Thermal pressurization during the transition from quasi-static nucleation to dynamic rupture

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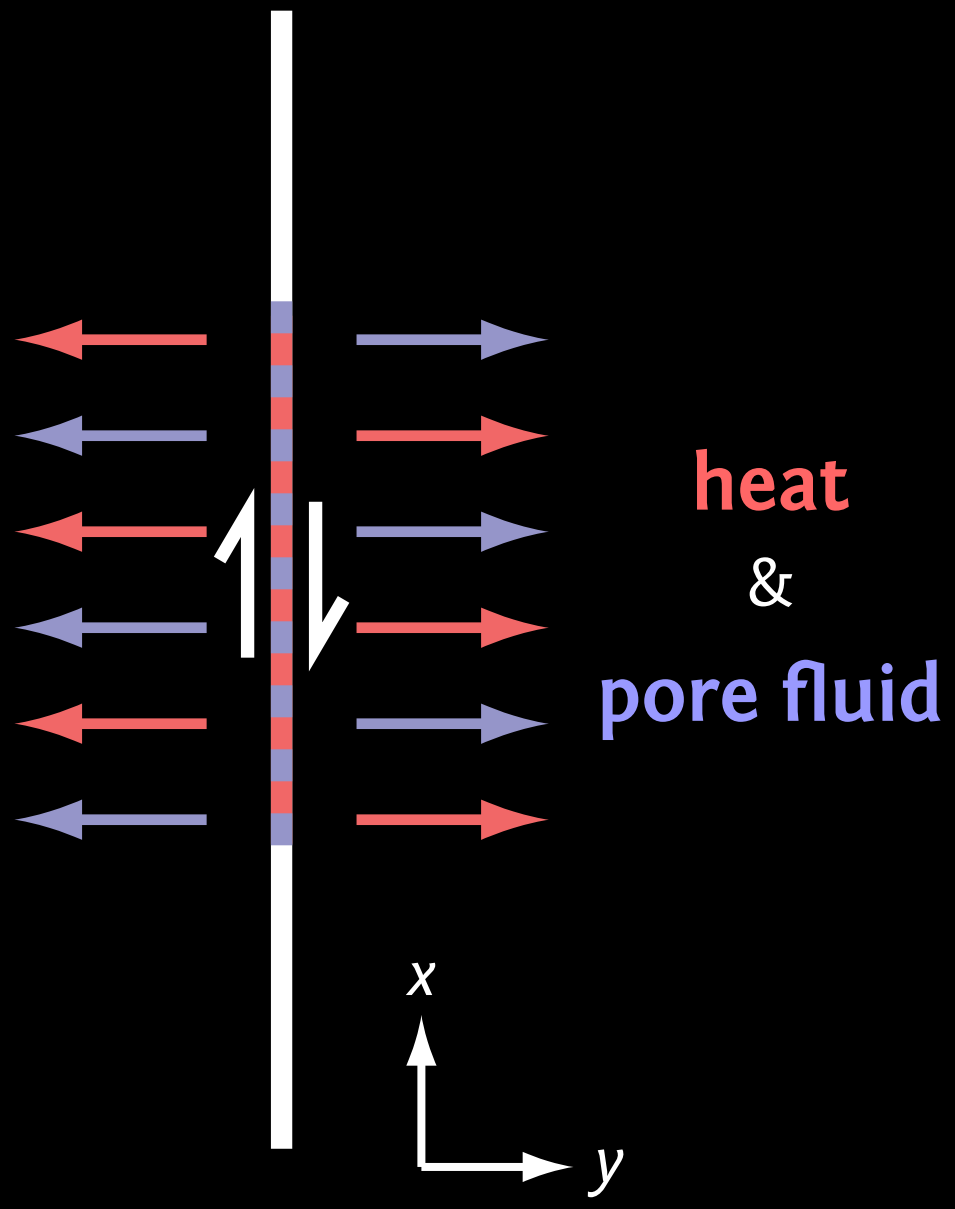
1. Shear heating-induced thermal pressurization leads to a near-total stress drop late in earthquake nucleation.

2. Heterogeneous fault properties or conditions are necessary to reconcile (1) with observations.

3. Even at subseismic slip speeds, the finite shear zone width must be modeled.

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); J. Andrews (2002); Noda & Shimamoto (2005); Wibberley & Shimamoto (2005); Rice (2006); Bizzari & Cocco (2006); Segall & Rice (2006); Noda, Dunham, & Rice (2009) Schmitt *et al.* (in review).

Governing equations

Equation of motion—quasidynamic or elastodynamic

$$\underbrace{\left[\mu_0 + a\ln\frac{v}{v_0} + b\ln\frac{\theta v_0}{d_c}\right]\left[\sigma - p(t)\right]}_{\text{friction \& thermal pressurization}} = \tau_0 + \underbrace{\phi(x,t) - \frac{G}{2v_s}v}_{\text{elasticity \& radiation}}$$

State evolution laws: $\dfrac{d\theta}{dt} = 1 - \dfrac{v\theta}{d_c}$ (aging); $\dfrac{d\theta}{dt} = -\dfrac{v\theta}{d_c}\ln\dfrac{v\theta}{d_c}$ (slip)

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

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

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

Numerical simulations

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

Finite difference thermal diffusion and pore pressure diffusion.

Remote, uniform stressing rate.

Adaptive substepping for diffusion.

Elasticity calculated with spectral boundary element method.

Quasi-static nucleation phase:
- Log-transformed diffusion grid.
- Poster S23A-2115 [*Bradley & Segall*] presented details.

Elastodynamic rupture phase:
- See *Noda, Dunham, & Rice* [2009] for details.

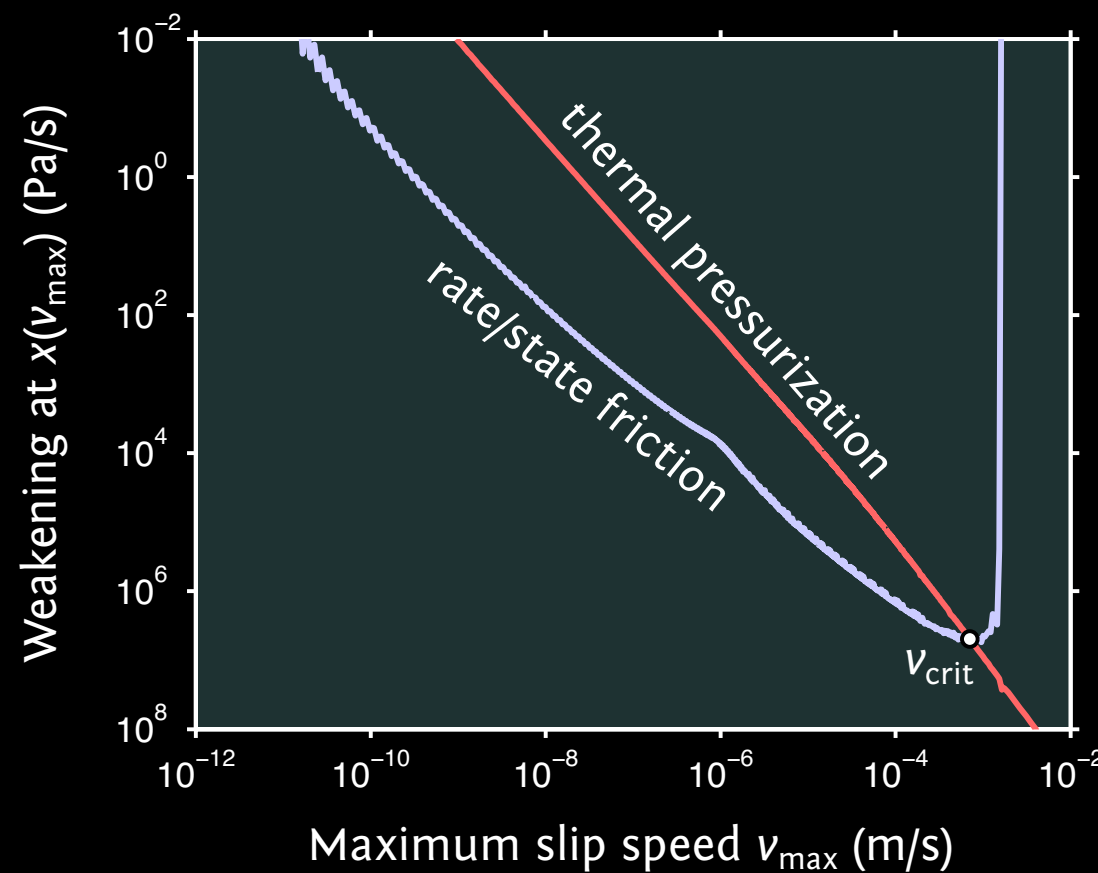
Prior results

For planar, zero-width faults with rate-state friction, thermal pressurization can become dominant during nucleation.

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

Parameters:

a/b = 0.8; d_c = 100 μm;
$c_{th} = c_{hyd} = 10^{-6}$ m²/s
$(\sigma - p_\infty)$ = 140 MPa



Importance of finite-width shear zones

A simple dimensional argument:

Diffusion time across shear zone:

$$t_{\mathrm{szd}} = \frac{h^2}{4c_{\mathrm{th}}}$$

Nucleation time:

$$t_{\mathrm{eq}} = f(a,b)\frac{d_c}{v}; \quad f(a,b) \approx 1$$

Slip speed for thermal boundary layer thickness h:

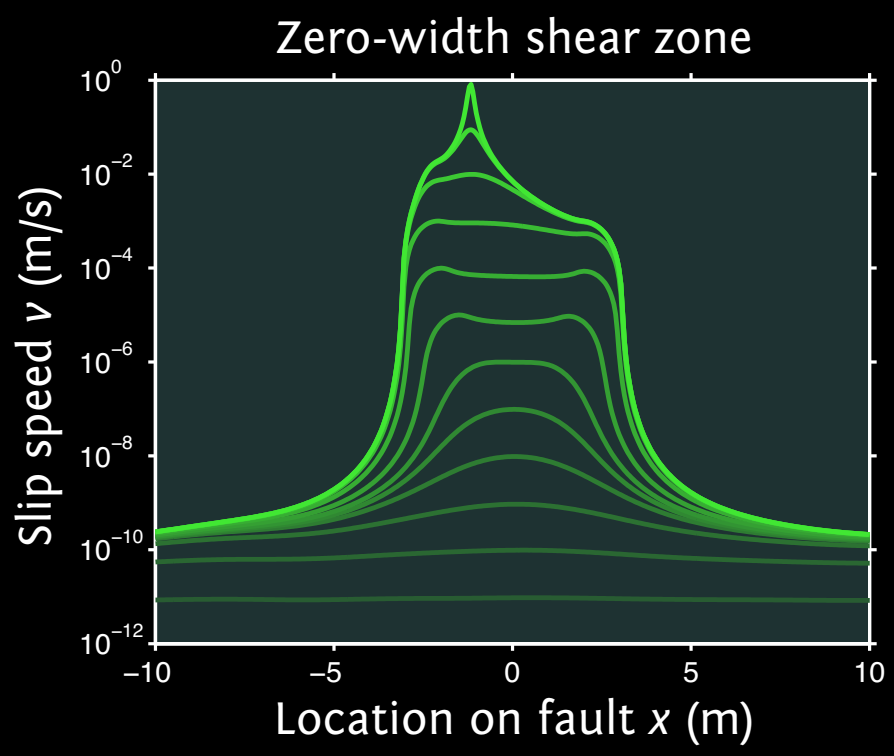
$$v \approx \frac{4c_{\mathrm{th}}d_c}{h^2}$$

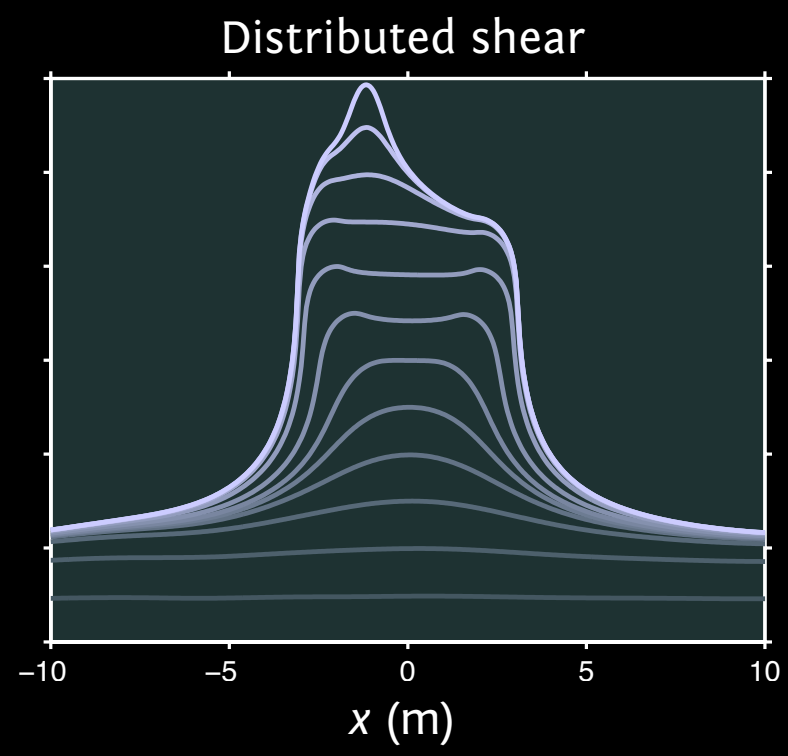
For $c_{\mathrm{th}} = 1$ mm²/s, $h = d_c = 100$ μm,

$$v \approx 40 \text{ mm/s}$$

Punchbowl fault; photo by J. Chester in *Rice* [2006]

Effect of distributed shear: Aging law





Heat source only at $y = 0$.

Slip singularity forms after TP dominates.

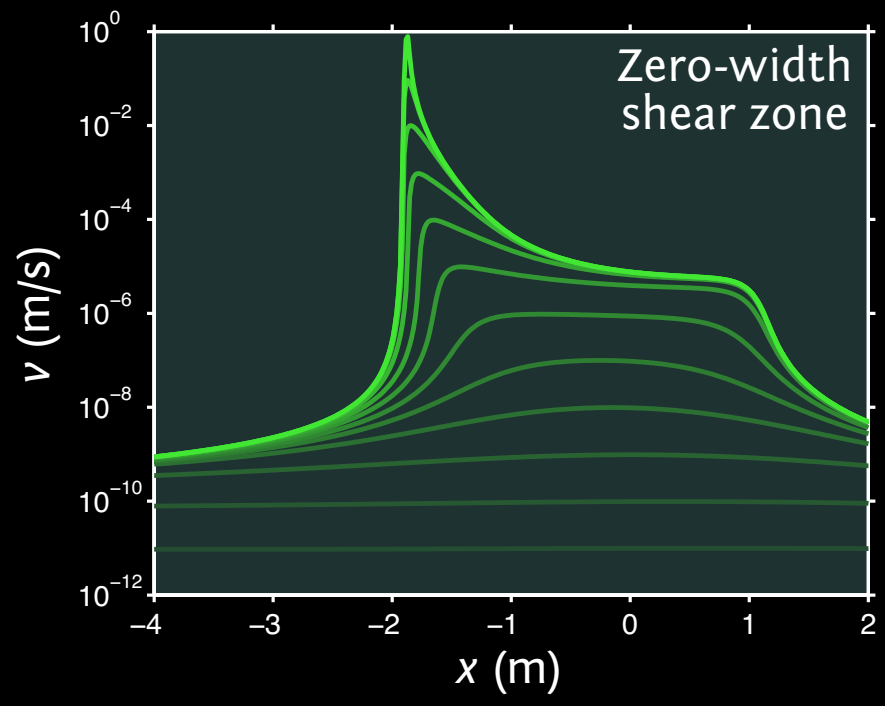
Gaussian shear distribution; 100 μm width.

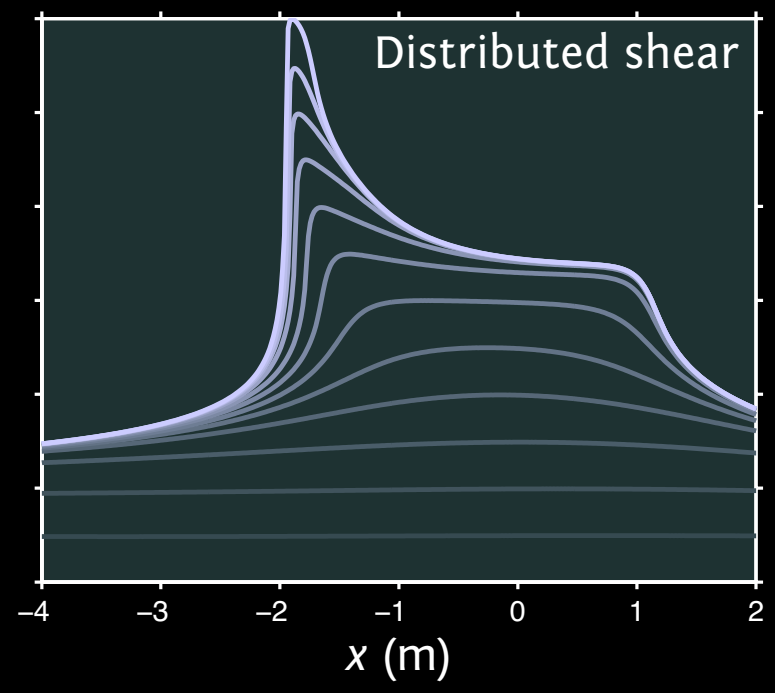
No slip singularity.

Smaller ΔT but not Δp.

Nucleation zone width grows toward $2L_\infty$ before contracting.
Critical velocity v_{crit} is unaffected.

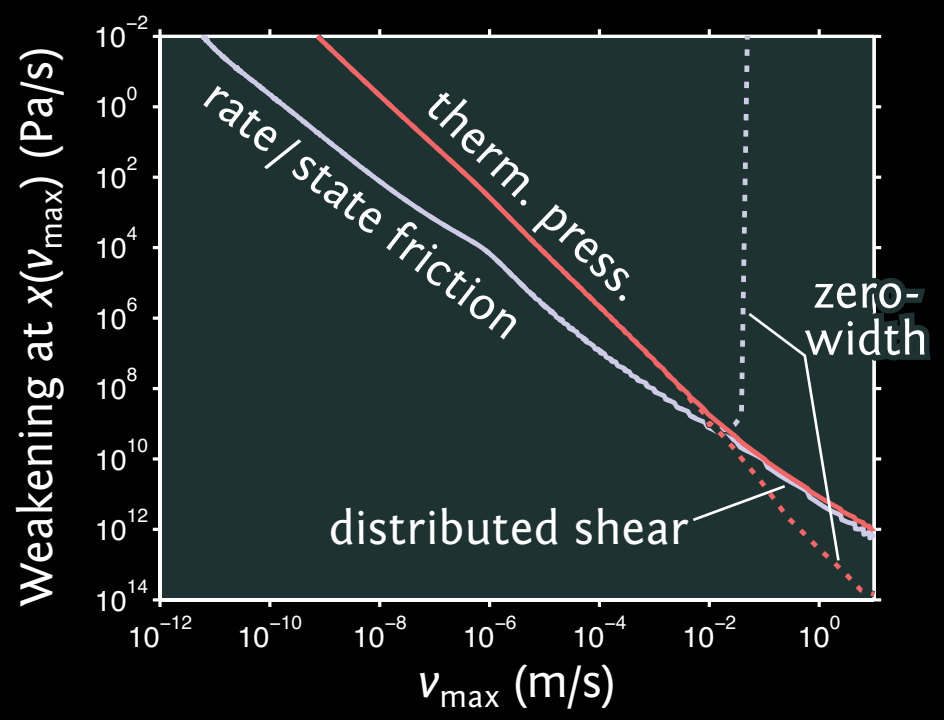
Effect of the distributed shear: Slip law



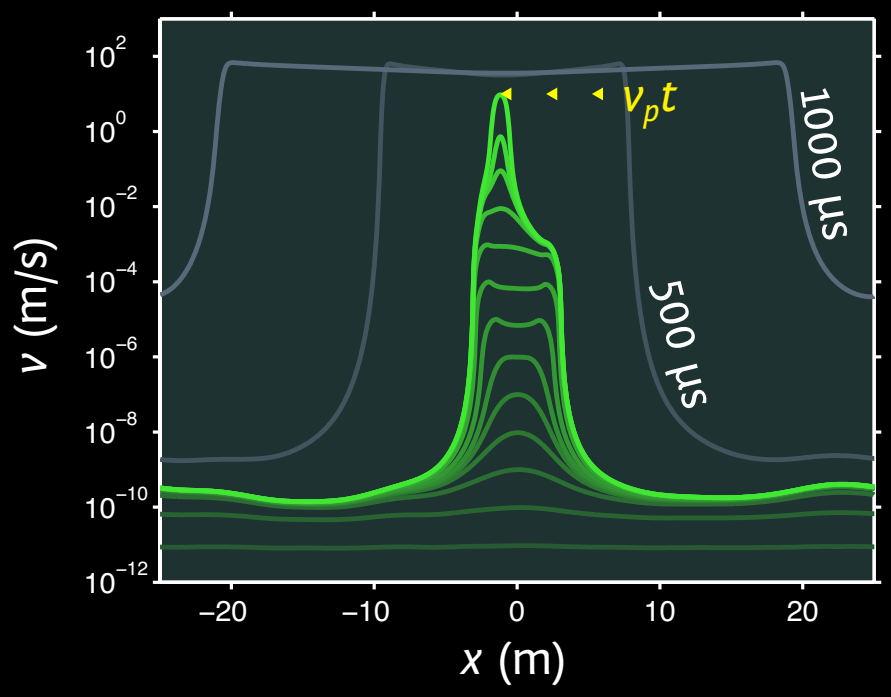


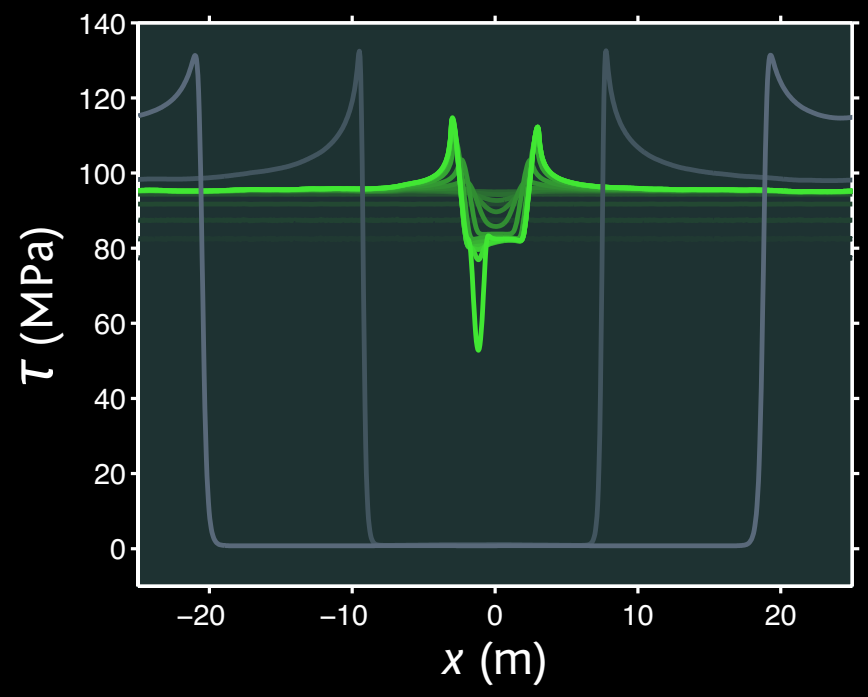
The effect of TP on pulse shape and speed is greatly reduced.

v_{crit} may be substantially higher, or may never occur.



Quasidynamic rupture – aging law nucleation



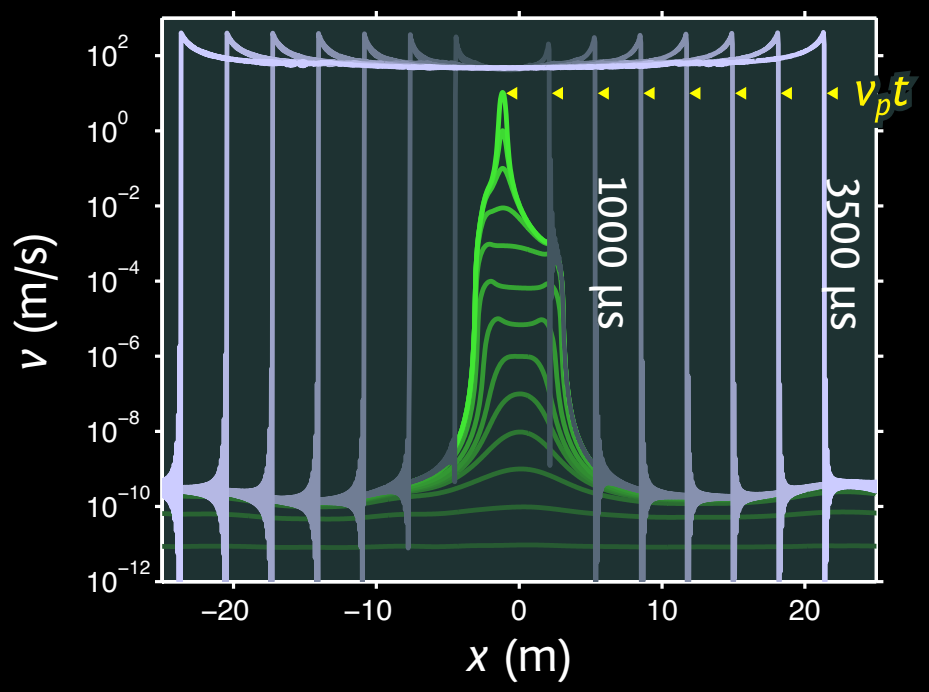


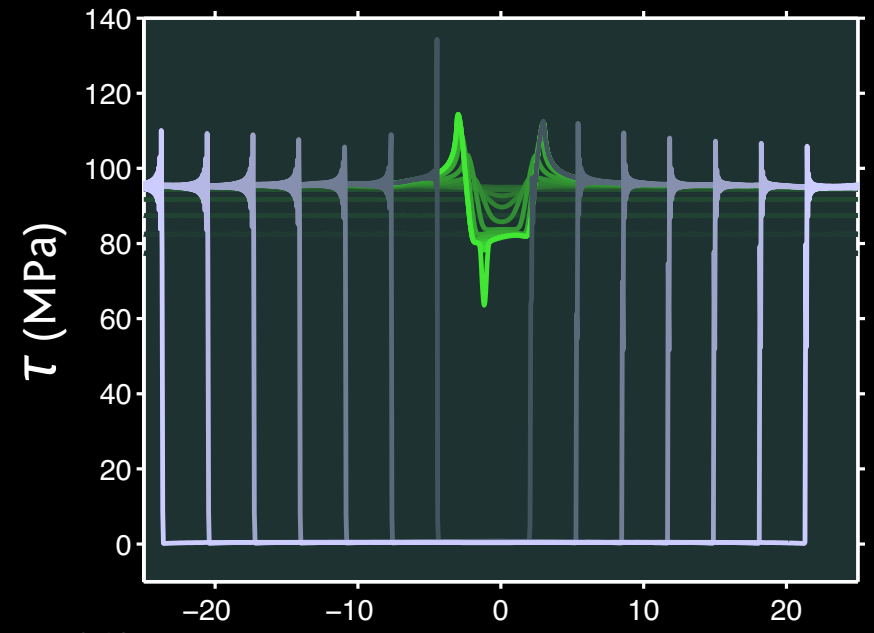
Slip speed is extremely high—60 m/s.

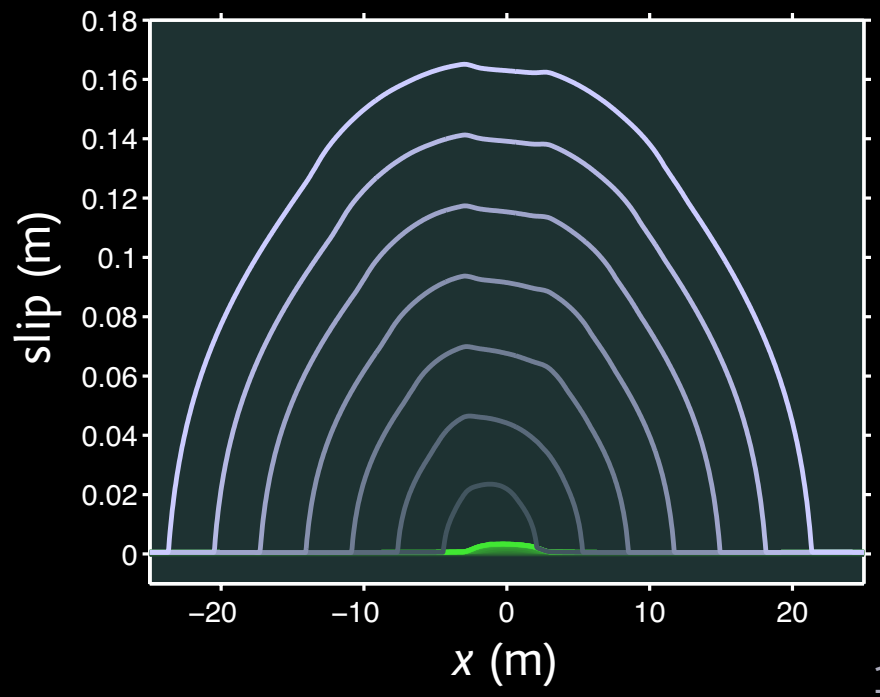
Complete release of shear stress.

Rupture grows at nonphysical speed.

Elastodynamic rupture







Slip speed is still extremely high.

Stress drop is still complete.

Supershear rupture growth.

Implications

1. Late in nucleation or early in seismic rupture, thermal pressurization leads to a total stress drop.

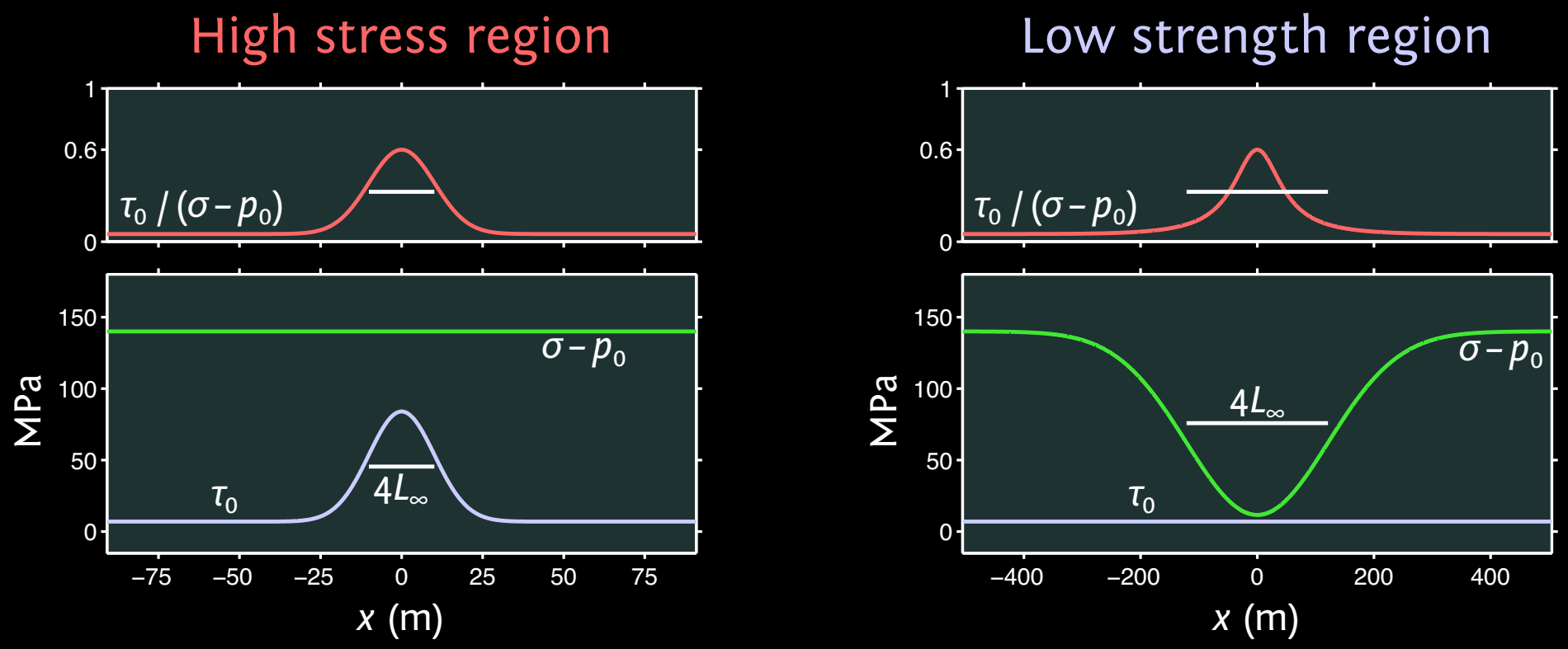
2. Uniform loading and material properties lead to a stress drop of $\sim\mu_0(\sigma - p)$.

3. $\Delta\tau \approx \mu_0(\sigma - p)$ is not compatible with inferred stress drops from natural earthquakes.

We must investigate heterogeneity that leads to smaller $\Delta\tau$.

Slip at small ambient τ_0 allows for pulse-like rupture.

Two sample models of heterogeneity

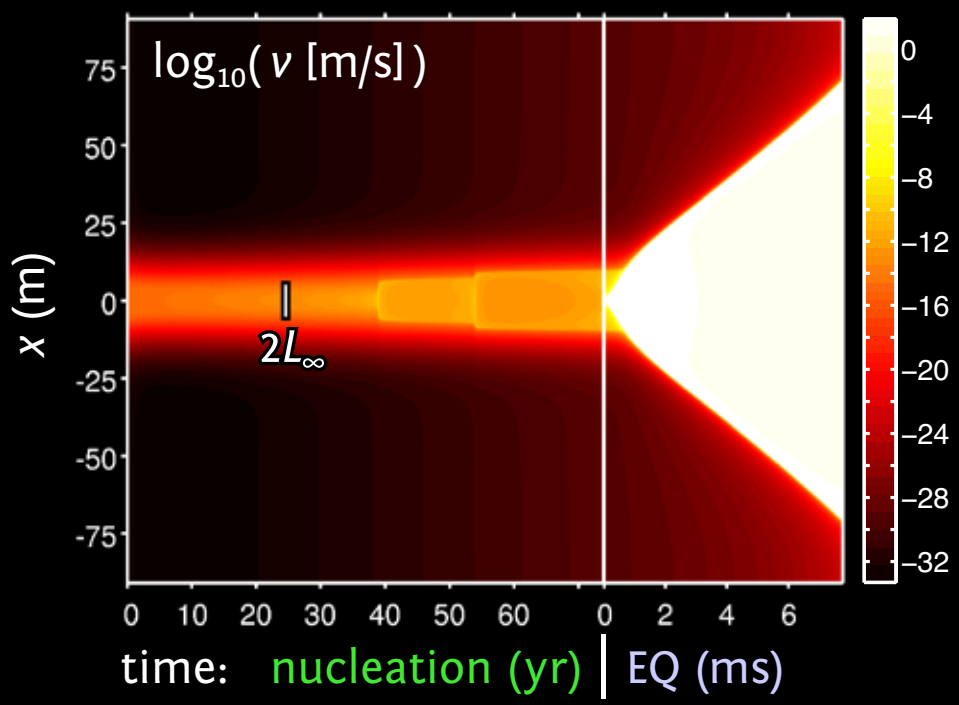


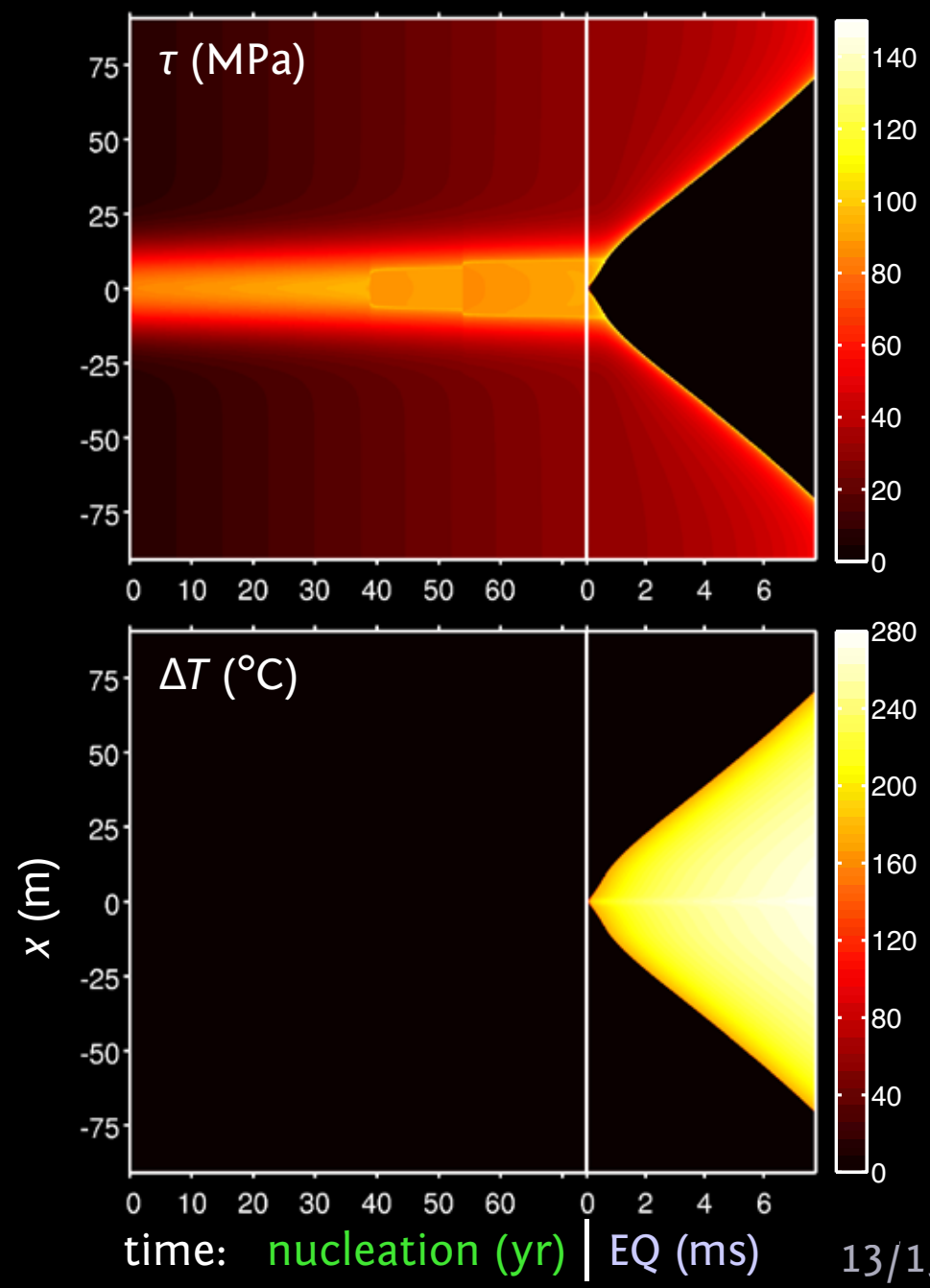
High stress: Region of elevated τ_0, uniform $\sigma - p_0$.
τ_0 variability is resolved into θ_{init}.

Low strength: Uniformly low τ_0, region of elevated p_0.

Both require heterogeneity half-width $w > 2L_\infty$ to initiate instability at low ambient stress.

Nucleation & rupture: high stress region



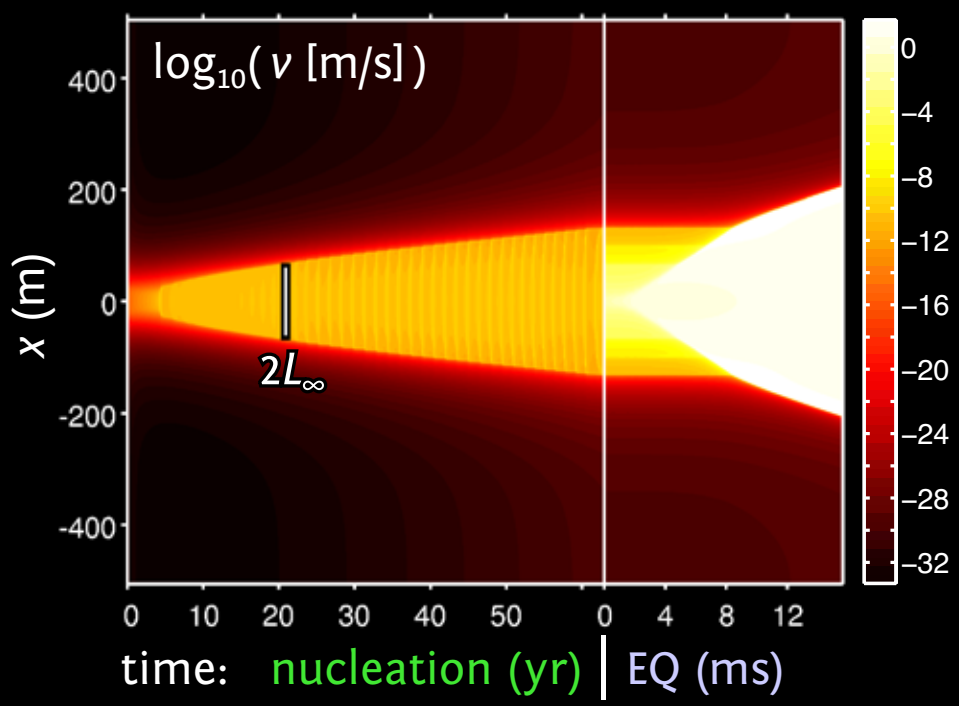


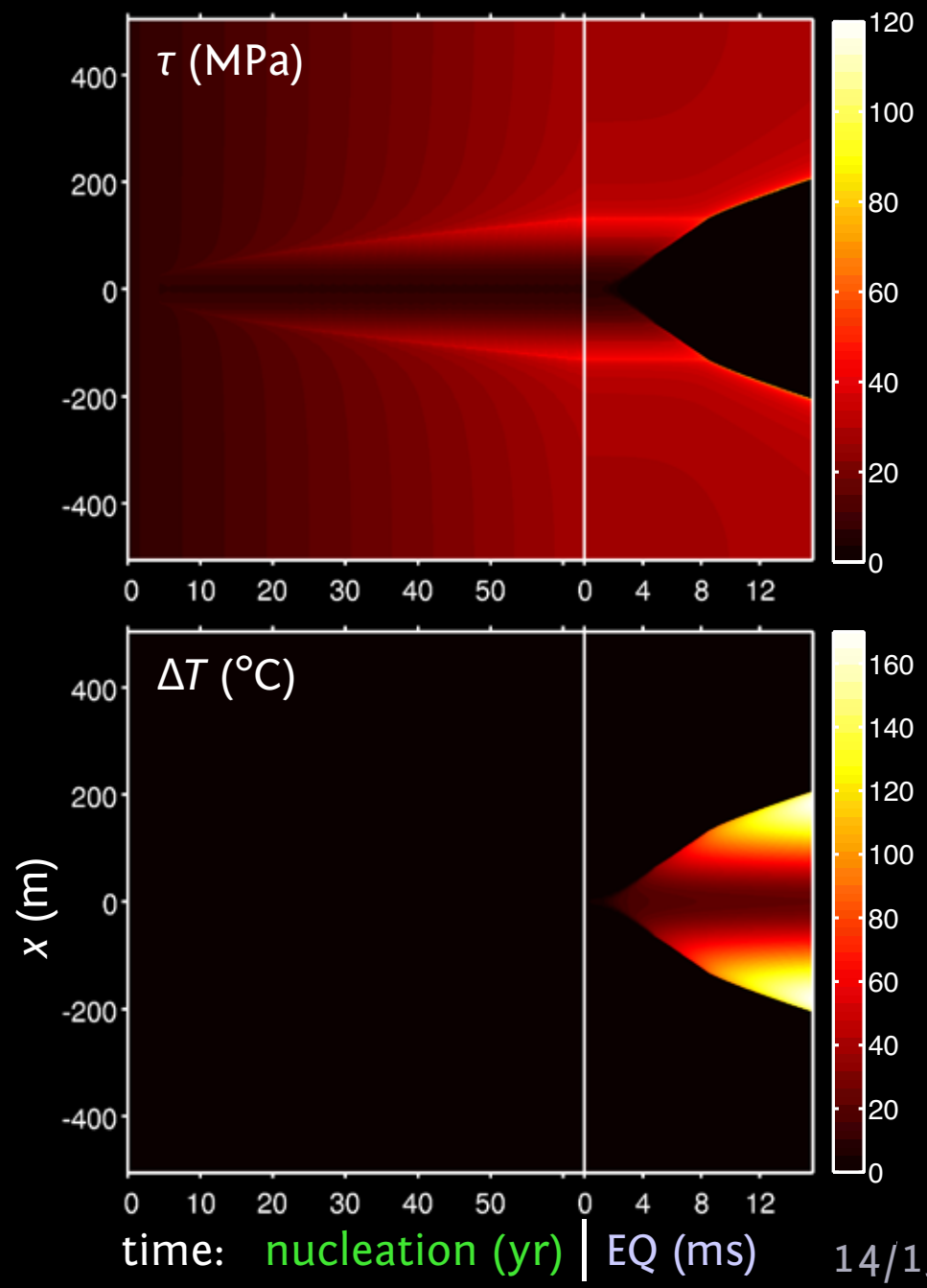
Crack-like rupture into low-stress region.

Total stress drop.

Large ΔT in high-stress region.

Nucleation & rupture: low strength region





Crack-like rupture into high-strength/low-stress region.

Total stress drop.

Small ΔT in low-strength region.

Conclusions

1. Even during nucleation, the width of the shear zone significantly affects thermal pressurization.
2. Thermal pressurization leads to a complete stress drop.
3. Nonuniformity (stress, material, geometry) is necessary to model natural earthquakes.

Outlook

The nucleation phase will be very difficult to observe directly, but heterogeneities may have observable signatures.