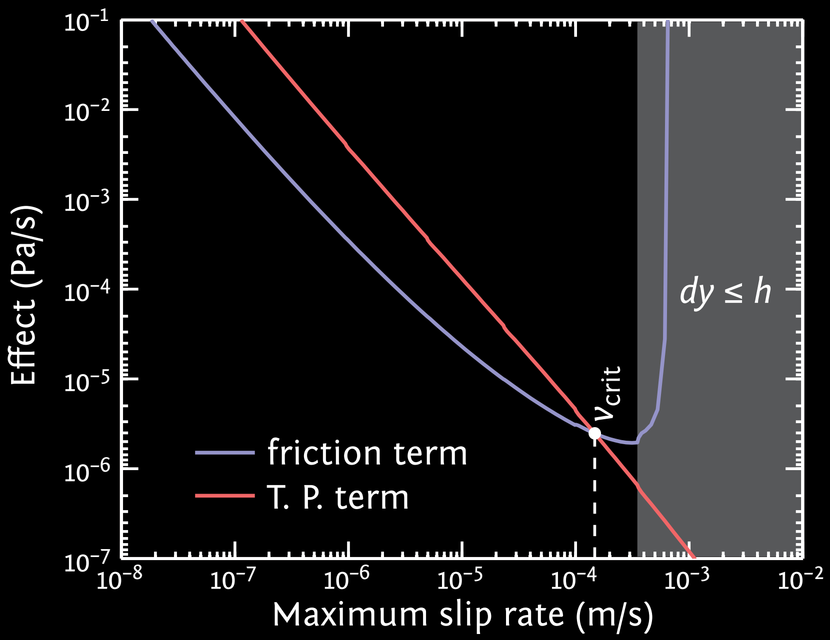


Why use a finite-width shear zone?



from Chester, via *Rice* (2006)

1. Finite-width shear zones are realistic. $h \approx 100\ \mu\text{m}$.

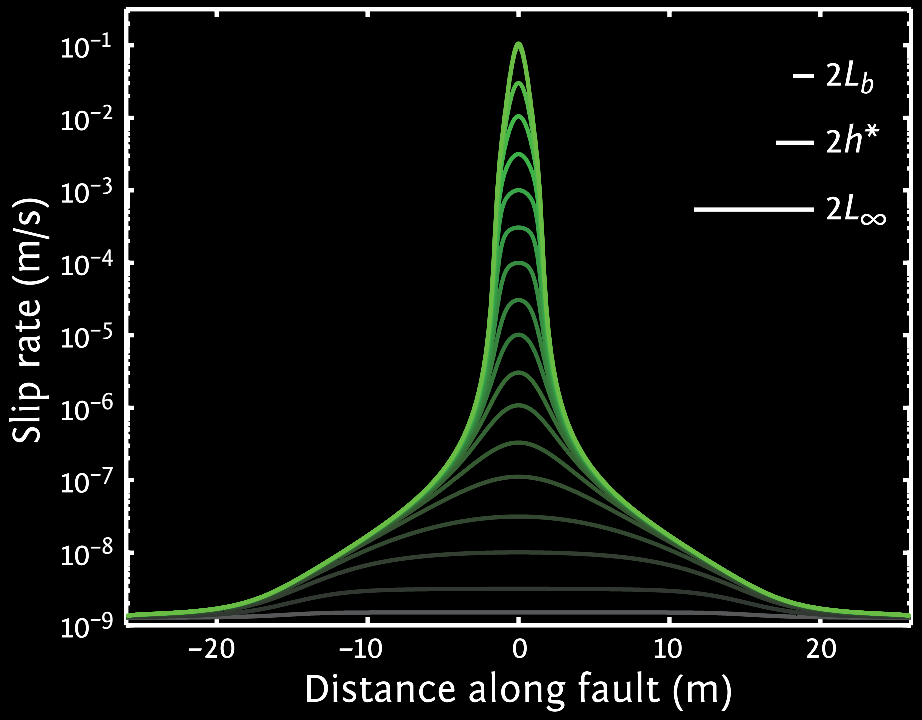


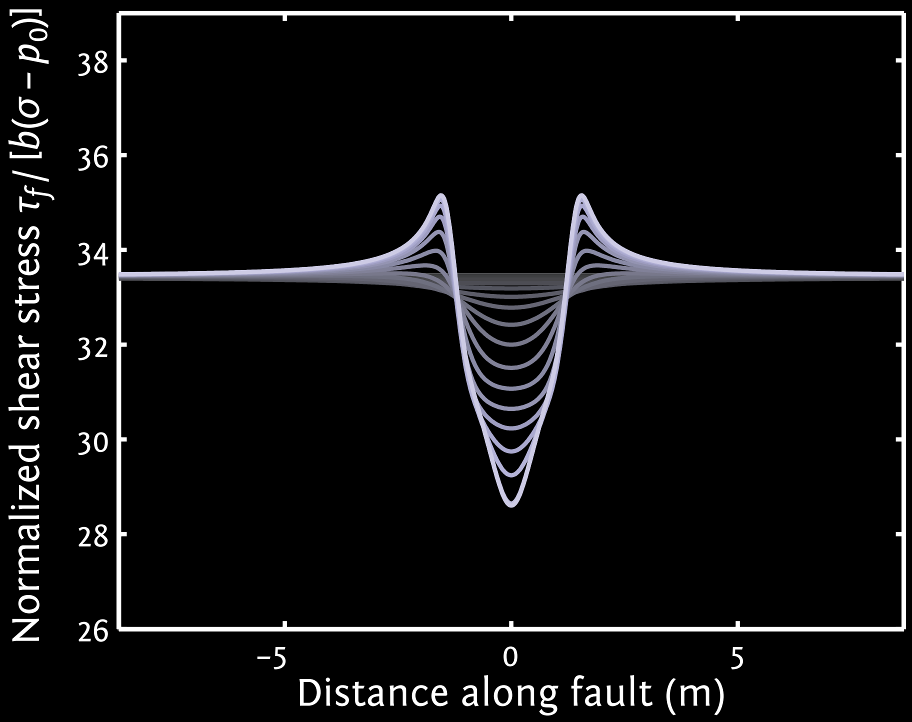
2. At moderate slip speeds, accuracy requires $\Delta y \approx h$ near v_{crit} . Boundary heating is incorrect at that scale due to the Courant condition, $\Delta t < \Delta y^2/4c$.

Results with the *Linker-Dieterich* effect

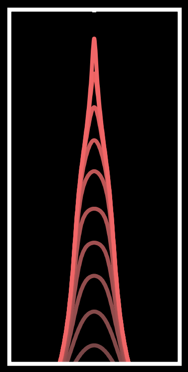
$$\alpha = \mu_0 = 0.6$$

The nucleation zone still shrinks, but not to a singularity.



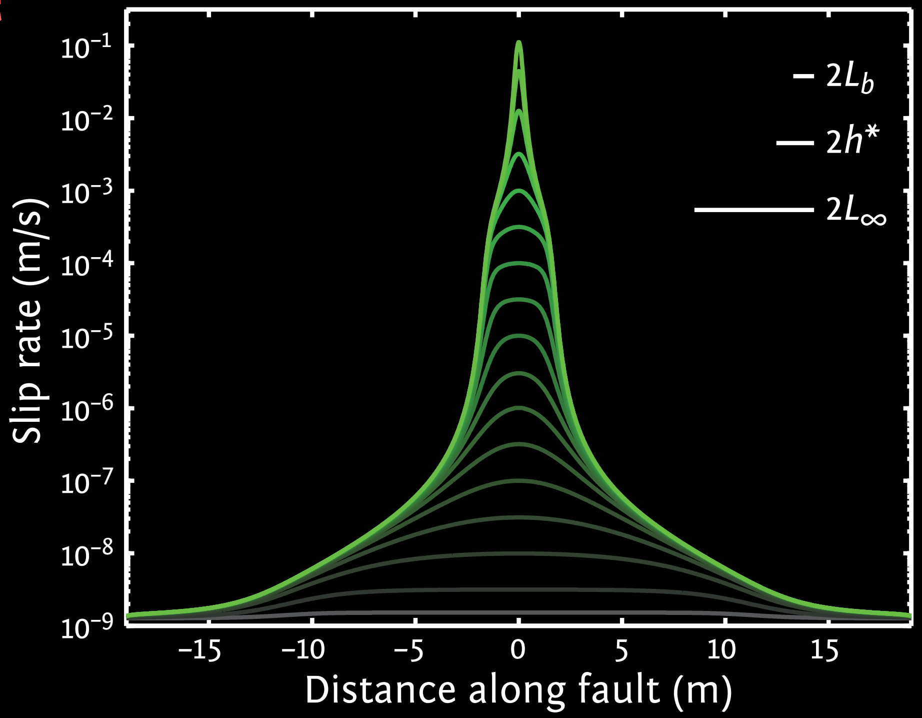


Compare to “standard” rate-state friction with thermal pressurization:



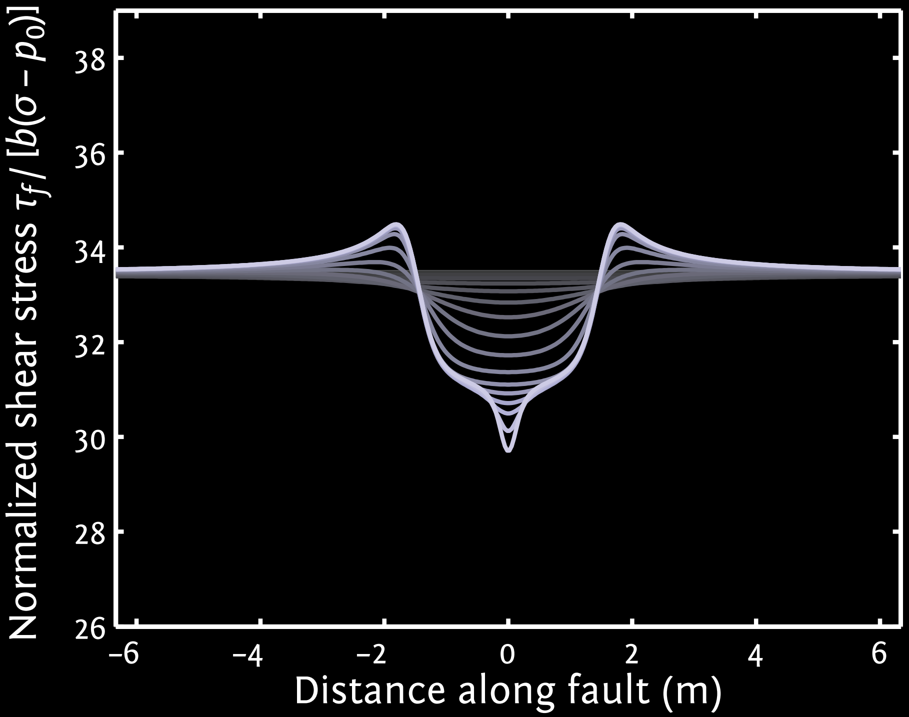
The result for the slip law is similar.

Results for finite shear zone



Gaussian shear distribution;
FWHM = 100 μm.

Nucleation zone contracts, but is still well-resolved numerically.



The result for slip law friction is similar.

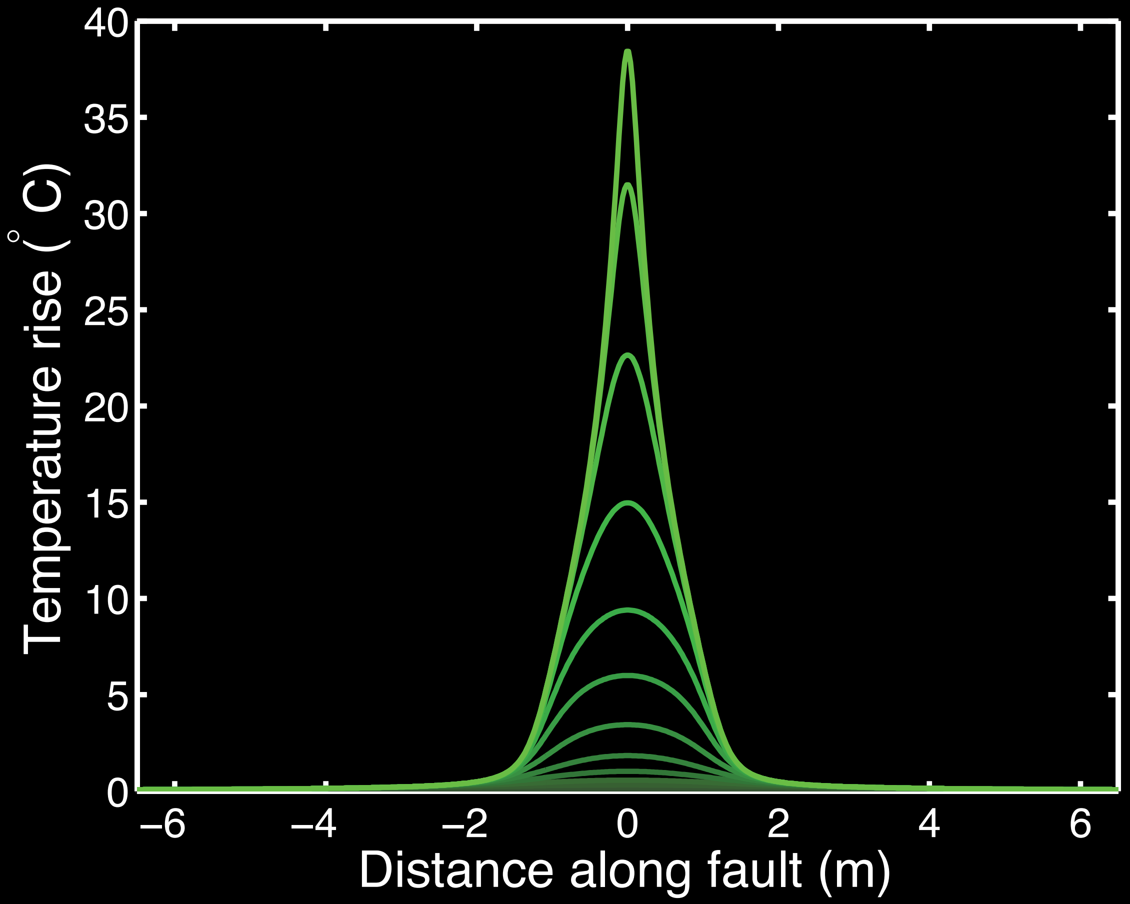
Conclusions

1. Thermal pressurization leads to contraction of the nucleation zone.
2. Both the effect of normal stress on state and using a finite-width shear zone regularize the behavior of the system.
3. Despite (2), the contraction of the nucleation zone persists.

Implications

1. Efforts to detect the nucleation phase *in situ* (SAFOD, NELSAM) will be *very* challenging.
2. Other stabilizing effects are required for the nucleation zone to expand prior to dynamic rupture (for example, dilatancy—see Segall *et al.*, U32A-06).

Temperature



Continuing to higher slip speeds