Incorporating Dynamic Weakening Mechanisms into Spontaneous Rupture Models

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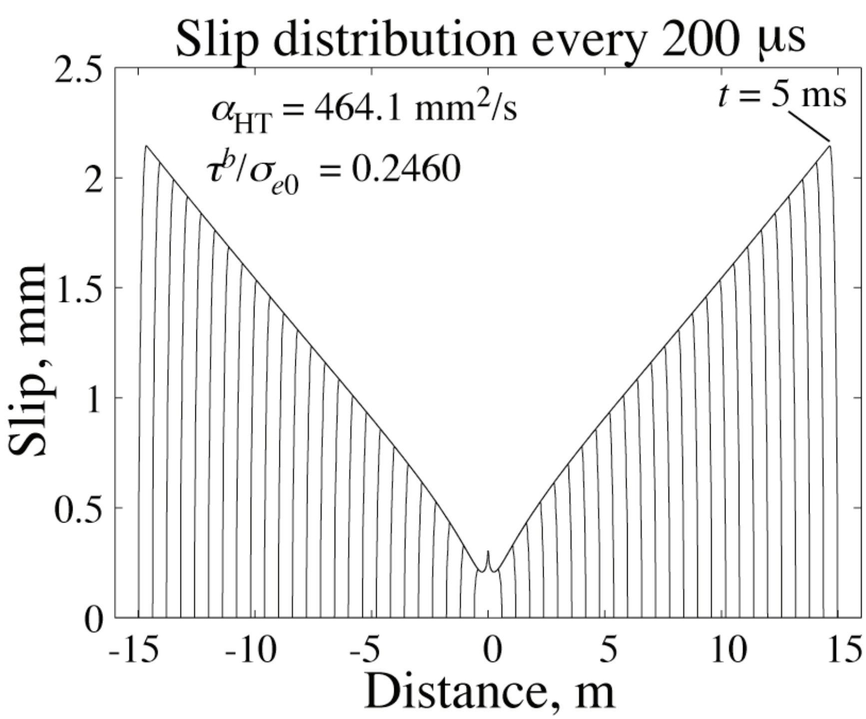
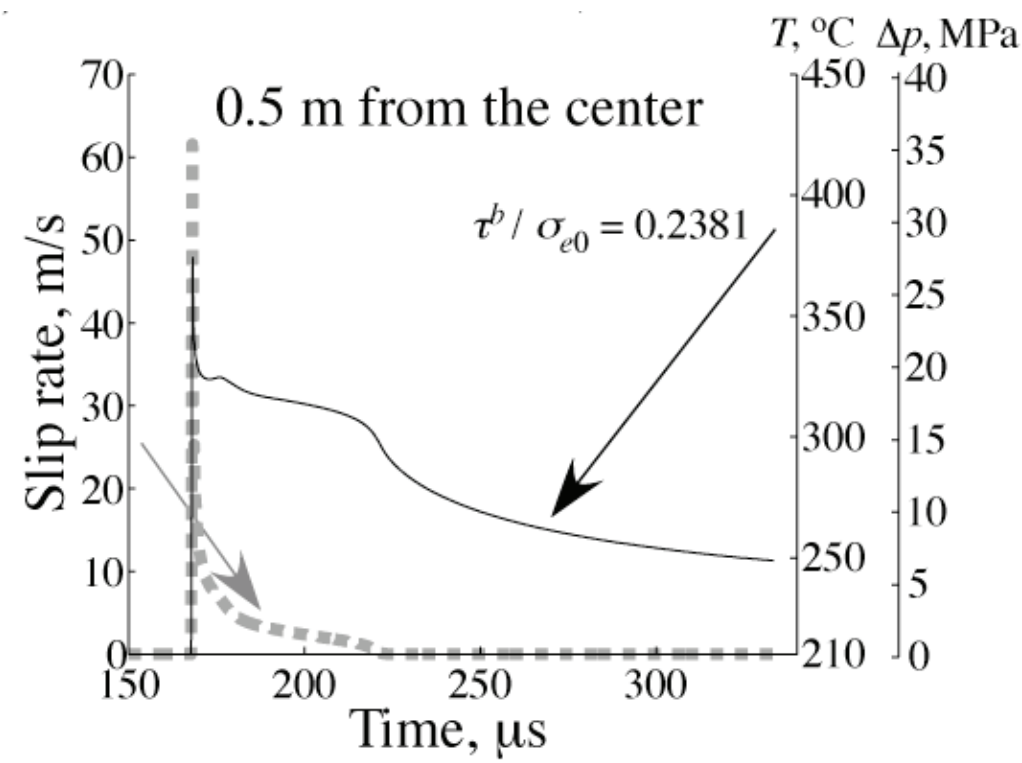




Context for Dynamic Weakening

Extreme localization of seismic slip on mature fault—Punchbowl fault

[F. Chester & J. Chester, 1998; J. Chester et al., 2003, 2005; J. Chester and D. Goldsby, 2003]

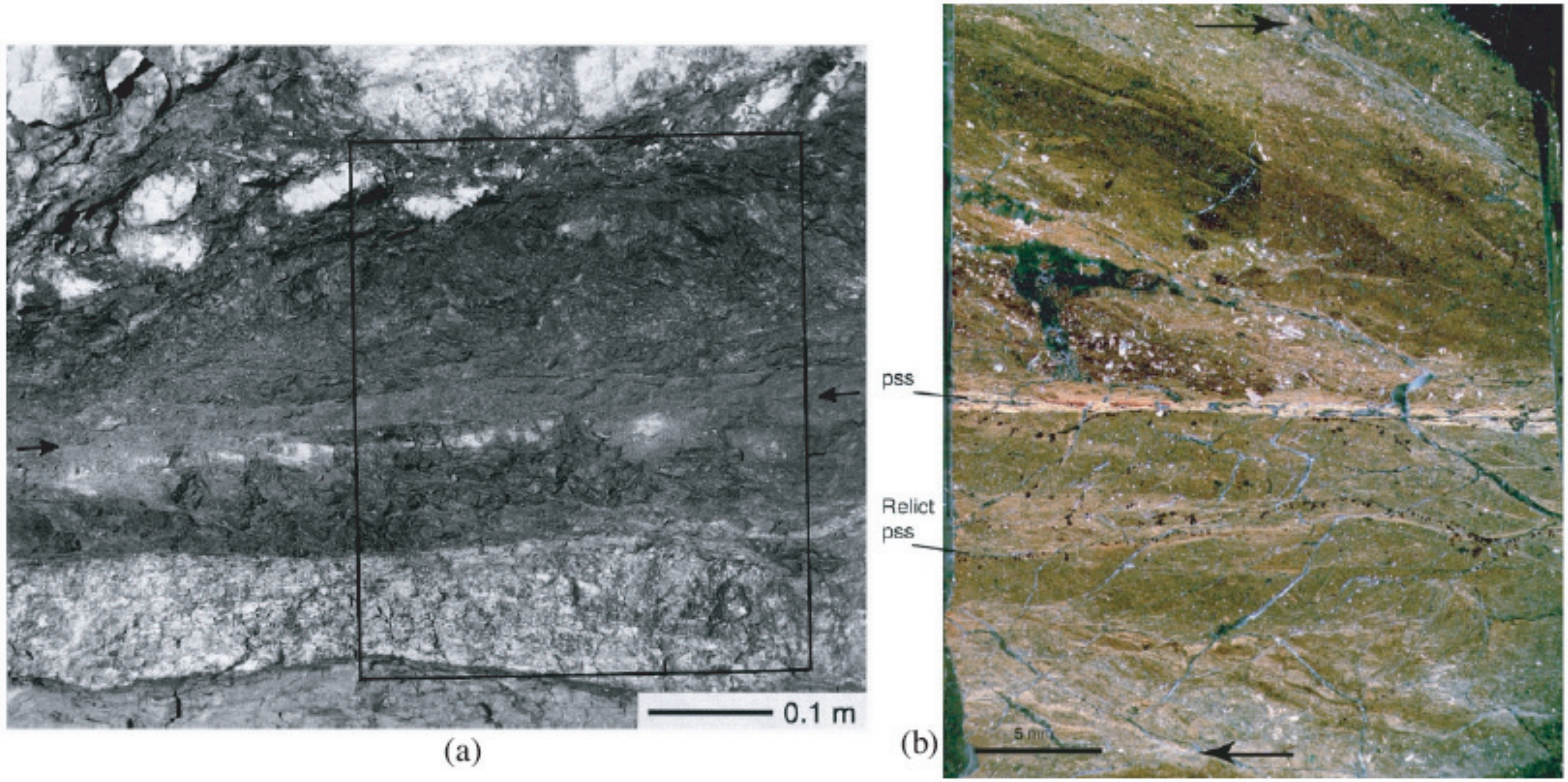


Figure 1: Principal slip surface (pss) along the Punchbowl fault. (a) From Chester and Chester [1998]: Ultracataclasite zone with pss marked by black arrows; note 100 mm scale bar. (b) From Chester et al. [2005a] (also, Chester et al. [2003] and Chester and Goldsby [2003]): Thin section; note 5 mm scale bar and ~1 mm localization zone (bright strip when viewed in crossed polarizers due to preferred orientation), with microshear localization of most intense straining to ~100-300 μm thickness.

[Rice, 2006]

Context for Dynamic Weakening

Weakening of fault shear strength τ due to changes in:

f = coefficient of friction
σ = normal stress
p = pore pressure

$$\tau = f(\sigma - p)$$

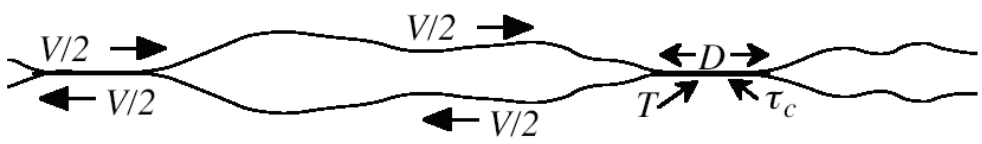
High temperatures expected from sliding at standard friction coefficients (f~0.6) and effective normal stresses (σ–p~100 MPa),

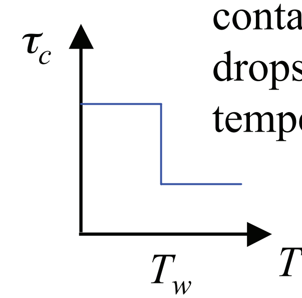
but evidence for melt (pseudotachylites) is not universally present.

Dynamic weakening (decrease in f and increase in p) reduces τ, but only during rapid sliding (~m/s).

Recent laboratory friction experiments and measurements of thermal and hydraulic properties of fault-zone materials constrain models of dynamic weakening (flash heating and thermal pressurization).

Flash Heating of Microscopic Asperity Contacts



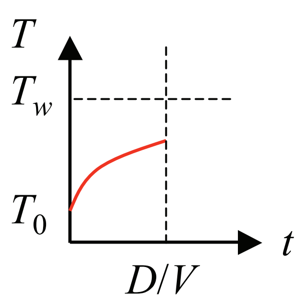


contact strength drops at weakening temperature

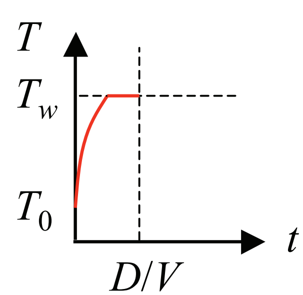
energy balance

$$\underbrace{\tau_c V t}_{\text{work by shear heating}} \sim \underbrace{\rho c (T - T_0)}_{\text{thermal energy storage}} \underbrace{\sqrt{\alpha_{th} t}}_{\text{thermal diffusion length}}$$

τ_c = contact strength
V = slip velocity
ρc = heat capacity
T = temperature
α_{th} = thermal diffusivity
D = asperity length



slow speeds: $V<V_w$

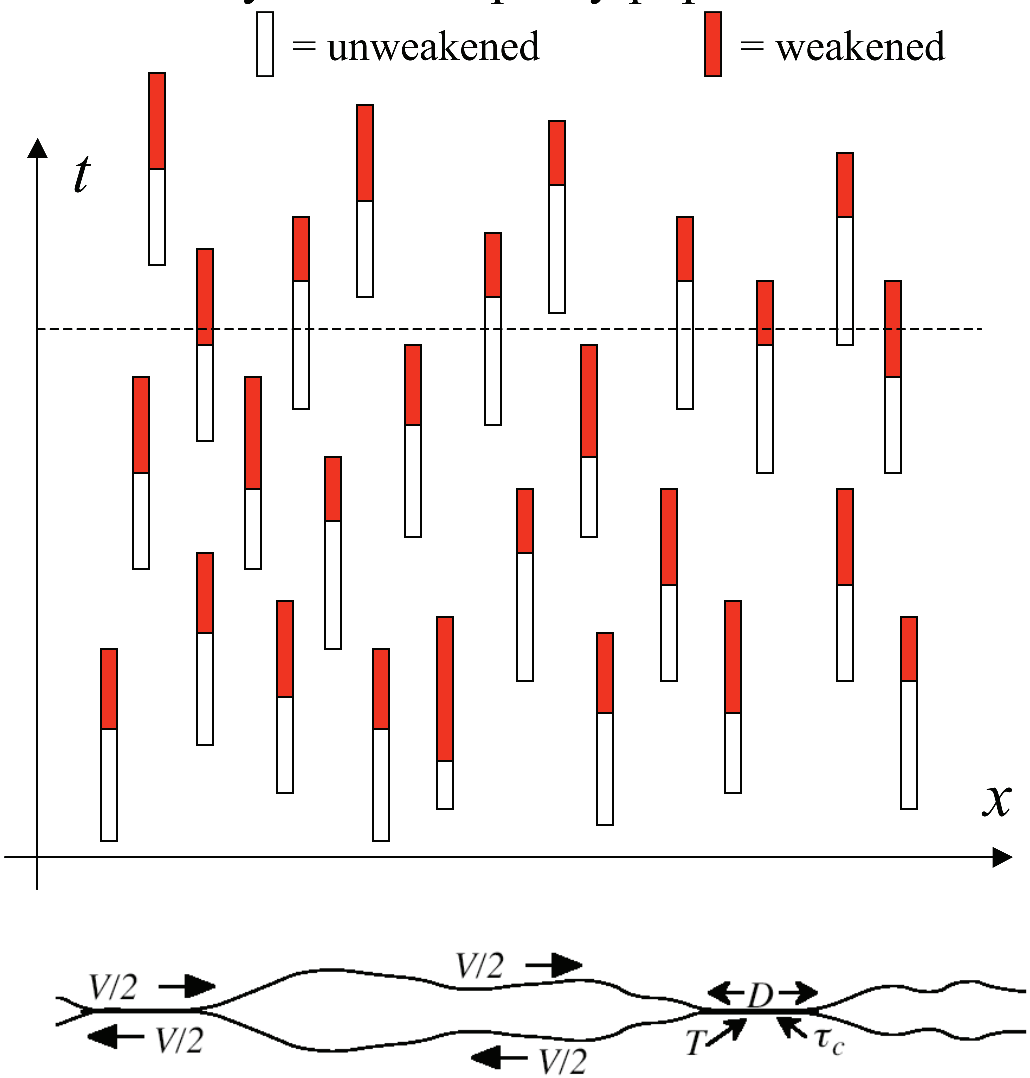


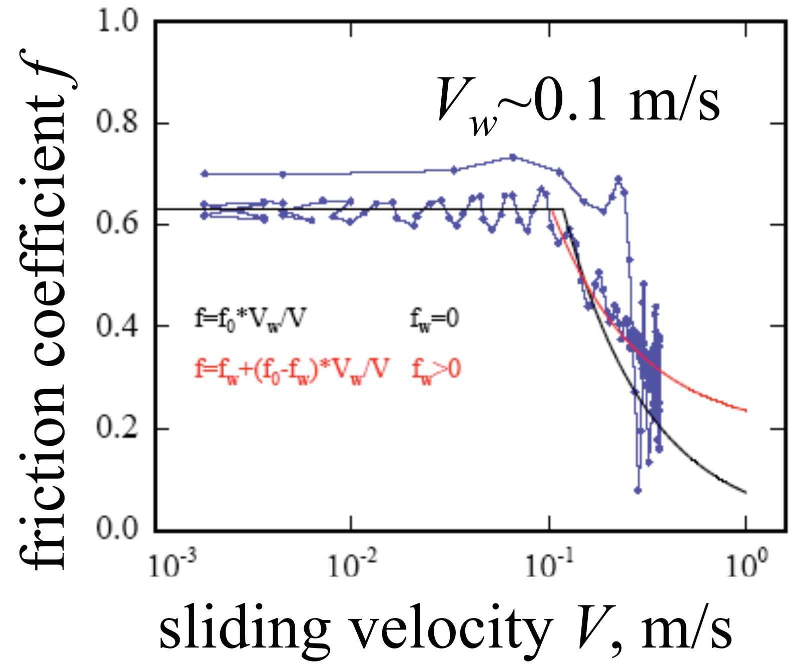
high speeds: $V>V_w$

V_w (weakening velocity) is V at which asperity reaches $T=T_w$ (weakening temperature at which τ_c abruptly drops) exactly at $t=D/V$ (asperity lifetime)

Ensemble of Contacts and Model for *f*(*V*)

macroscopic strength determined by current asperity population





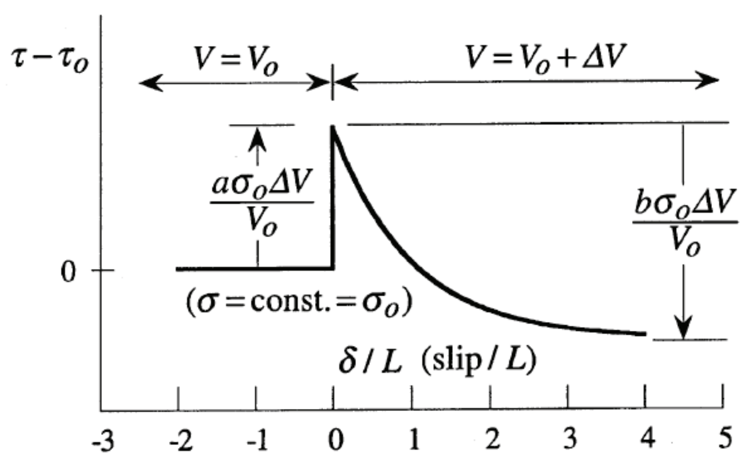
experimental results of Tullis and Goldsby [2003] and fits to theoretical model of flash heating by Rice [1999] and its extension by Beeler [unpublished]

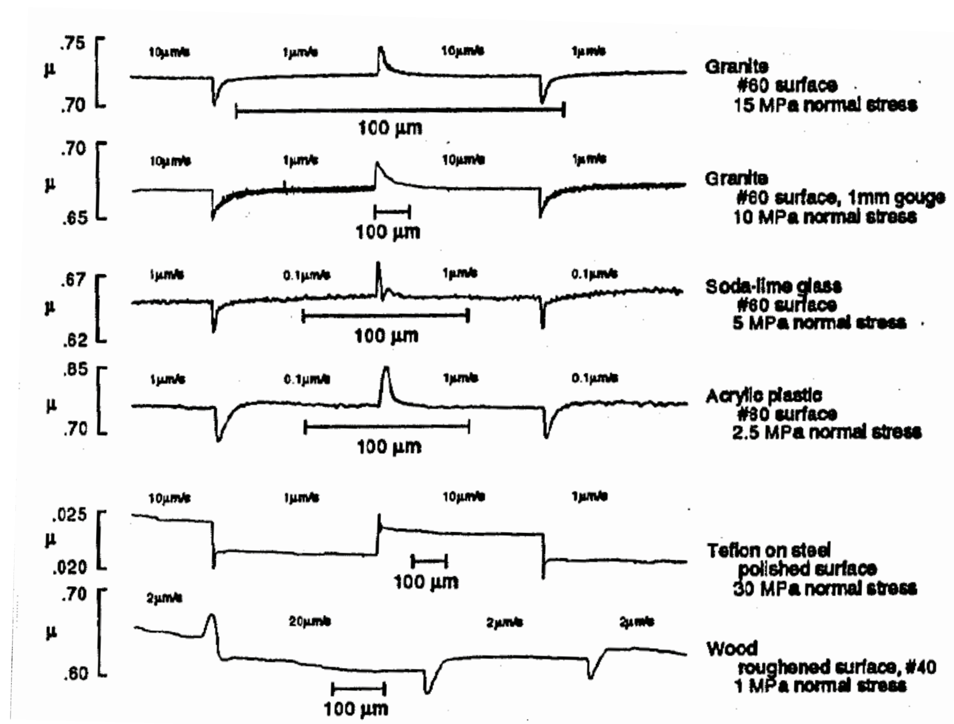
Rate-and-State Framework for f

Framework for coefficient of friction f includes:

1. flash heating model for $f_{ss}(V)$
2. direct effect (parameter a)—evidence for thermally activated process (dislocations) at asperity contacts
3. evolution to new steady state over slip L

$$\frac{df}{dt} = \frac{a}{V}\frac{dV}{dt} - \frac{V}{L}\left[f - f_{ss}(V)\right]$$





[Dieterich and Kilgore, 1994]

Thermal Pressurization: Model for *p*

Conservation of energy:

$$\frac{\partial T}{\partial t} = \alpha_{th}\frac{\partial^2 T}{\partial y^2} + \frac{\tau\dot{\gamma}}{\rho c}, \quad \int \dot{\gamma}(y)\,dy = V$$

T = temperature
α_{th} = thermal diffusivity
$\dot{\gamma}$ = strain rate (over finite shear zone)
V = slip velocity

Conservation of fluid mass:

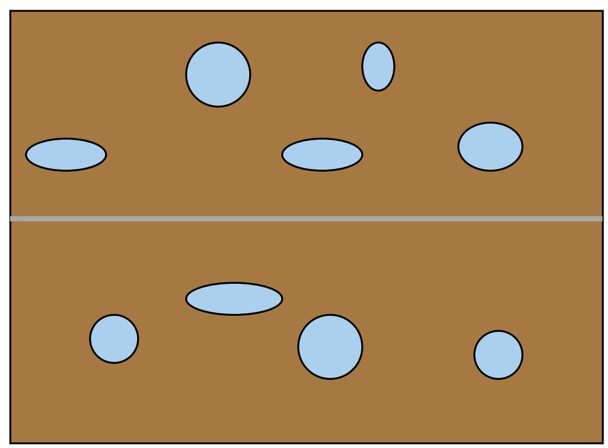
$$\frac{\partial p}{\partial t} = \Lambda\frac{\partial T}{\partial t} + \alpha_{hy}\frac{\partial^2 p}{\partial y^2}$$

p = pore pressure
α_{hy} = hydraulic diffusivity
Λ = pressure-temperature coupling

treat thermodynamic properties as constants (i.e., neglect pressure dependence of permeability, etc.)

[Rice, 2006; building on Sibson, 1973 and many others; thermal and hydraulic properties from variety of laboratory studies of fault-zone materials (from exhumed faults and drilling projects)]

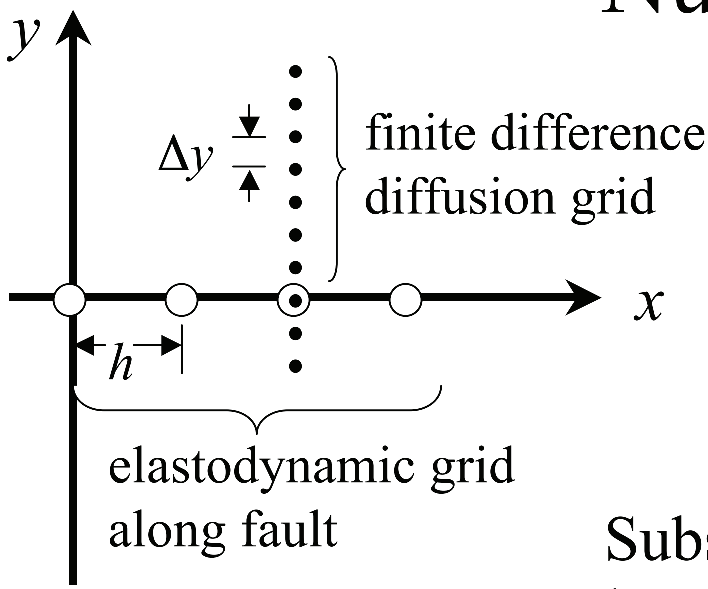
heat while holding fluid mass m fixed (undrained response)



- thermal expansion coefficient of water ($\sim 10^{-3}$ K^{-1}) >> pores
- water and pores equally compressible ($\sim$GPa^{-1})

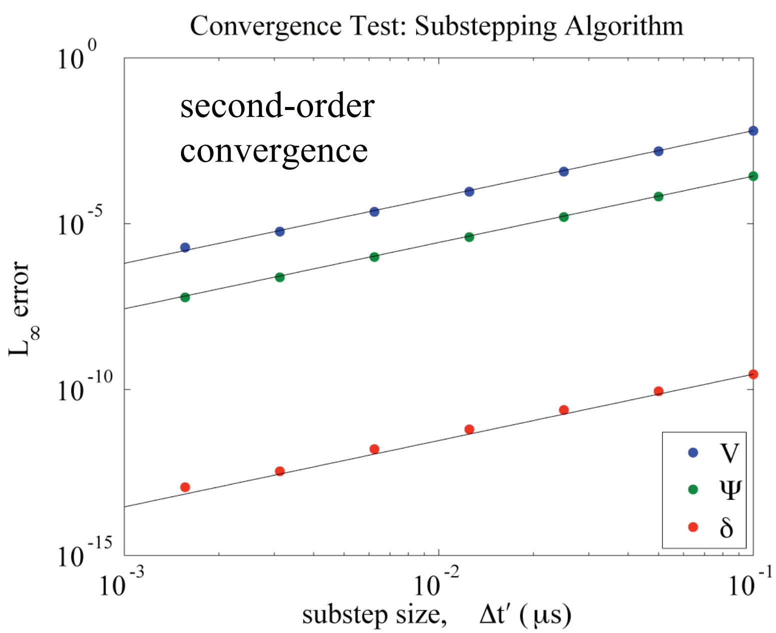
$$\Lambda = \left(\frac{\partial p}{\partial T}\right)_m \sim \text{MPa/K}$$

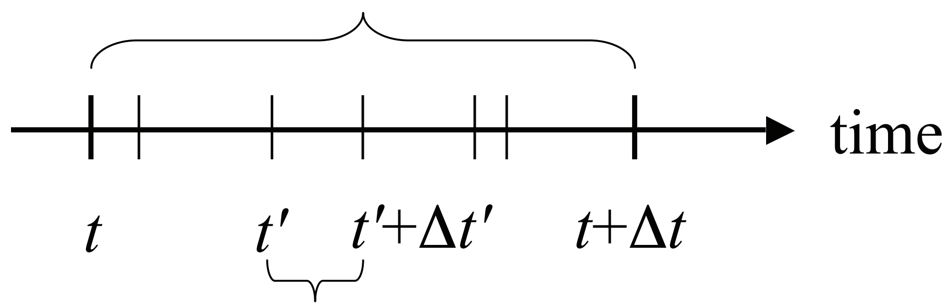
Numerical Methodology



elastodynamic response currently from boundary integral equation method, although similar implementation in finite difference / finite element codes

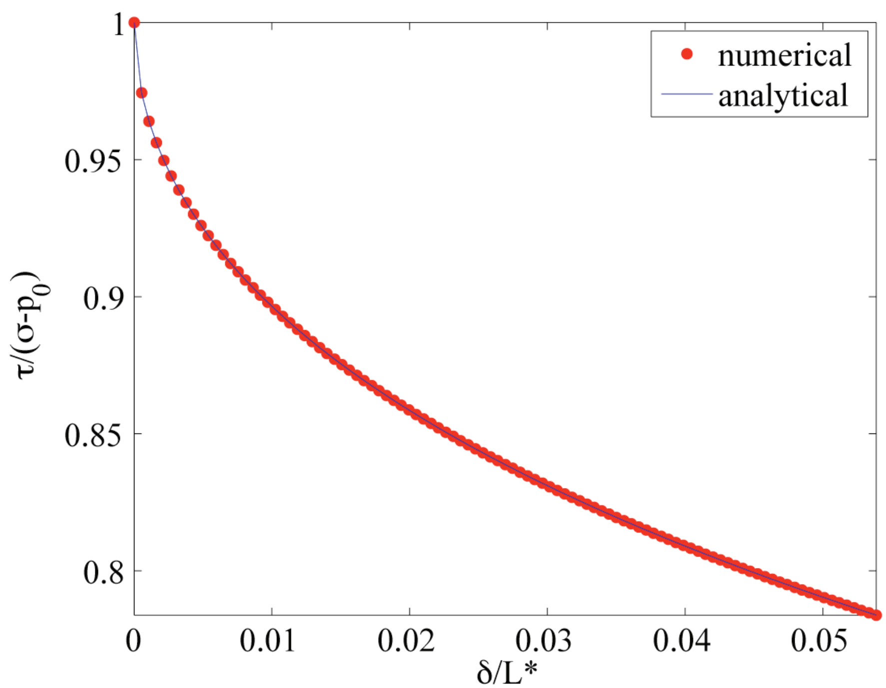
Substepping: elastodynamic time step $\sim h/c_s$ larger than diffusive time step $\sim \Delta y^2/\alpha_{hy}$

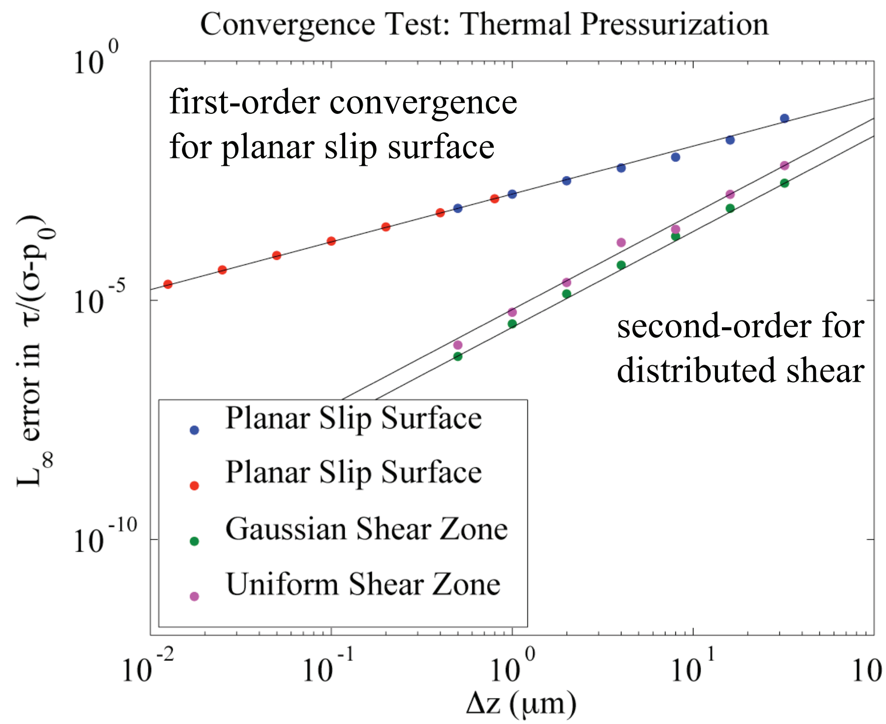




integrate diffusion equations and friction law with adaptive time steps via embedded Runge–Kutta methods

Finite Differences for Thermal Pressurization





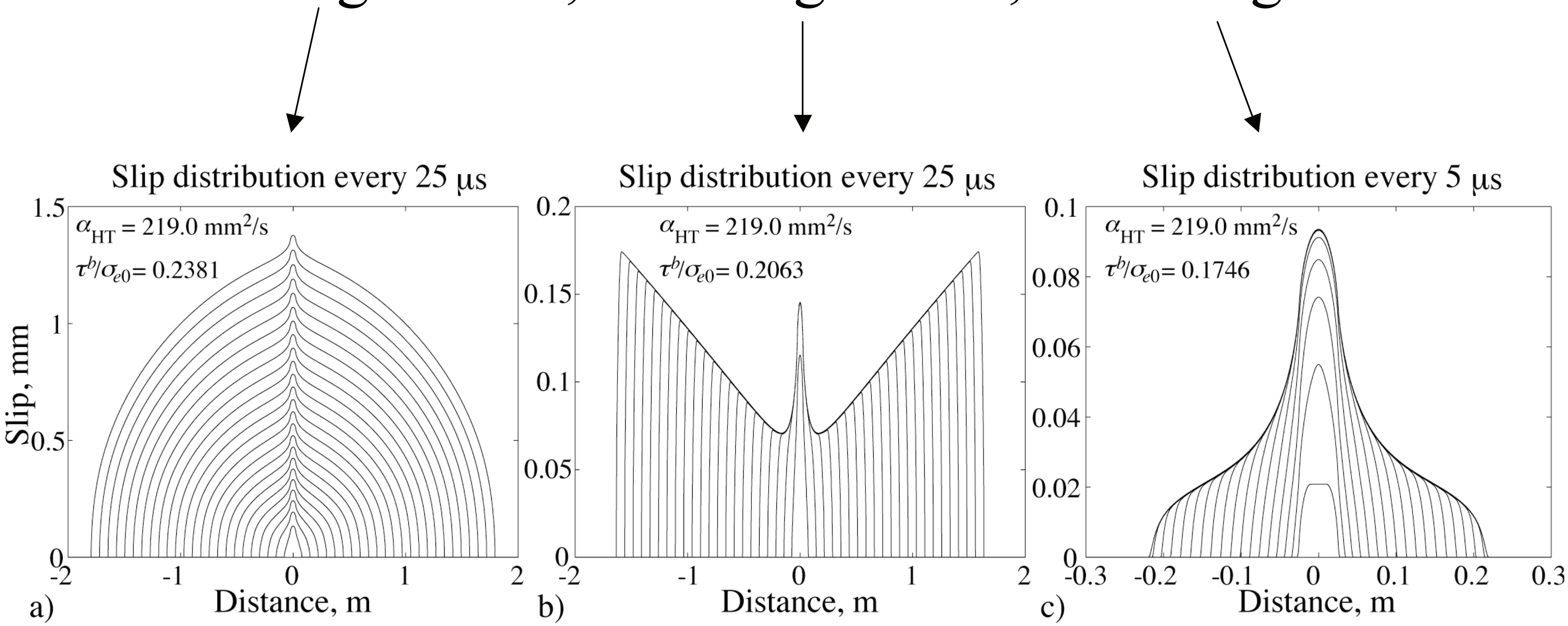
analytical solution for weakening over slip δ due to thermal pressurization of planar fault at constant f and V [Rice, 2006]

$$\tau \sim f(\sigma - p_0)\sqrt{\frac{L^*}{\pi\delta}} \text{ for large } \delta$$

$$L^* = \frac{4}{f^2}\left(\frac{\rho c}{\Lambda}\right)^2 \frac{\left(\sqrt{\alpha_{hy}+\alpha_{th}}\right)^2}{V} \approx 4 - 30 \text{ mm}$$

continual weakening allows fracture energy to increase with slip, as indicated by seismic observations

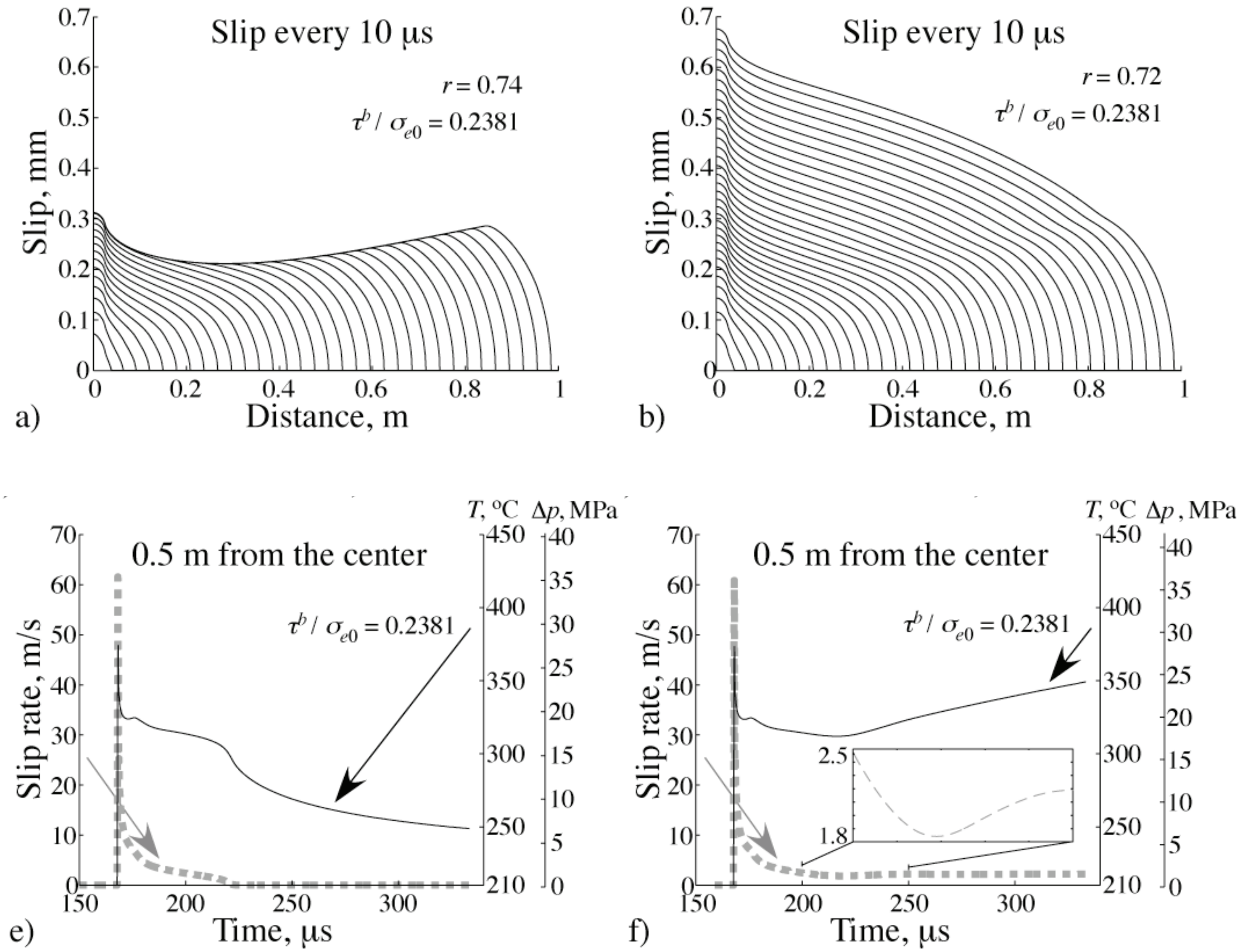
Rich Phenomenology:
Growing Cracks, Growing Pulses, Arresting Pulses



nucleation procedure: overstress small asperity in center

[Noda, Dunham, and Rice, in preparation, 2007]

Properties of Pulses and Cracks



[Noda, Dunham, and Rice, in preparation, 2007]

Pulse Generation by Under-Stressing

Cracks only exist when solution exists to:

Long-wavelength elastodynamic response:

$$\tau \approx \tau_0 - \frac{\mu}{2c_s} V$$

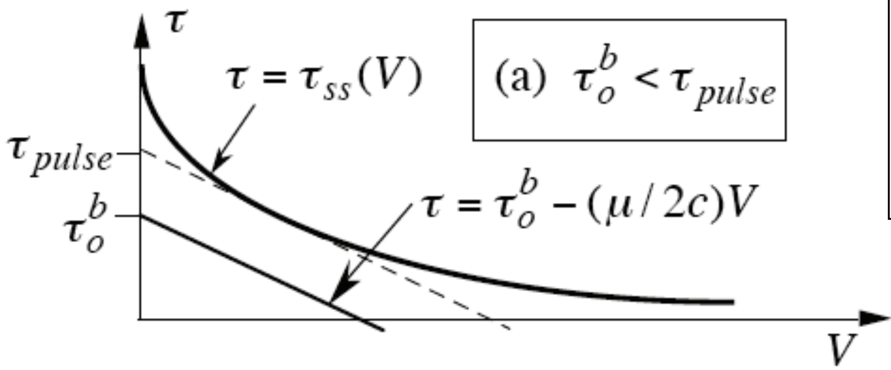
τ_0 = initial stress on fault
μ = shear modulus
c_s = shear-wave speed
V = slip velocity

Steady-state friction:

$$\tau = \tau_{ss}(V)$$

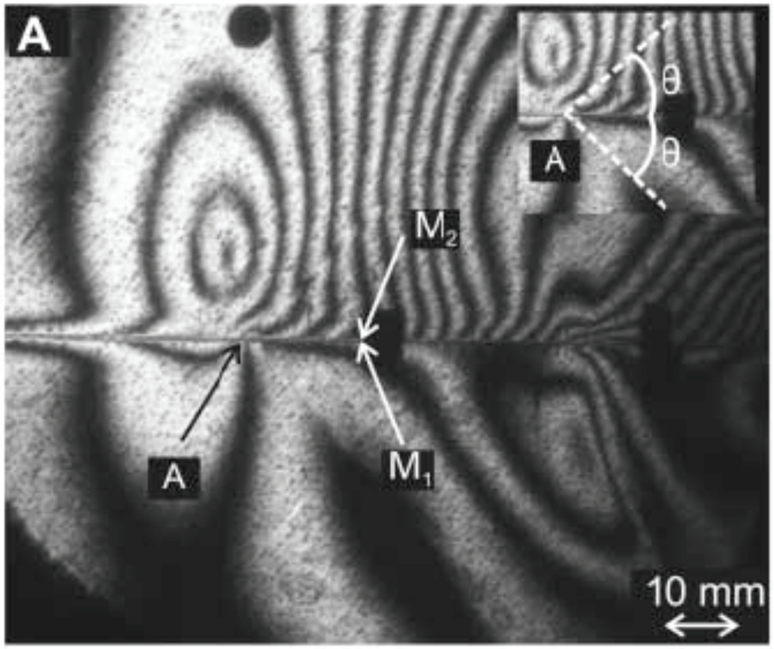
By decreasing $\tau_0 < \tau_{pulse}$, solution ($V \neq 0$) ceases to exist and only slip pulses are found on fault.

τ_0, a free parameter in single earthquake simulations, is constrainable only by modeling earthquake cycle.

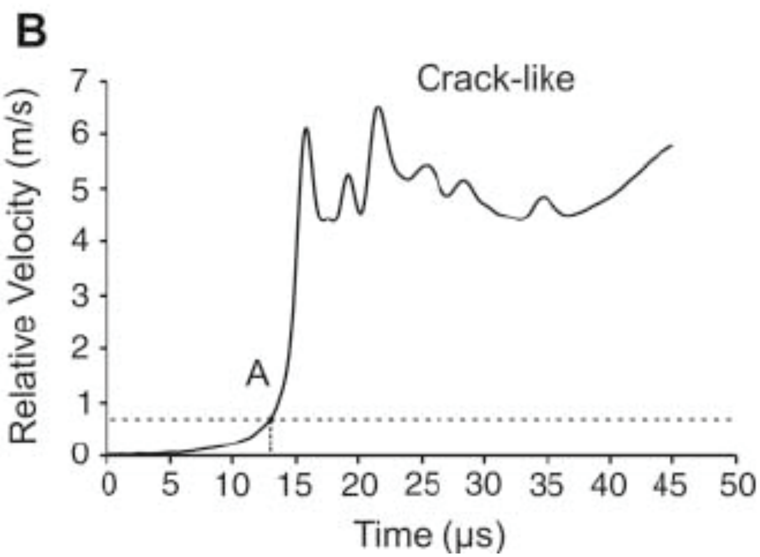


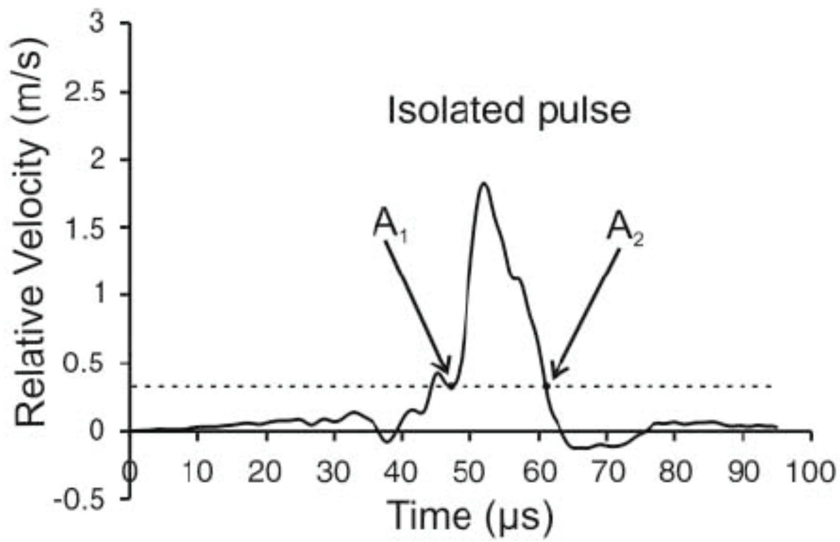
[Zheng and Rice, 1998]

Theory Consistent with Laboratory Experiments



(transition from crack to pulse as shear/normal load decreases)

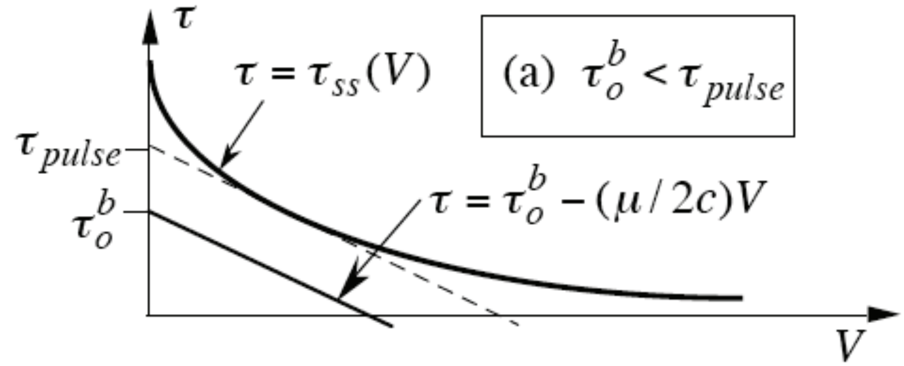




[Lykotrafitis et al., 2006]

Generalizing the Theory

$$\tau = \tau_{ss}(V) \rightarrow$$
$$\tau = f_{ss}(V)(\sigma - p)$$



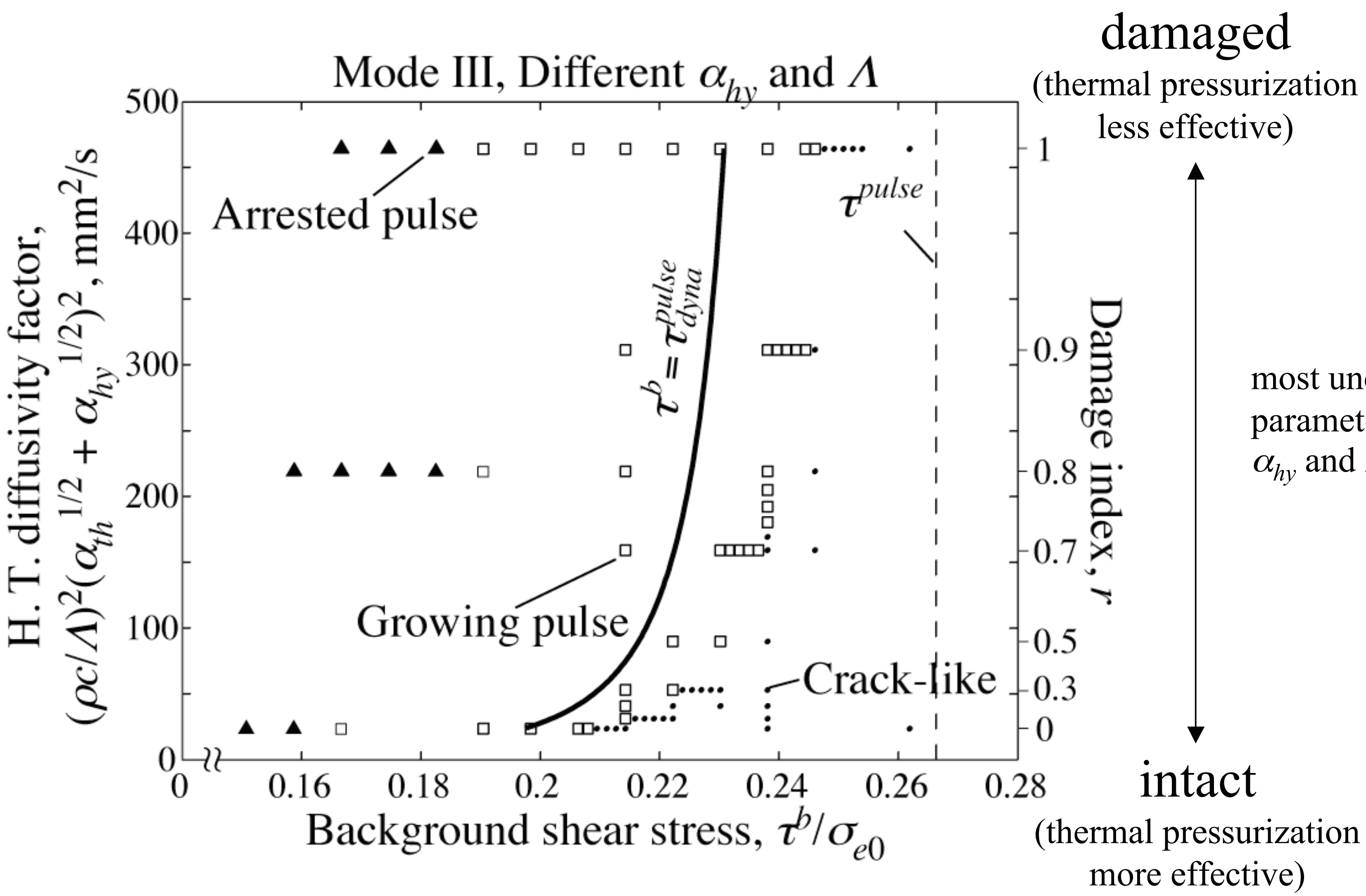
Increasing p lowers $\tau_{ss}(V)$, potentially bringing crack solution into existence, appropriate value of p exploits scale separation between thermal pressurization (L^*~10 mm) and flash heating (L~10 μm) by permitting use of f_{ss}(V)

characteristic slip for thermal pressurization [Rice, 2006] is

$$L^* = \frac{4}{f^2}\left(\frac{\rho c}{\Lambda}\right)^2 \frac{\left(\sqrt{\alpha_{hy}} + \sqrt{\alpha_{th}}\right)^2}{V} \approx 4 - 30 \text{ mm}$$

(and finite width shear zone introduces another scale…)

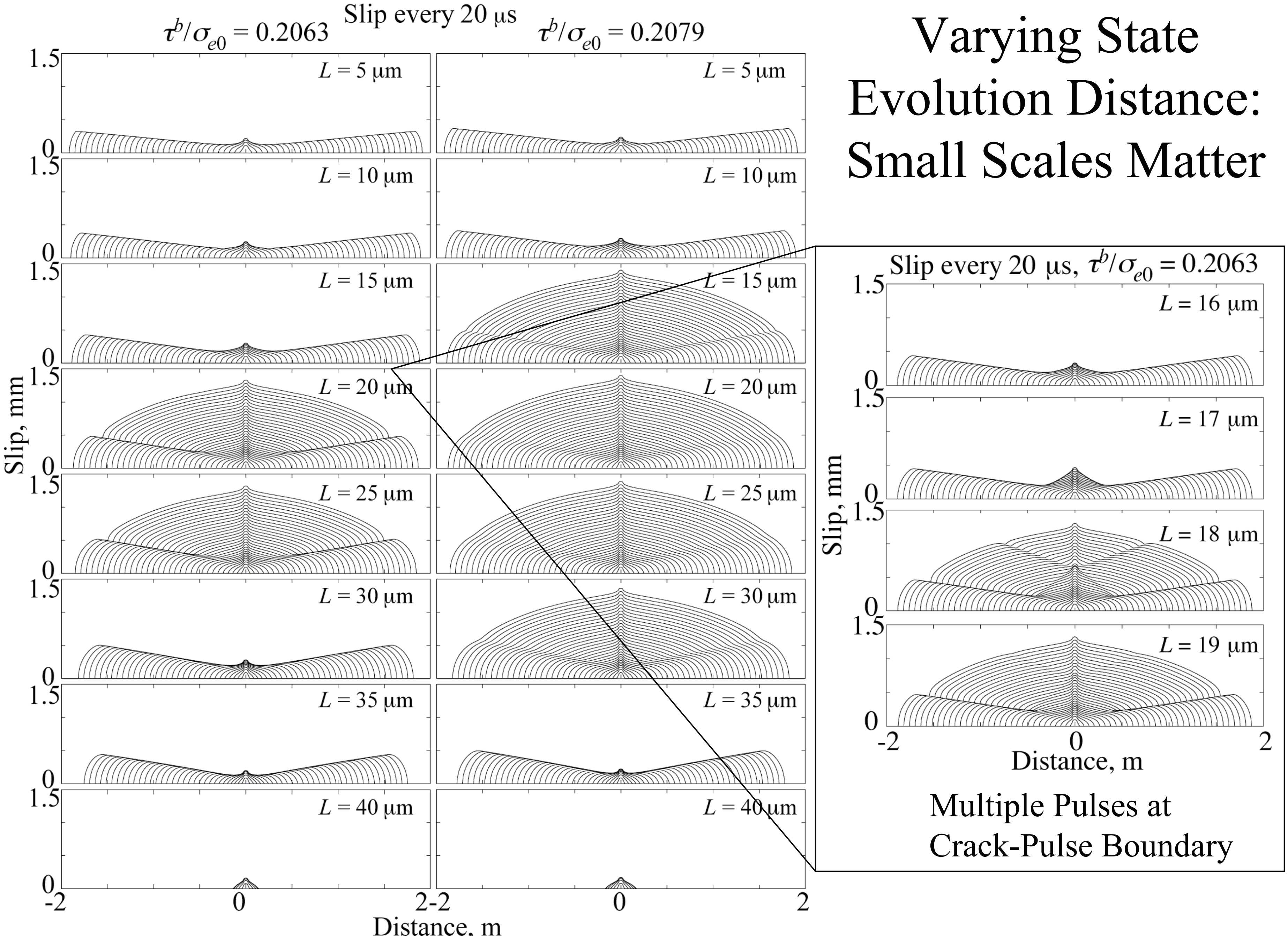
Mapping Parameter Space: Effect of Hydrothermal (H.T.) Properties



most uncertain parameters are α_{hy} and Λ

[Noda, Dunham, and Rice, in preparation, 2007]

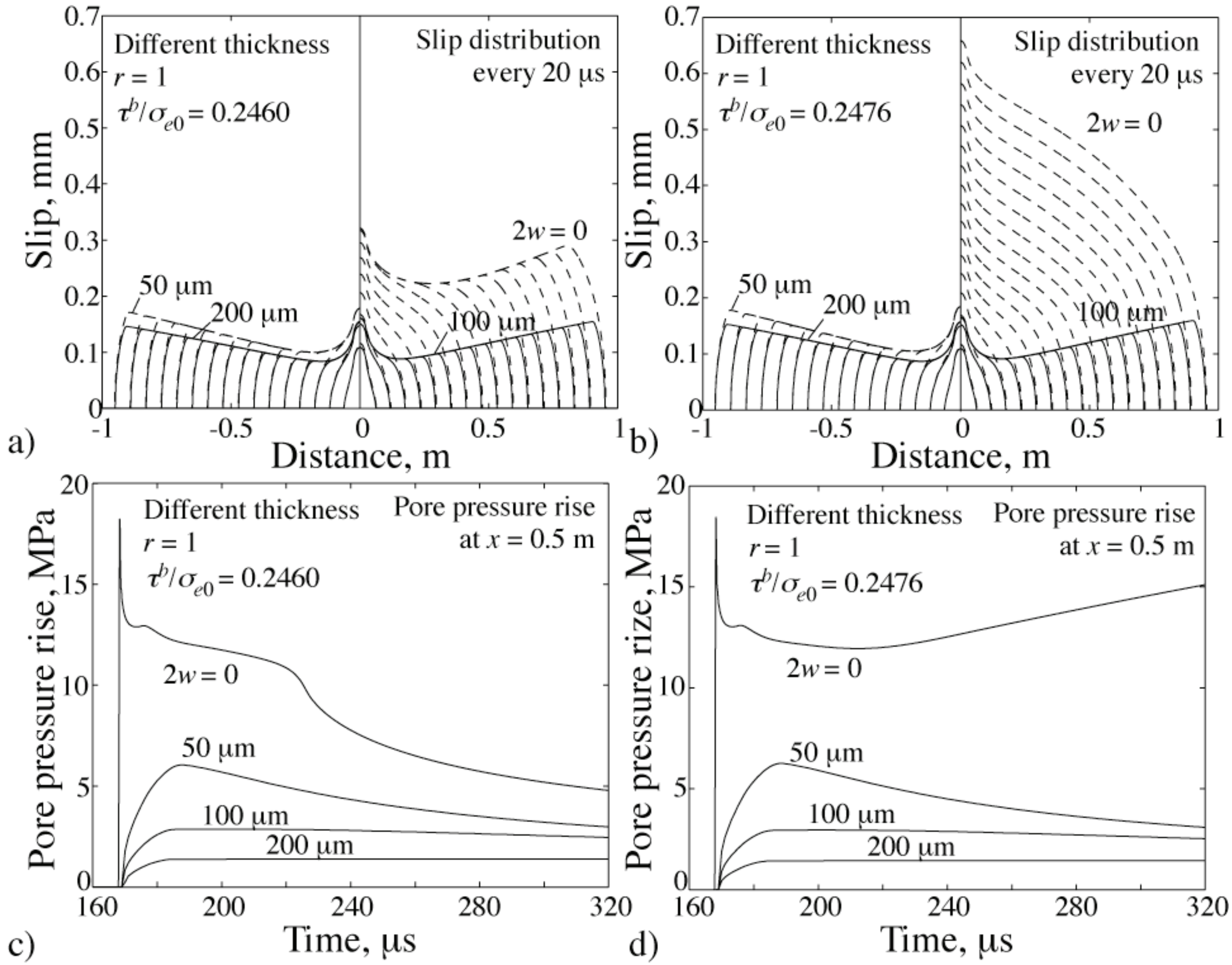
Varying State Evolution Distance: Small Scales Matter



Multiple Pulses at Crack-Pulse Boundary

[Noda, Dunham, and Rice, in preparation, 2007]

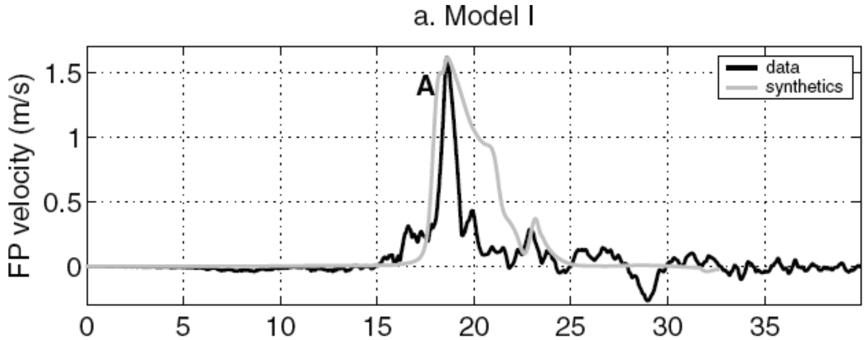
Shear Zone Thickness Matters



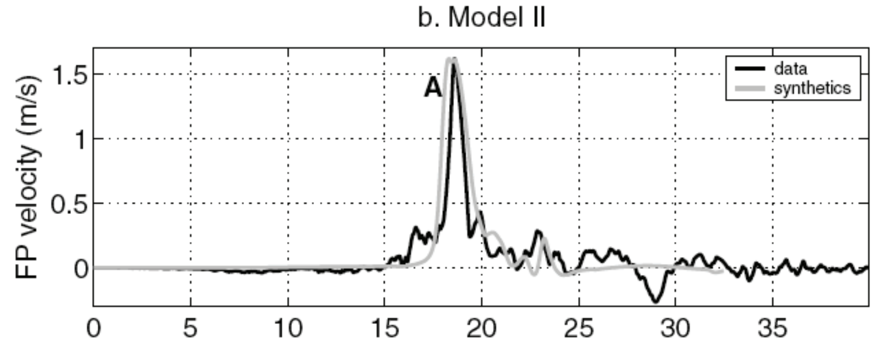
[Noda, Dunham, and Rice, in preparation, 2007]

Consistency with Natural Events

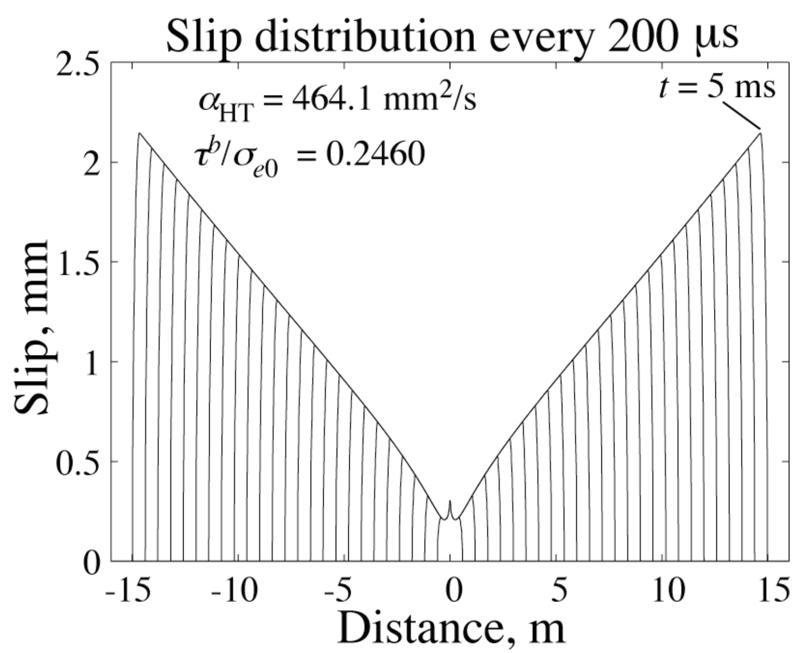
cracklike rupture from
slip-weakening friction



slip pulse from friction with
velocity-weakening steady state



slip pulses observed in earthquakes: evidence from near-source ground motion records
(example above 3 km from 2002 Denali Fault earthquake [Dunham and Archuleta, 2004])



proper scaling with event size:
mm slip over 10 m fault
m slip over 10 km fault

[Noda, Dunham, and Rice, in preparation, 2007]

Conclusions:

Dynamic weakening mechanisms permit faults to operate at far lower average stress levels ($\tau/\sigma \sim 0.25$) than expected from static friction measurements ($\tau/\sigma \sim 0.6$); helps solve heat flow problem

Thermal pressurization gives proper scaling of fracture energy with event size, and velocity-weakening friction generates pulses

-reasonable static stress drops (~MPa)

-faults can host consecutive large events (stress not reduced to zero after event)

-huge slip velocities (>10 m/s) last only ~10 μs (unobservable)

Overlap with Quasi-static Community:

Initial stress levels (from earthquake cycle models)

Hydrology over interseismic time scales (3D diffusion problem)