Thermal pressurization is significant during earthquake nucleation—before seismic slip

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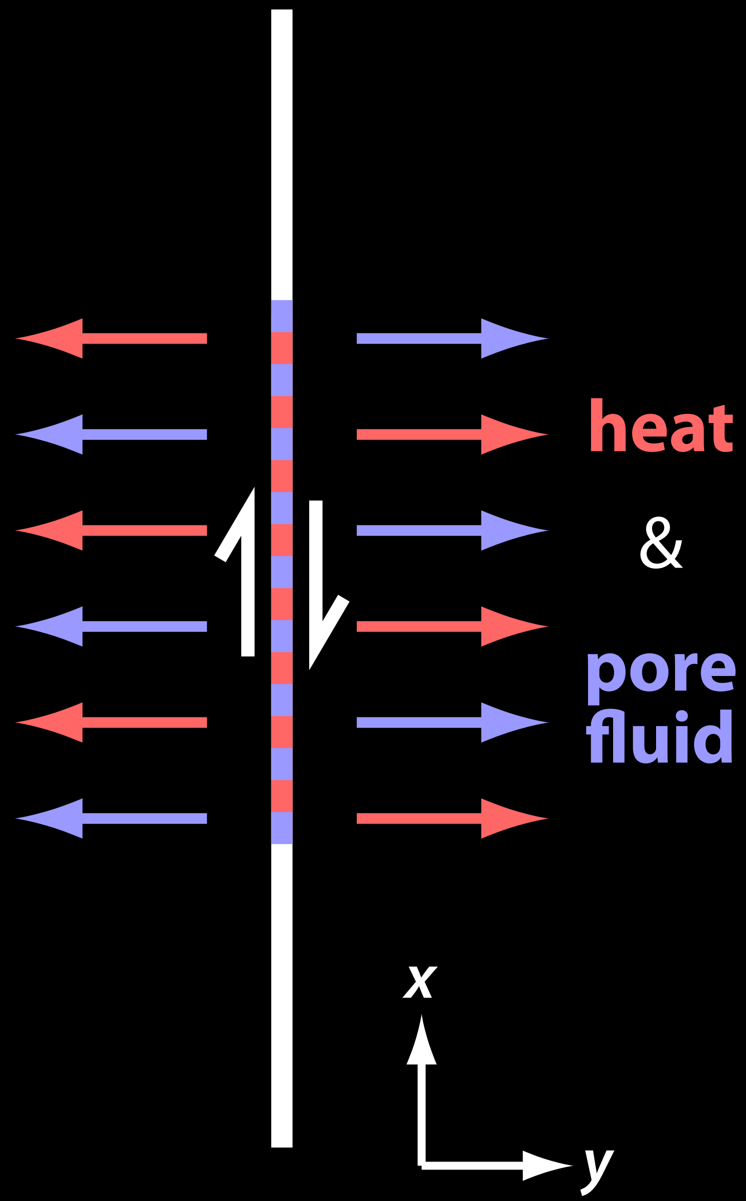
Thermal pressurization

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.



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

Questions

1. At what critical slip speed does thermal pressurization dominate frictional weakening?

2. How does that critical slip speed depend on hydraulic diffusivity near the fault?

3. How does thermal pressurization influence earthquake nucleation?

Equations: friction and stress

Equation of motion (elastic stress & radiation damping)

$$\frac{G}{2\pi}\int_{-\infty}^{\infty} \frac{\partial u/\partial \xi}{\xi - x}\, d\xi - \mu(v,\theta)(\sigma - p) = \frac{\rho v_s}{2} v$$

Friction law

$$\mu = \mu_0 + a \ln\left(\frac{v}{v_0}\right) + b \ln\left(\frac{\theta v_0}{d_c}\right)$$

Evolution law

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

"aging law" "slip law"

Equations: fluid and heat transport

Shear heating on fault $$\left.\frac{dT}{dy}\right|_{y=0} = -\frac{\tau v}{2\rho c_p c_{th}}$$

Pore pressure diffusion $$c_{hyd}\frac{d^2p}{dy^2} - \frac{dp}{dt} = -\Lambda\frac{dT}{dt}$$

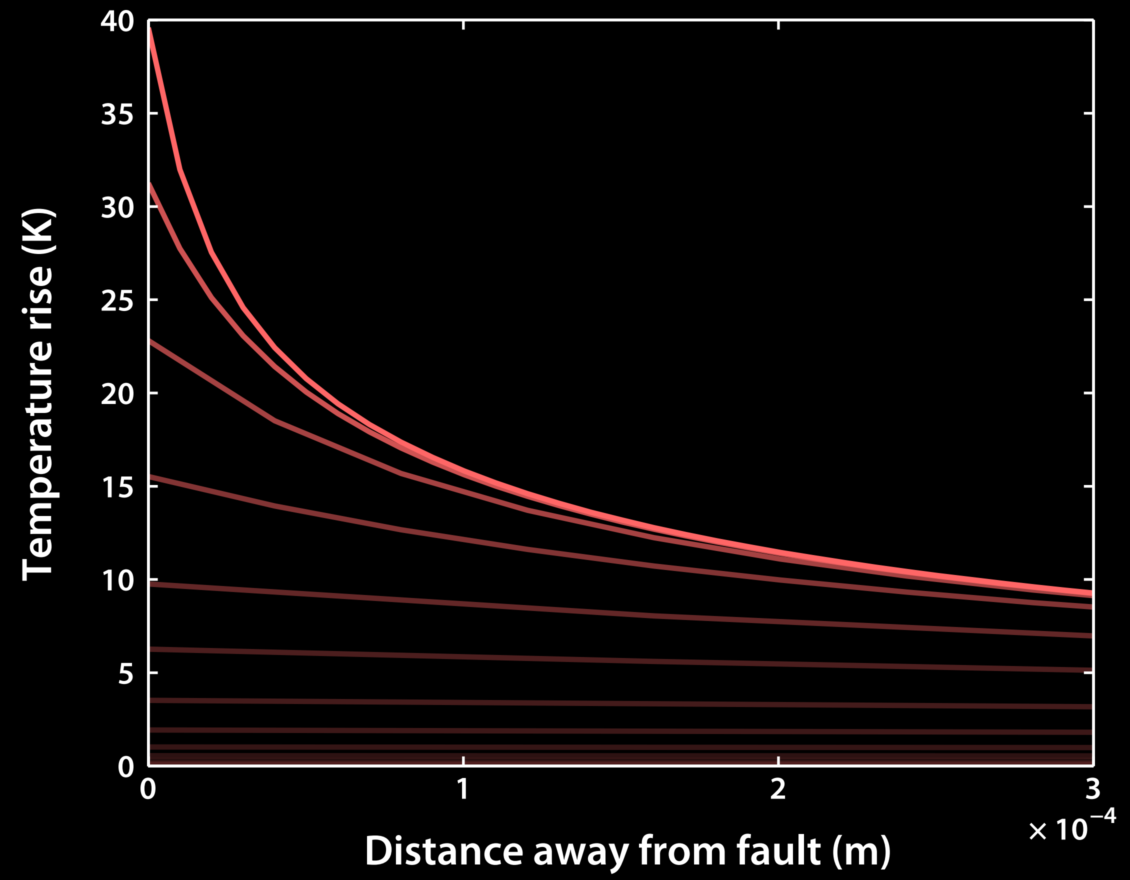
Homogeneous material causes pressure on the fault to be proportional to temperature on the fault (Rice 2006):

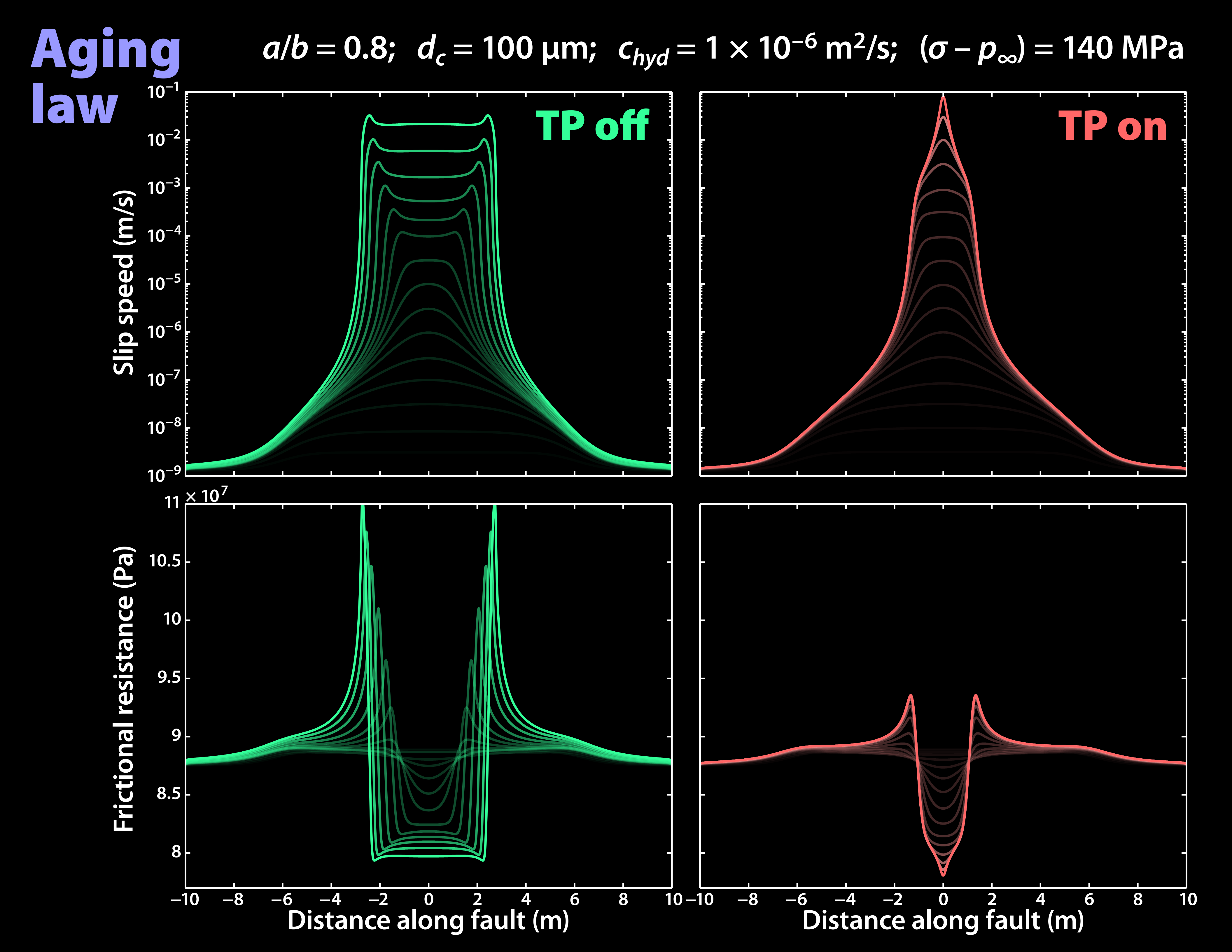
$$\Delta p = \Lambda\left(1 + \sqrt{\frac{c_{hyd}}{c_{th}}}\right)^{-1}\Delta T \qquad \text{where} \qquad \Lambda = \frac{\lambda_f - \lambda_\varphi}{\beta_f + \beta_\varphi}$$

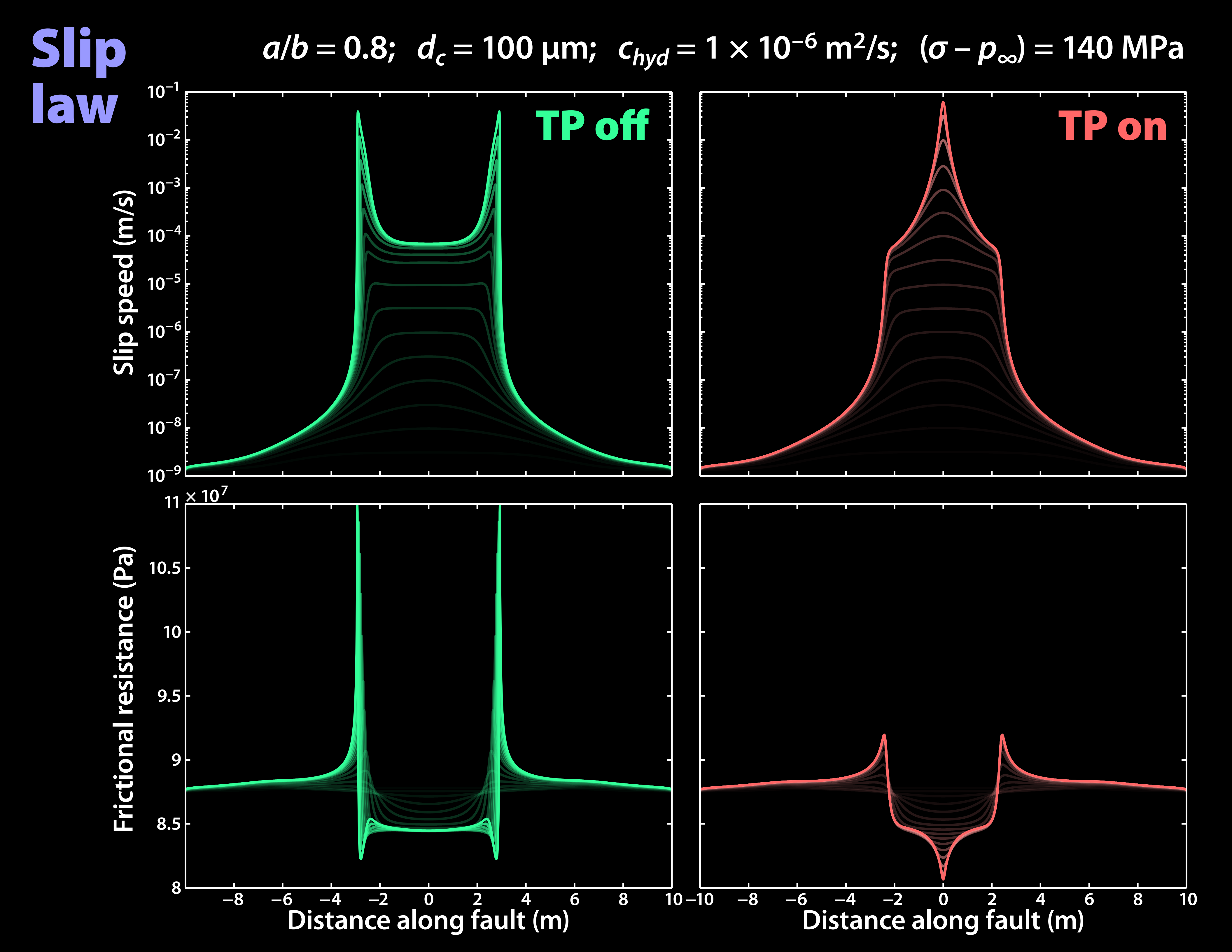
Thus we need only to compute the temperature field.

Numerical simulations

- 2D simulations (fault is a line).
- Finite difference calculation for thermal diffusion normal to the fault.
- Automatic grid refinement if accuracy demands it.




Aging law
a/b = 0.8; d_c = 100 μm; c_hyd = 1 × 10^−6 m^2/s; (σ − p_∞) = 140 MPa
TP off
TP on
Slip speed (m/s)
Frictional resistance (Pa)
× 10^7
Distance along fault (m)
Distance along fault (m)

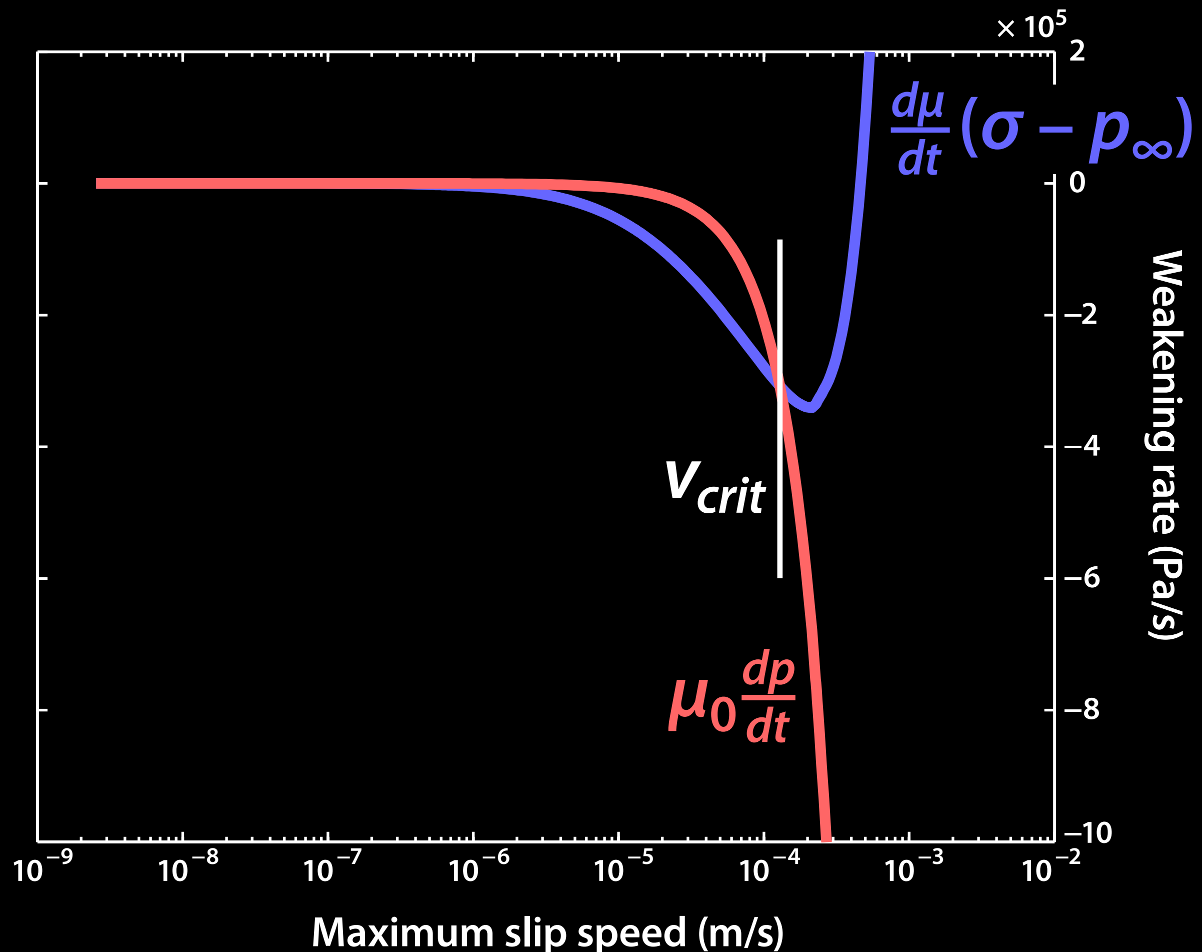


Slip law
a/b = 0.8; d_c = 100 μm; c_hyd = 1 × 10⁻⁶ m²/s; (σ − p_∞) = 140 MPa
TP off
TP on
Slip speed (m/s)
Frictional resistance (Pa)
× 10^7
Distance along fault (m)
Distance along fault (m)

Determining the critical velocity

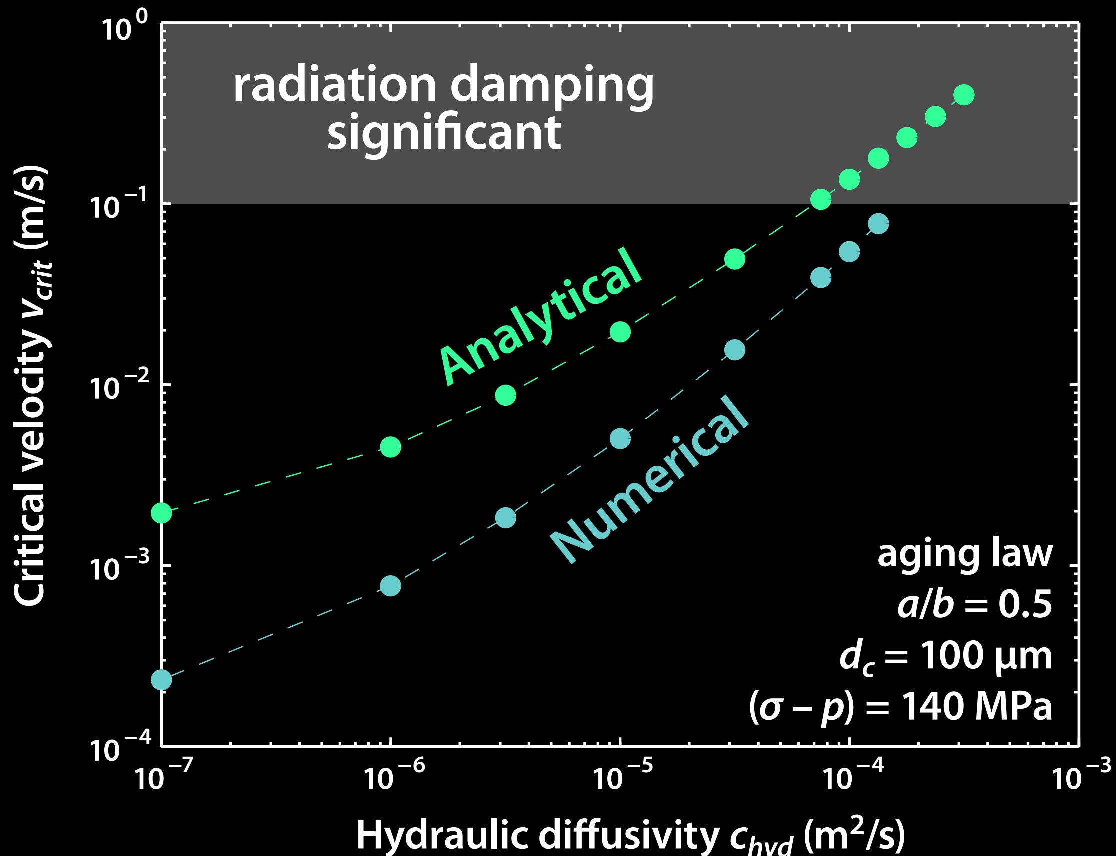
Beyond a critical velocity v_{crit}, increasing fluid pressure is the dominant weakening mechanism.

Thermal pressurization becomes important well before seismic slip speeds.



v_{crit} and hydraulic diffusivity

Rice (2006) estimates c_{hyd} from recent studies of fault core permeability: $c_{hyd} = 5 \times 10^{-7}\ \mathrm{m^2/s}$ to $7 \times 10^{-7}\ \mathrm{m^2/s}$.



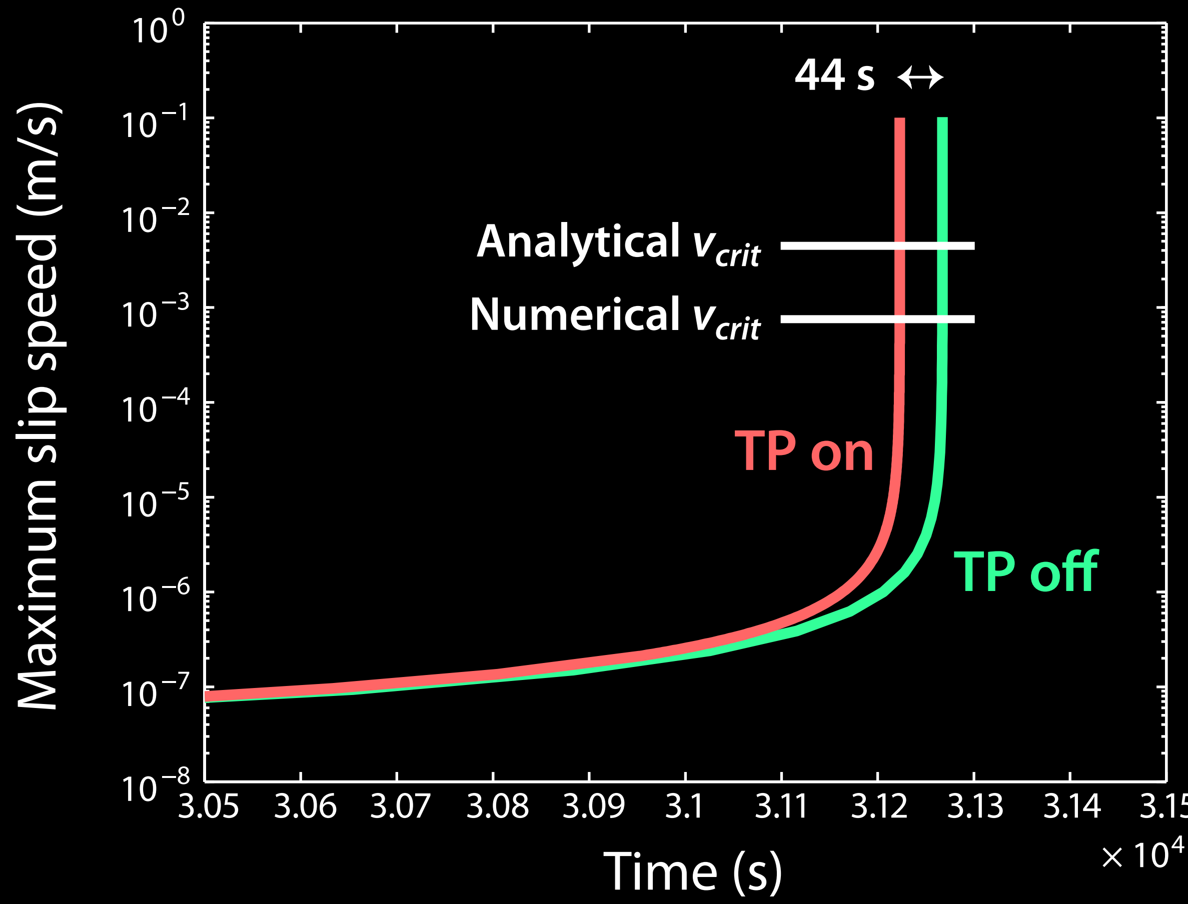
Analytical v_{crit}

For aging law friction, Segall & Rice (2006) estimate:

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

Slip speed versus time

While thermal pressurization becomes important at slow slip speeds, it only slightly advances the time-to-instability.



Conclusions

1. Thermal pressurization becomes important during quasi-static nucleation.
   - This may be inconsistent with hypothesized changes in behavior at intermediate earthquake magnitudes.

2. TP causes the nucleation zone to contract for both aging and slip laws.
   - Detecting earthquake precursory strain is even more challenging.

3. TP does not significantly affect the time to nucleate.
   - Models of seismicity rate changes based on rate-state nucleation (*e.g.* Dieterich 1994) will not be biased by TP.