Earthquake Ruptures with Thermal Weakening and the Operation of Faults at Low Overall Stress Levels

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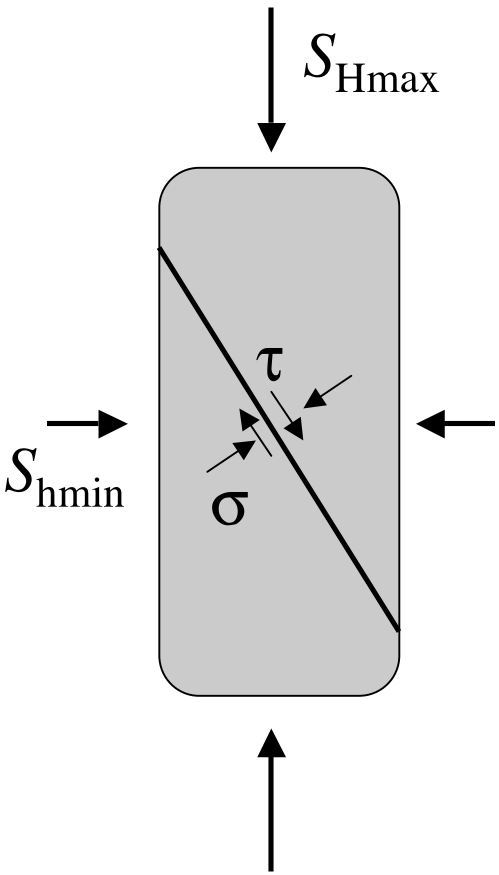
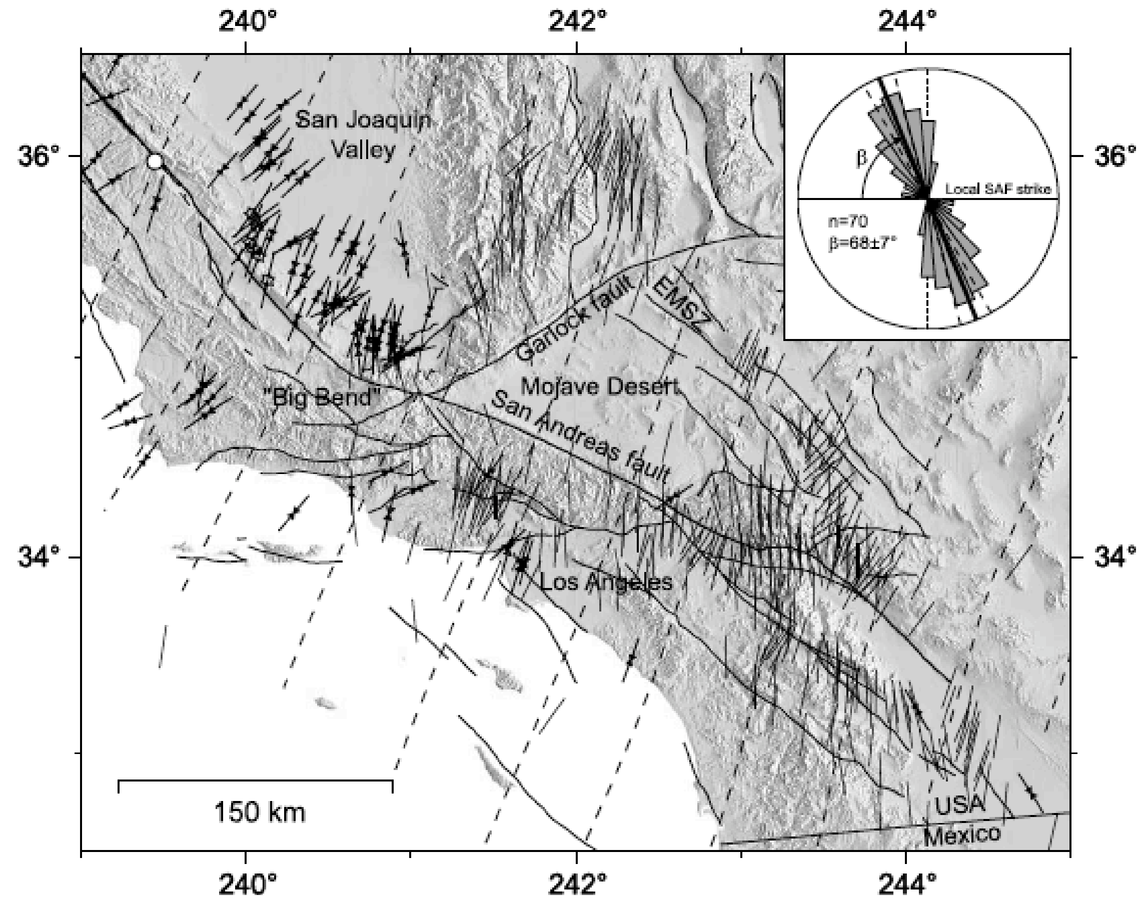
Maximum compressive stress at 68±7° from local SAF strike

(from borehole breakouts, hydraulic fracturing, earthquake focal mechanisms)

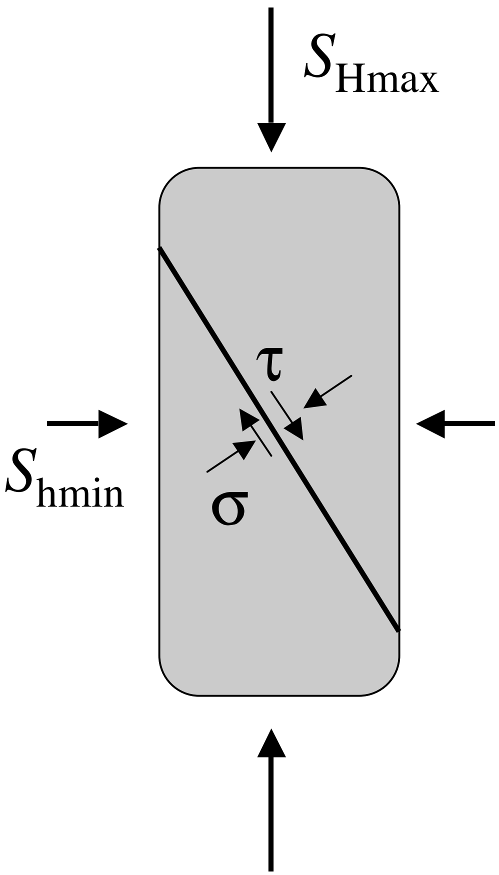


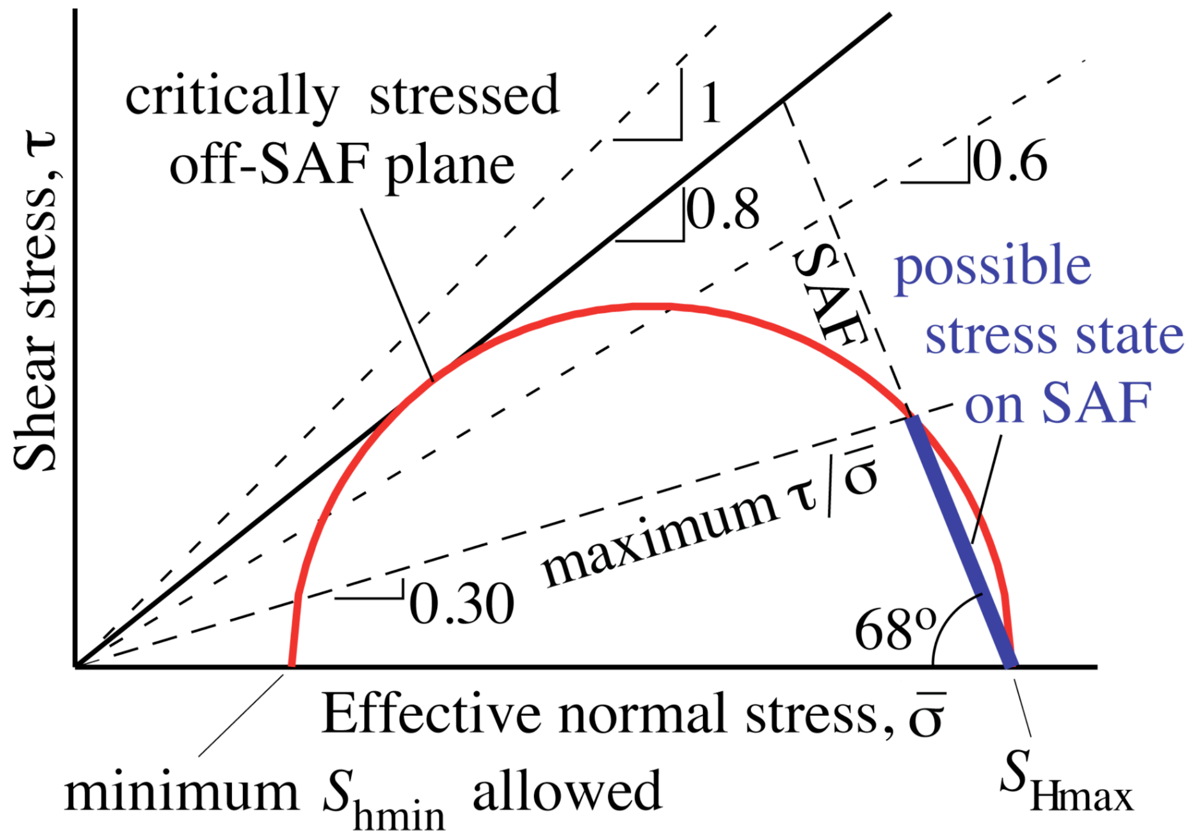


[Townend and Zoback, 2004]

1. Maximum compressive stress at 68±7° from local SAF strike
2. Stresses in crust cannot exceed static friction (assuming $f_s \sim 0.8$)

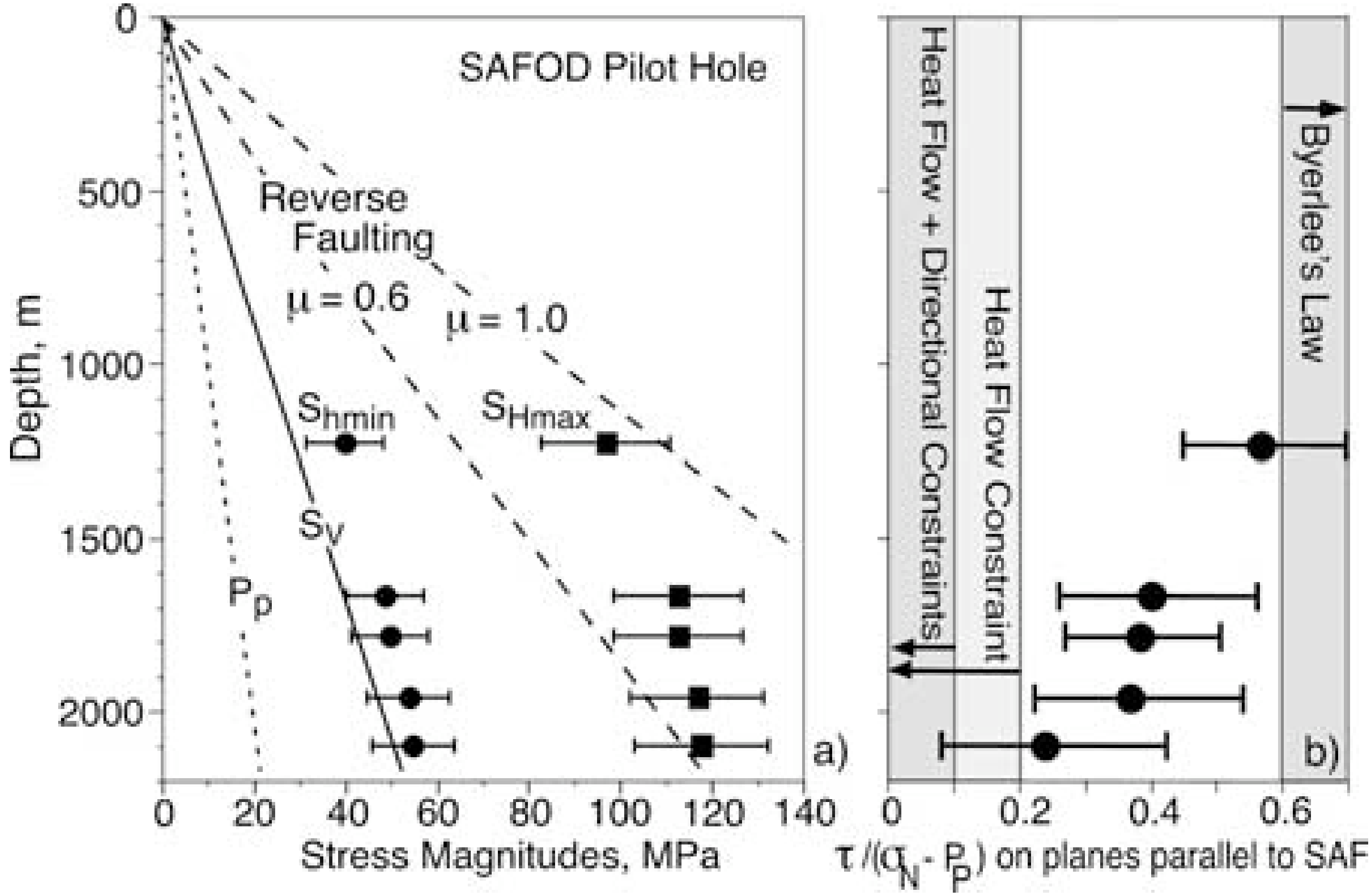
$\Rightarrow$ Maximum $\tau/(\sigma - p)$ on SAF is ~0.3





[Noda, Dunham, and Rice, submitted 2008]

Stresses in SAFOD Pilot Hole: $\tau/(\sigma - p) \approx 0.2\text{–}0.3$ at 2.2 km depth



[Hickman and Zoback, 2004]

Fault Mechanics and Dynamic Weakening Mechanisms

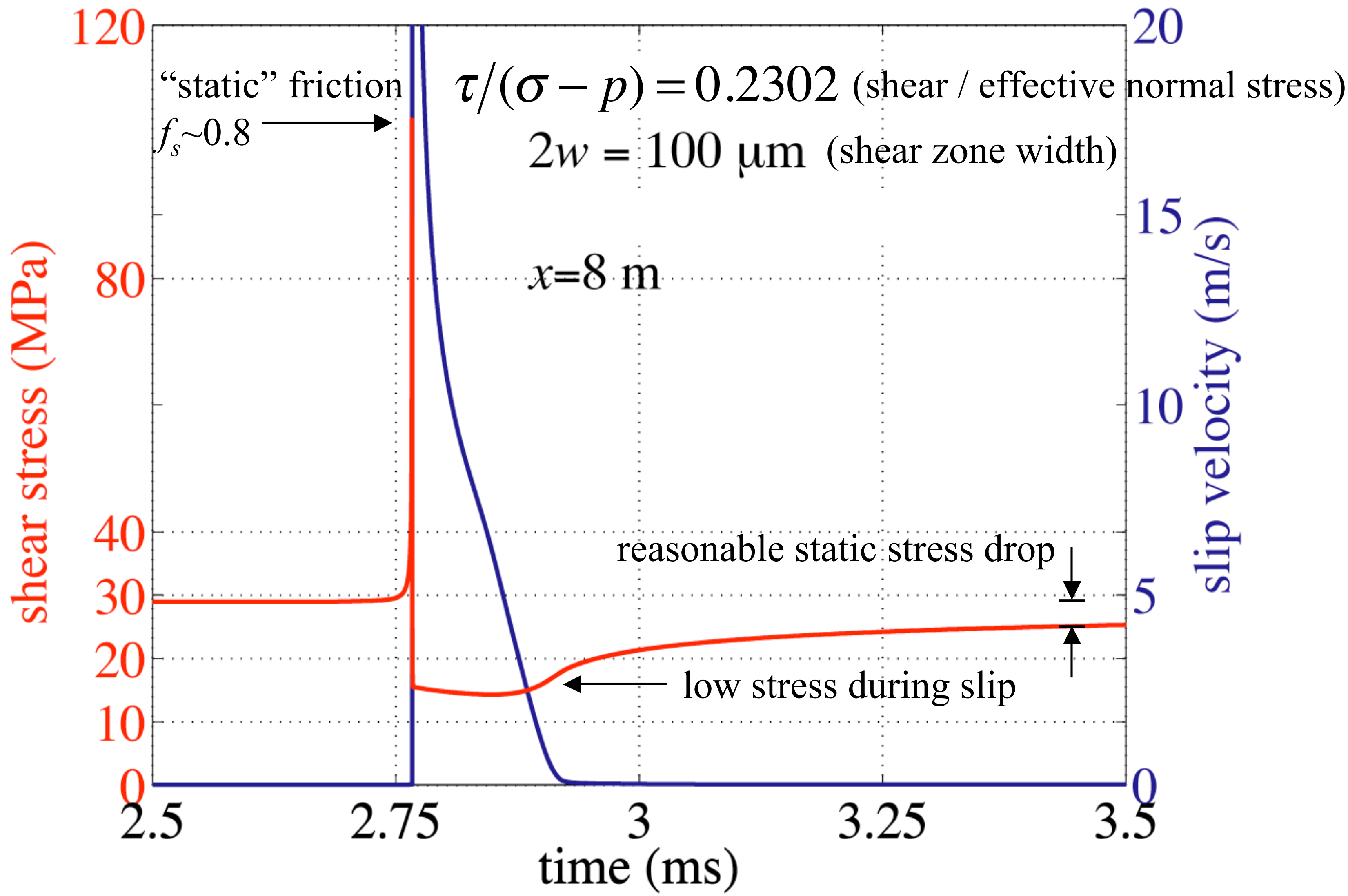
Stress constraints: low stresses acting on major faults
Geologic constraints: lack of pseudotachylytes (melted rock) near slip surface
Heat flow constraints: lack of heat flow signature around faults

Dynamic weakening reduces fault shear strength, τ, but *only during rapid sliding* (V~m/s); caused by changes in:

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

f = coefficient of friction (reduced by flash heating of asperity contacts)
p = pore pressure (raised by thermal pressurization)
σ = normal stress

Features of a Dynamic Weakening Model

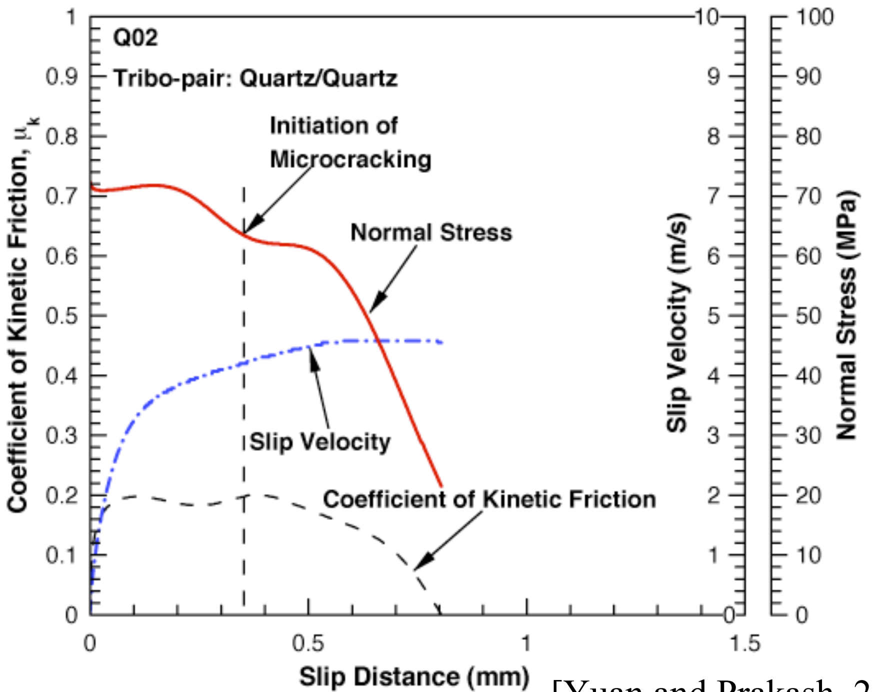


[Noda, Dunham, and Rice, submitted 2008]

Weakening Mechanisms

1. Flash Heating of Microscopic Asperity Contacts

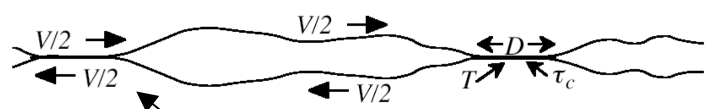
Strongly velocity-weakening friction



[Yuan and Prakash, 2008]

(in rate-and-state framework, using lab values of L~10 μm)

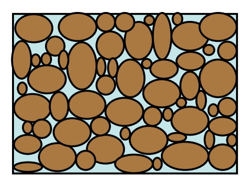
$$\frac{df}{dt} = \frac{a}{V}\frac{dV}{dt} - \frac{V}{L}\left[f - f_{ss}(V)\right]$$



contacts heated until they weaken/melt
(or slide out of existence)

[Rice, 1999, 2006; Beeler and Tullis, 2003; Tullis and Goldsby, 2003; Beeler et al., 2008]

2. Thermal Pressurization of Pore Fluid



undrained pressurization

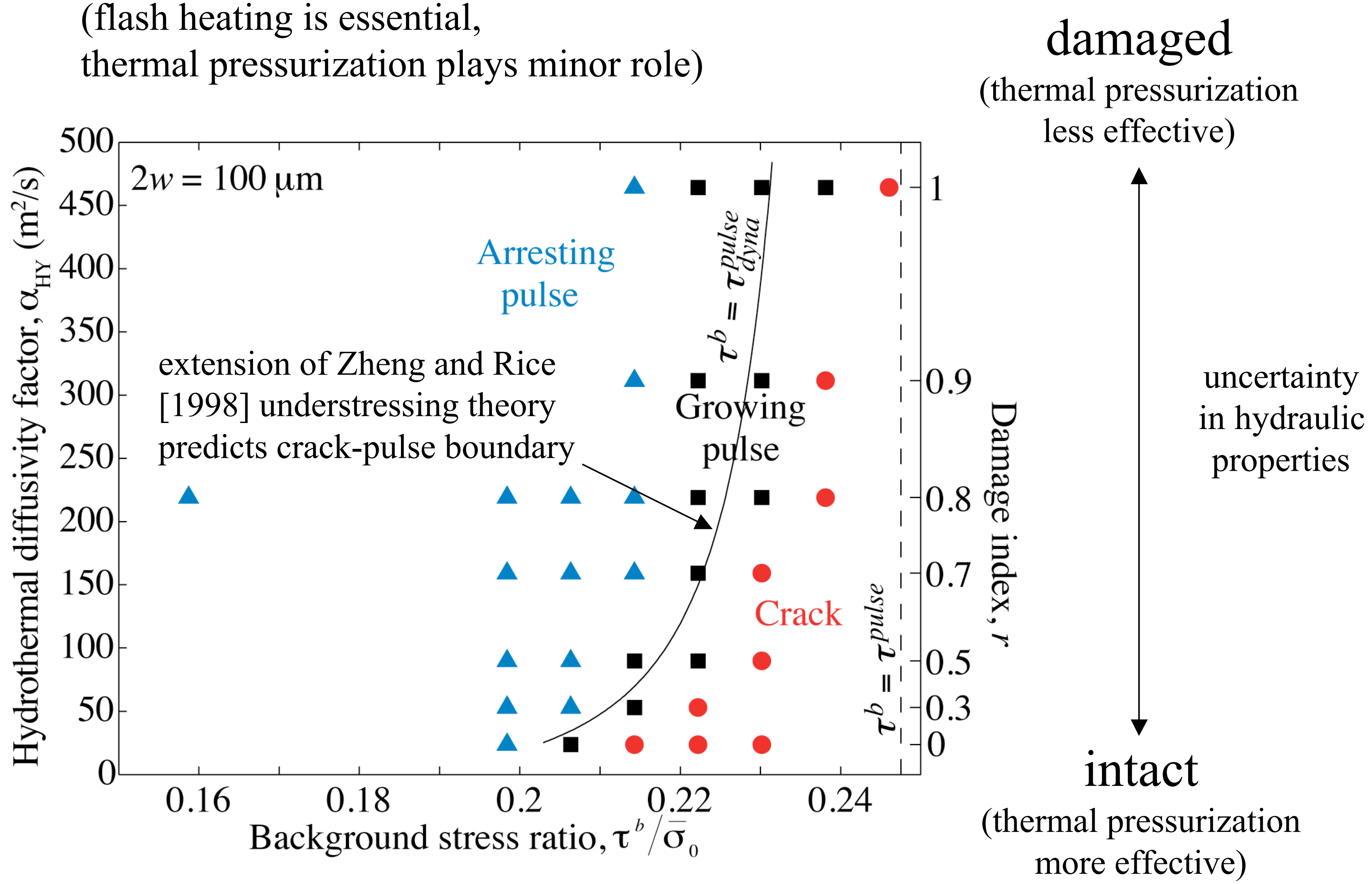
$$\left(\frac{\partial p}{\partial T}\right)_u \sim \text{MPa/K}$$

Conservation of energy and fluid with
- distributed shear zone (~100 μm wide)
- diffusion of heat and fluid ("adiabatic, undrained" when transport neglected)
- thermal and hydraulic properties from drilling projects and exhumed faults

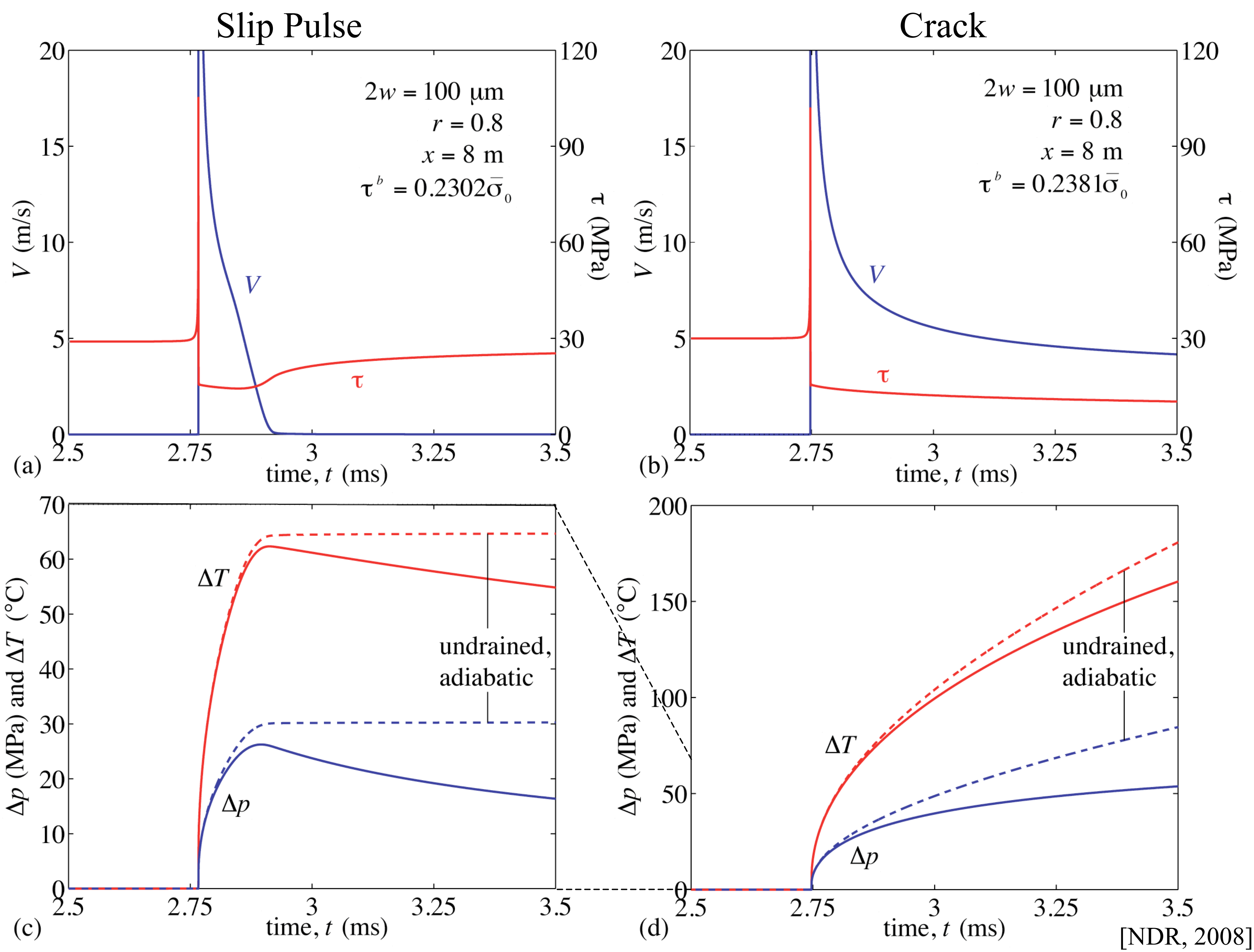
[Rice, 2006; building on Sibson, 1973 and many others]

Faults Host Ruptures at Low Background Stress Levels

(flash heating is essential,
thermal pressurization plays minor role)



[Noda, Dunham, and Rice, submitted 2008]

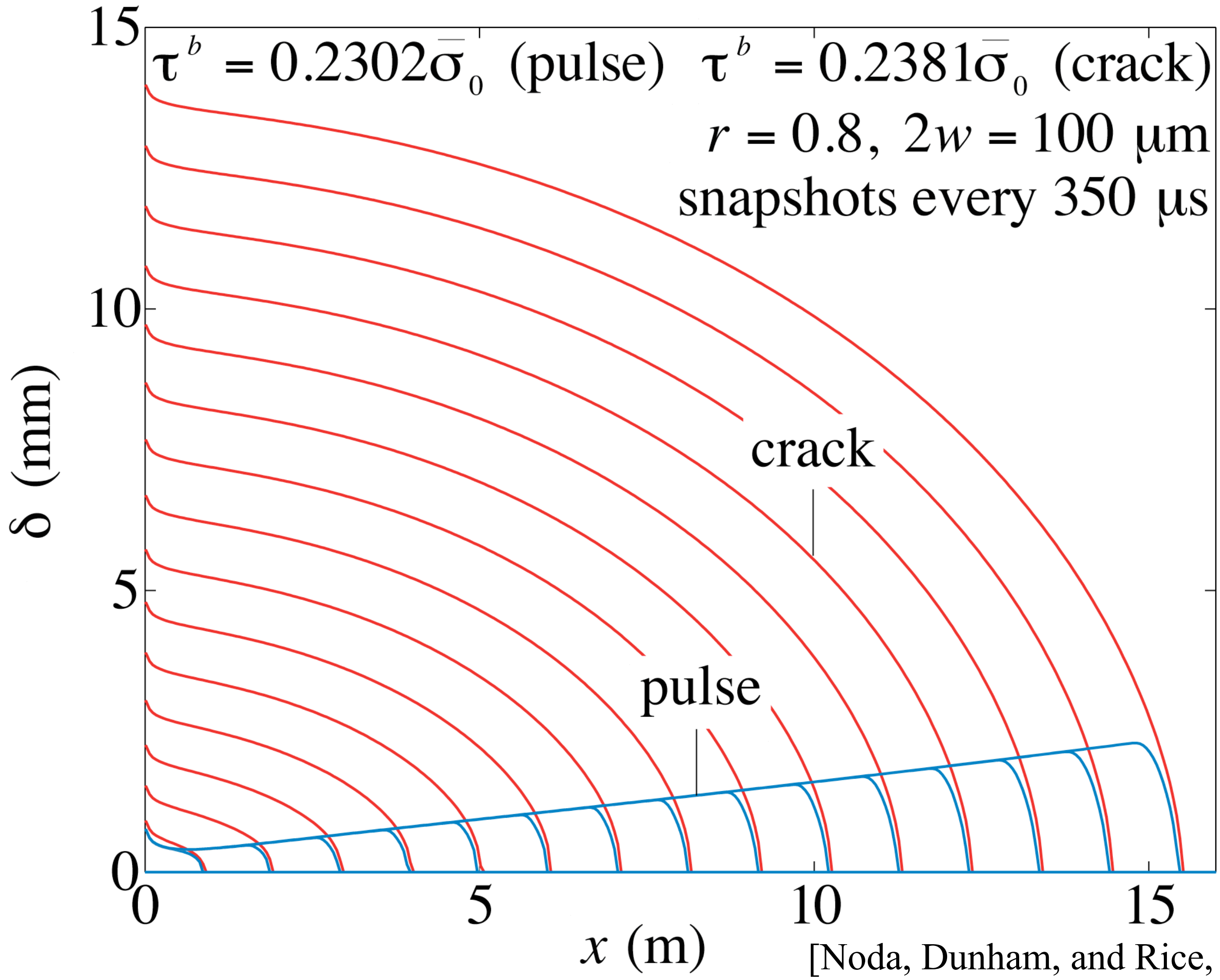


Slip Pulse
Crack
2w = 100 μm
r = 0.8
x = 8 m
τ^b = 0.2302σ̄_0
τ^b = 0.2381σ̄_0
V (m/s)
τ (MPa)
V
τ
time, t (ms)
(a)
(b)
(c)
(d)
Δp (MPa) and ΔT (°C)
ΔT
Δp
undrained,
adiabatic

[NDR, 2008]

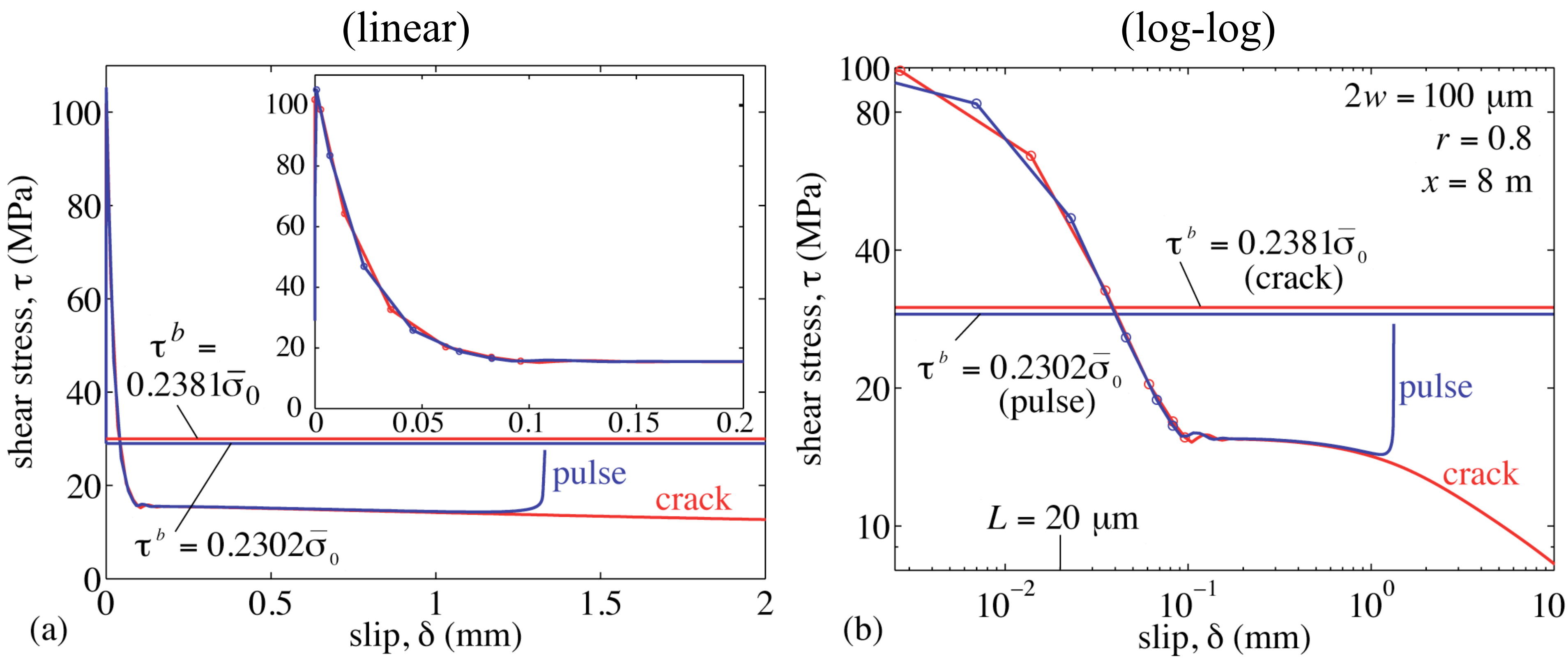
Self-Similar Scaling

Scaling (of slip pulses, not cracks) consistent with natural earthquakes:
~0.14 mm slip / m rupture length = 0.14 m/km



[Noda, Dunham, and Rice, submitted 2008]

Succession of Weakening Mechanisms at Rupture Front



State evolves very quickly, subsequent weakening from thermal pressurization

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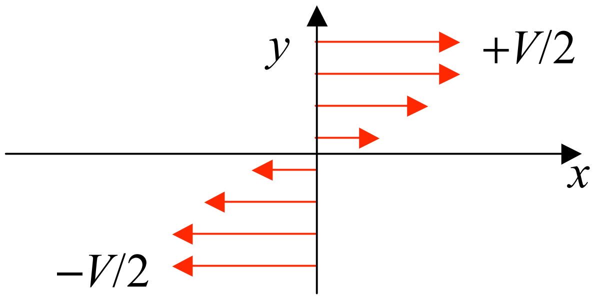
Summary: Strong rate-weakening permits slip pulses on faults at $\tau/(\sigma-p)\sim 0.3$ (rupture mode fairly insensitive to thermal pressurization)

Open question: How to use these laws in large-scale simulations? Increase L? Increase both L and hydraulic properties (holding dimensionless ratios fixed)?

[Noda, Dunham, and Rice, submitted 2008]

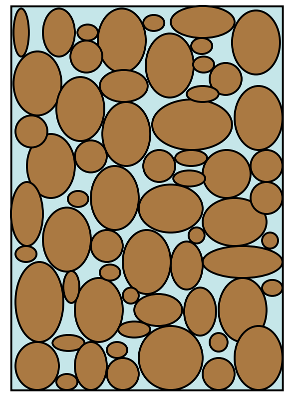
Thermal Pressurization of Pore Fluids by Distributed Shear Heating



$$\int \dot{\gamma}(y)\,dy = V$$

$\dot{\gamma}$ = strain rate
V = slip velocity

heat while holding fluid mass m fixed (undrained response)



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

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

Conservation of energy

adiabatic

$$\frac{\partial T}{\partial t} = \cancel{\alpha_{th}\frac{\partial^2 T}{\partial y^2}} + \frac{\tau\dot{\gamma}}{\rho c}$$

T = temperature
α_{th} = thermal diffusivity
ρc = volumetric heat capacity

Conservation of fluid mass (neglecting changes in p from fault-zone strains)

undrained

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

p = pore pressure
α_{hy} = hydraulic diffusivity
Λ = undrained pressurization

[Rice, 2006; building on Sibson, 1973 and many others; thermal and hydraulic properties of fault-zone materials constrained by measurements from exhumed faults and drilling projects)]