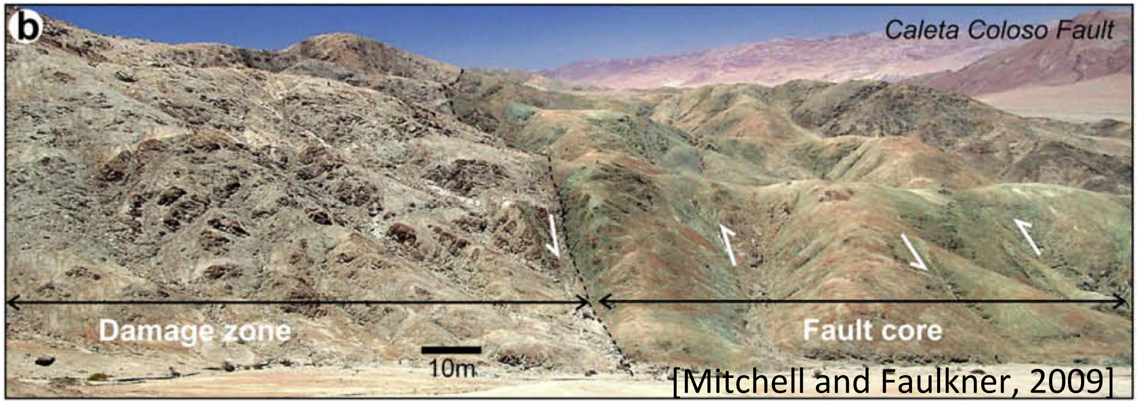
Inelastic Deformation During Earthquake Ruptures: Damage Zones and Strain Localization

Eric M. Dunham, Stanford University



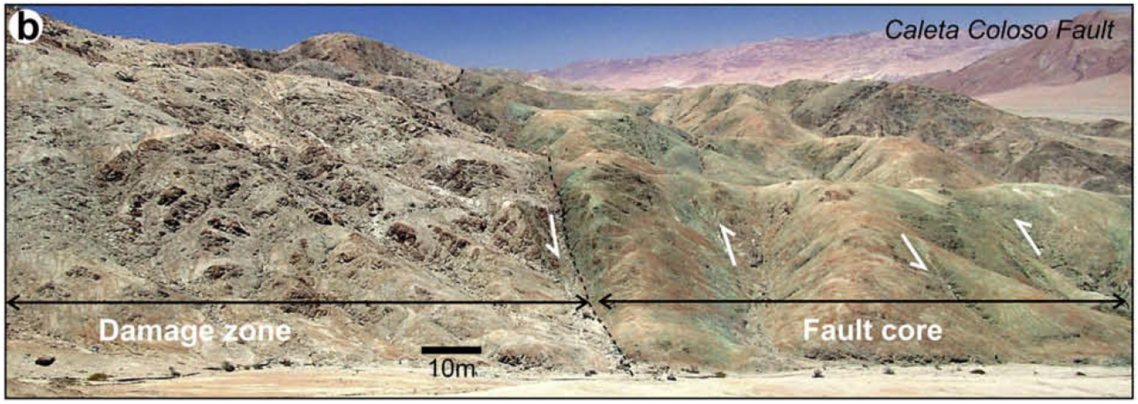
[Mitchell and Faulkner, 2009]

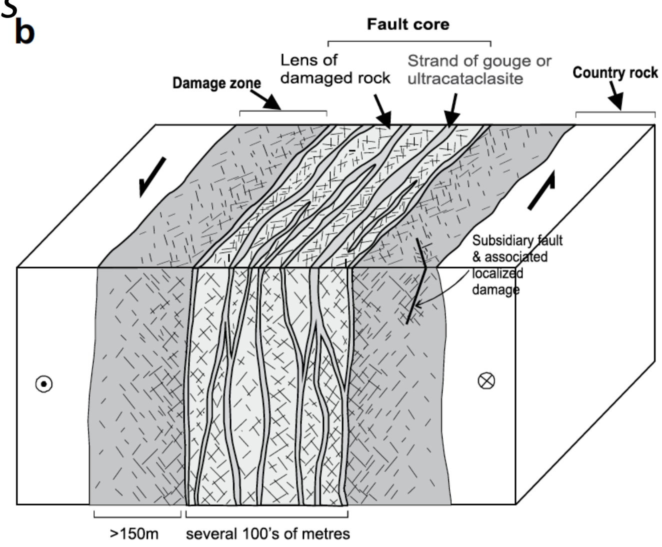
Motivating questions:

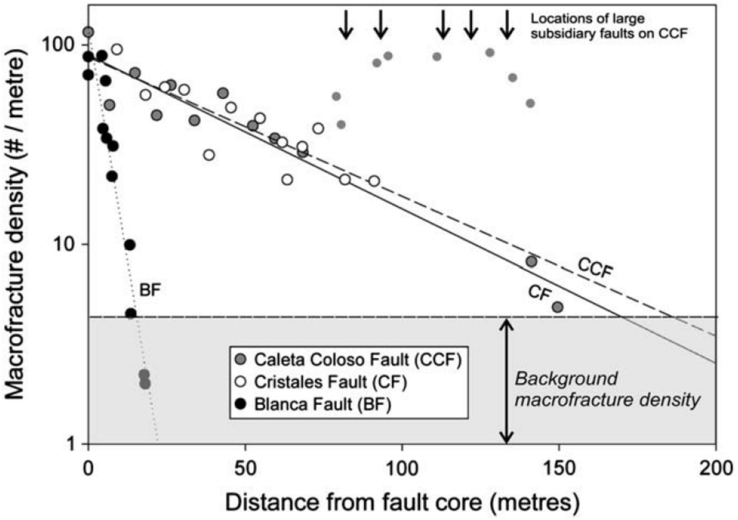
- damage zones, permeability structure of crust
- long-term evolution of fault systems
- crustal stress levels
- earthquake energy balance and self-similarity

Where is inelastic deformation expected?

- damage zones are heavily fractured regions extending ~100 m from major faults
- regardless of whether damage zones are created by inelastic deformation during rupture, or are relic of fault maturation process, *further inelastic deformation is expected in this weakened region during earthquakes*







inelastic deformation = slip on microcracks, opening of wing cracks

[Mitchell and Faulkner, 2009, study of faults in Atacama desert, Chile]

Where is inelastic deformation expected?

strategy: examine stress field around propagating rupture in *elastic* medium, where is *failure criterion* met? [Poliakov et al., 2002; Rice et al., 2005]

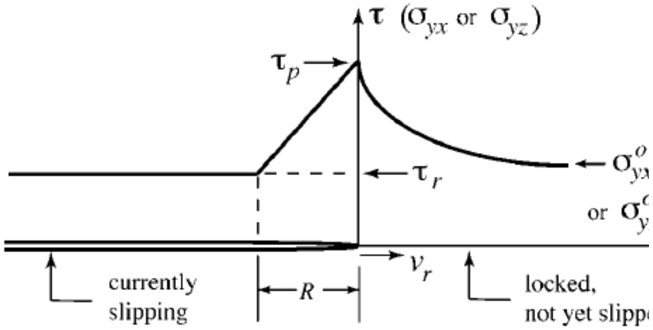
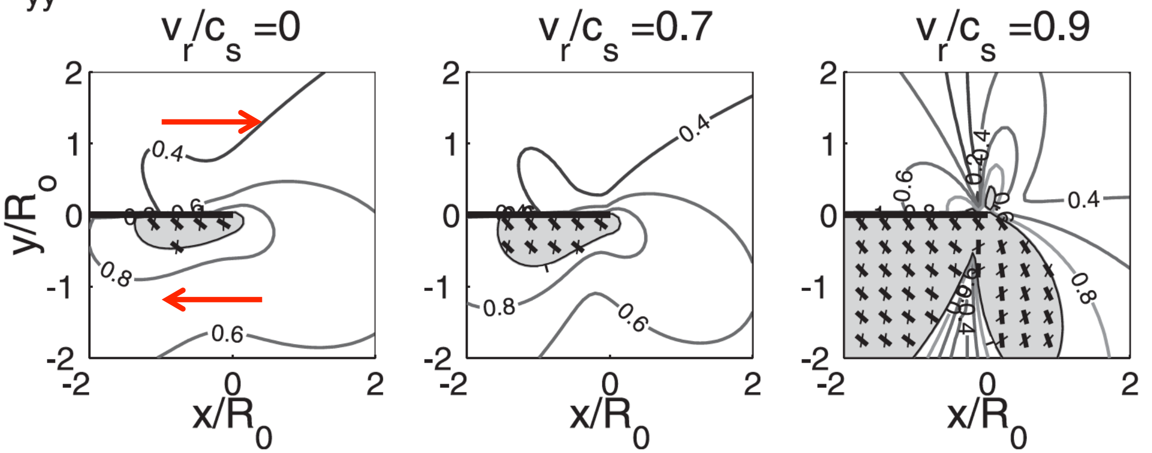
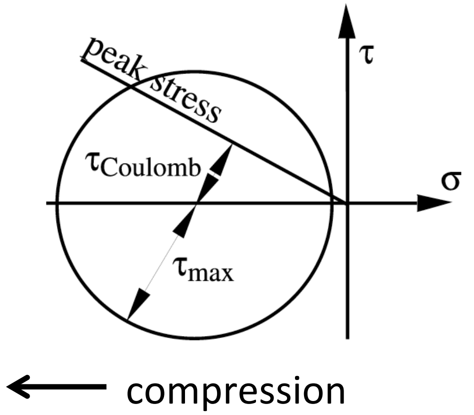


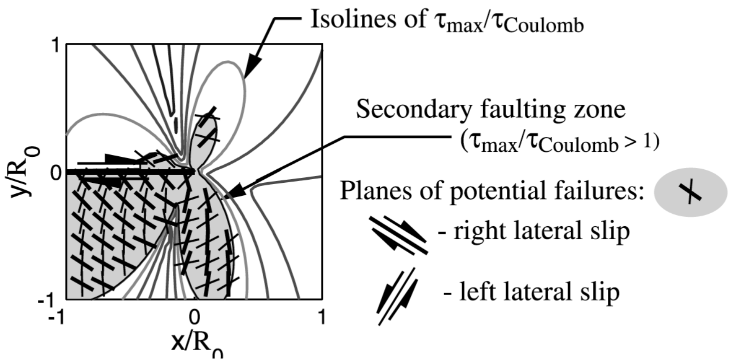
Figure 1. Nonsingular slip-weakening ruptur model with a linear variation of shear stress (fro peak strength τ_p to residual strength τ_r) with distanc from the crack tip in the slip-weakening zone. Afte

$\sigma^o_{xx}/\sigma^o_{yy}$ =0.8 increasing rupture velocity →





Mohr-Coulomb failure

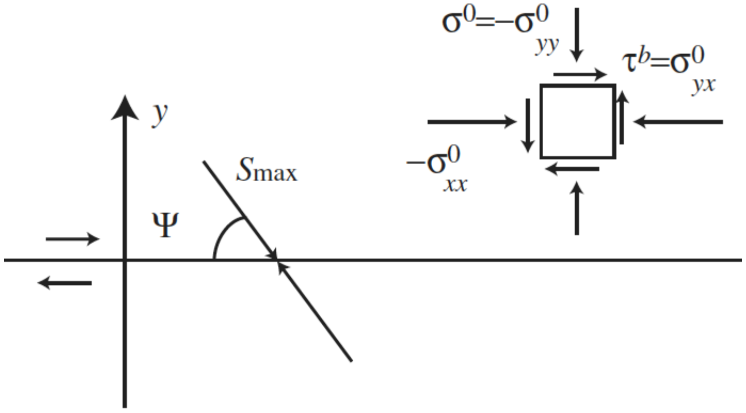


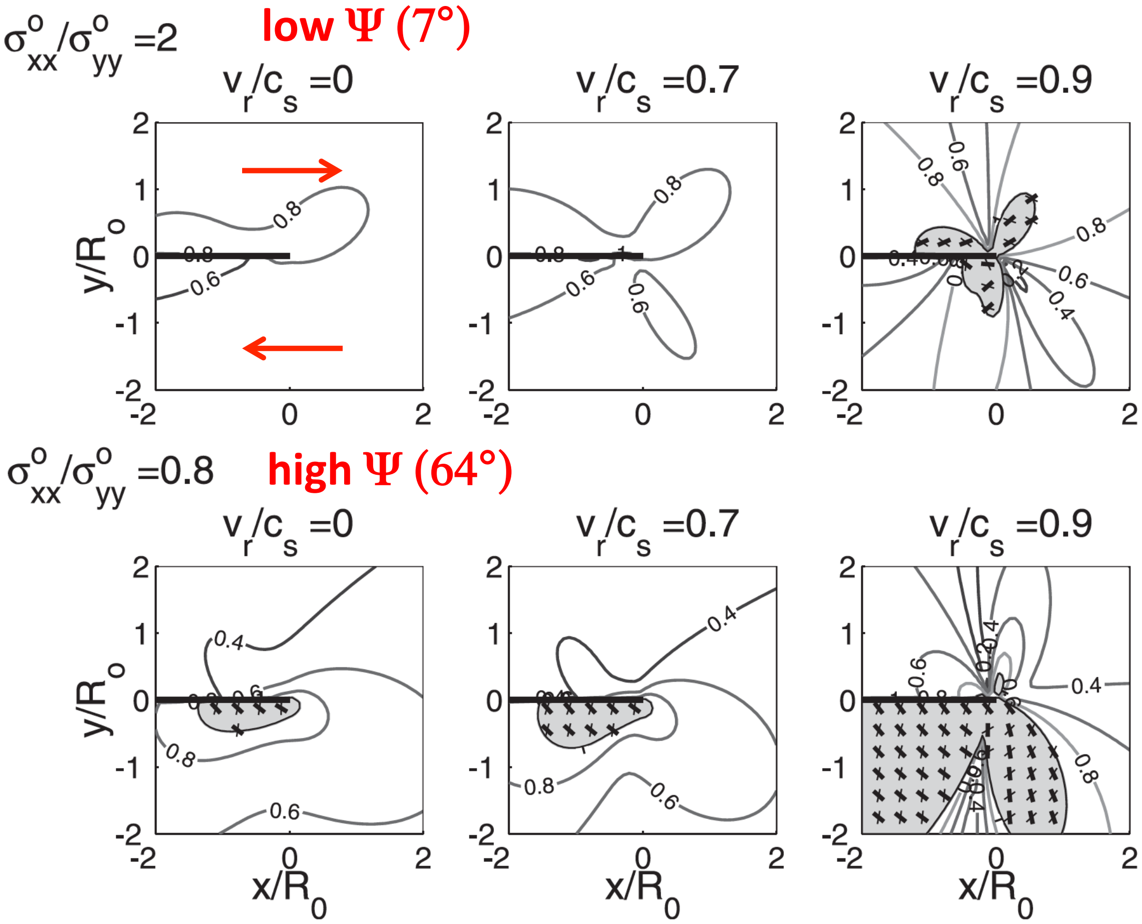
failure expected at high rupture velocities, primarily on *extensional* side of fault for initial stress state shown, out to distance ~R_0 ~ 100 m

Where is inelastic deformation expected?

strategy: examine stress field around propagating rupture in *elastic* medium, where is *failure criterion* met? [Poliakov et al., 2002; Rice et al., 2005]

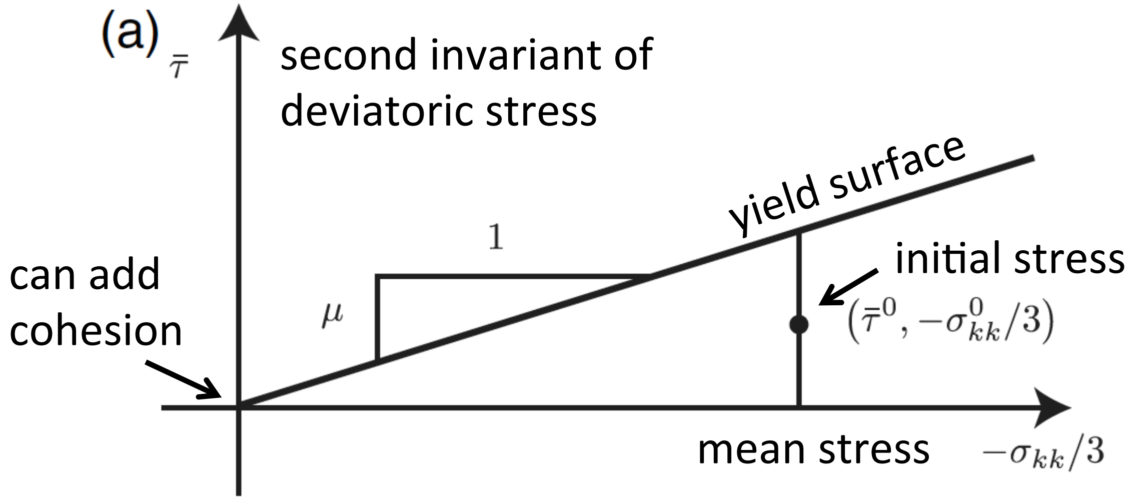
failure location determined by Ψ (orientation of maximum compressive stress to fault)





Drucker-Prager Plasticity

moving toward *dynamic rupture models with continuum plasticity*: most widely adopted rheology is Drucker-Prager



second invariant of deviatoric stress

yield surface

can add cohesion

initial stress

mean stress

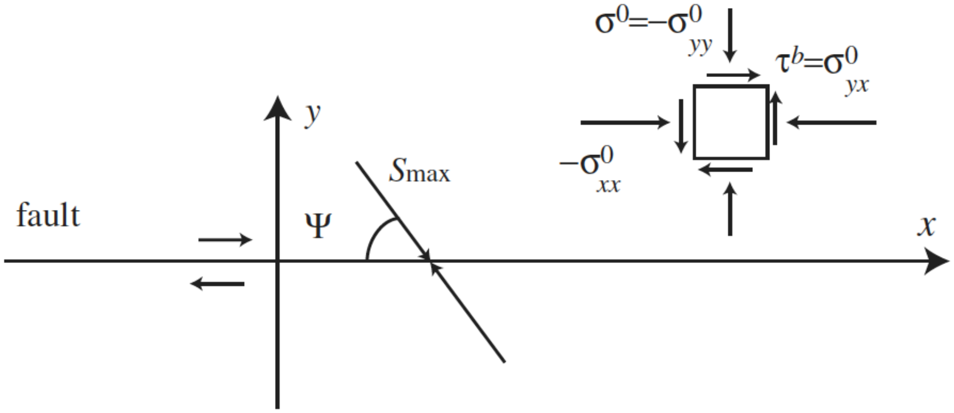
failure can occur by

- *increasing deviatoric stress*
- *decreasing mean stress*

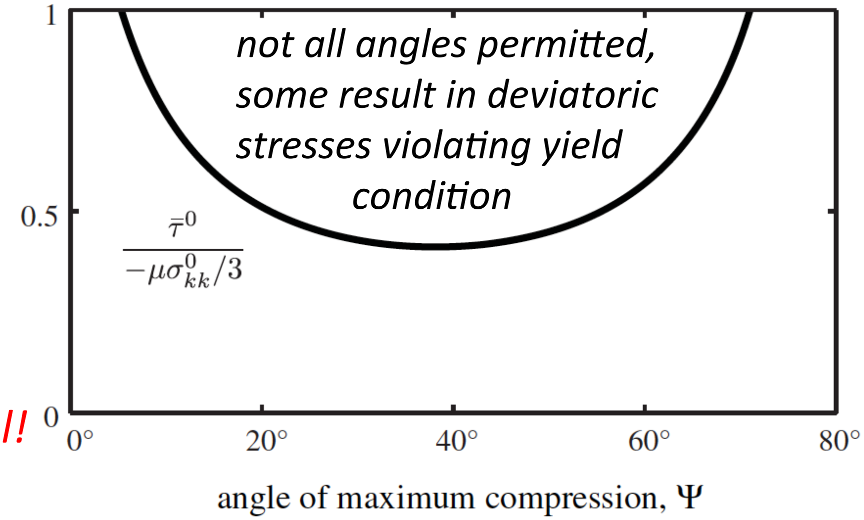
deviatoric plastic strain accompanied by *volumetric* plastic strain (dilatancy)

Selection of Initial Stresses

fix shear/normal stress on fault (chosen to give reasonable stress drop assuming some friction law) but vary prestress angle Ψ (or, equivalently, fault-parallel normal stress)



fault needs to be weaker than surrounding material!

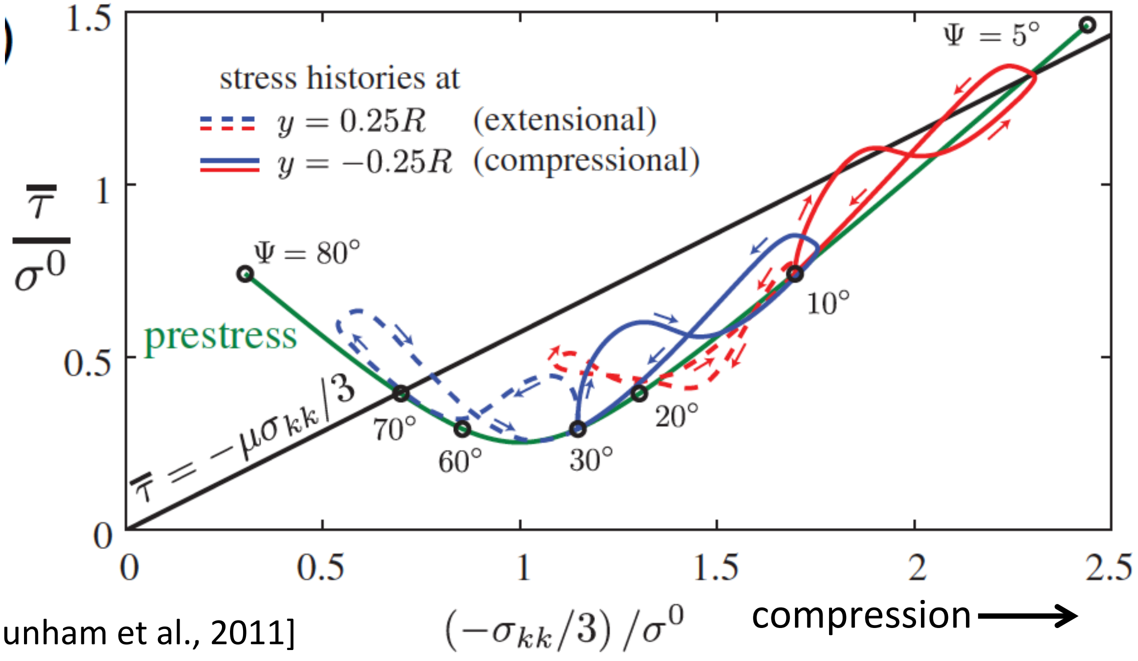


not all angles permitted, some result in deviatoric stresses violating yield condition

[Dunham et al., 2011]

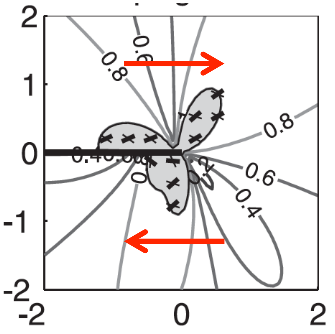
Predicted Location of Plastic Strain

stress trajectories at a point off of fault, calculated using Poliakov et al. [2002] solution, for fixed shear/normal stress on fault and variable prestress angle Ψ

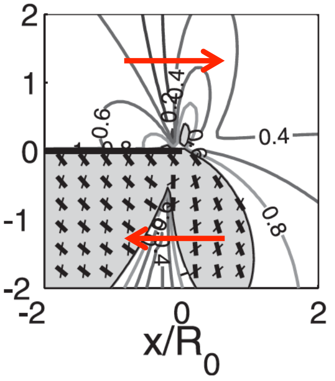


[Dunham et al., 2011]

low Ψ (7°)



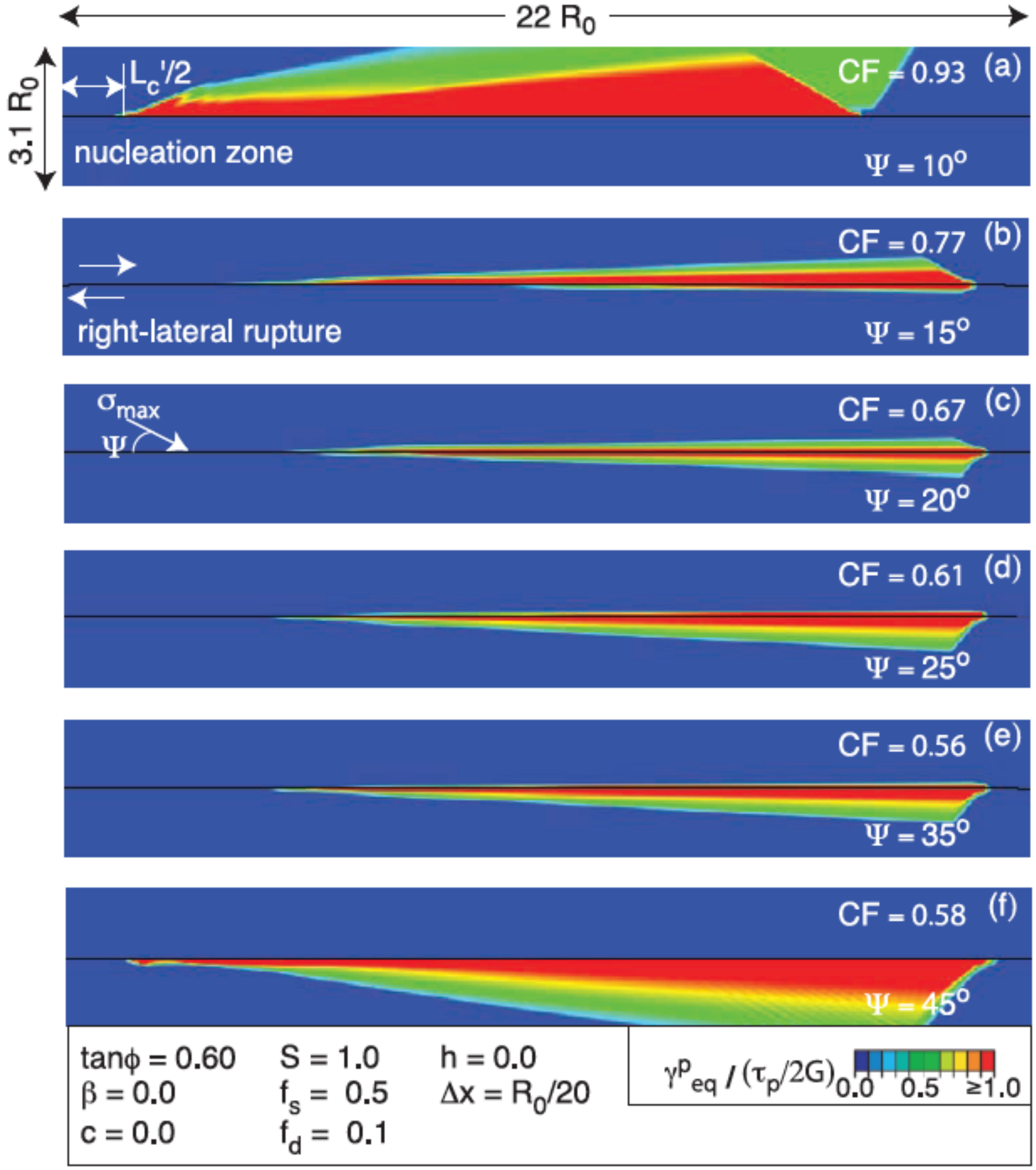
high Ψ (64°)



[Poliakov et al., 2002]

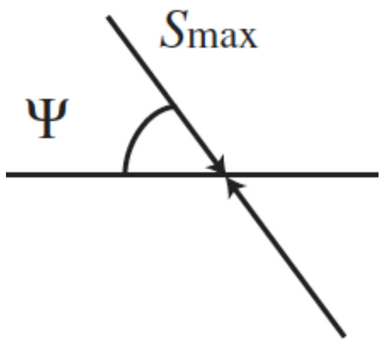
- does side of fault where plastic strain occurs depend on where rupture nucleates?
- can we determine propagation direction from asymmetry of damage zones?

Location of Plastic Strain



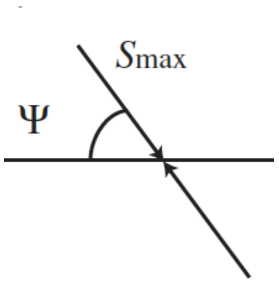
dynamic rupture simulations with Drucker-Prager plasticity

increasing Ψ ↓

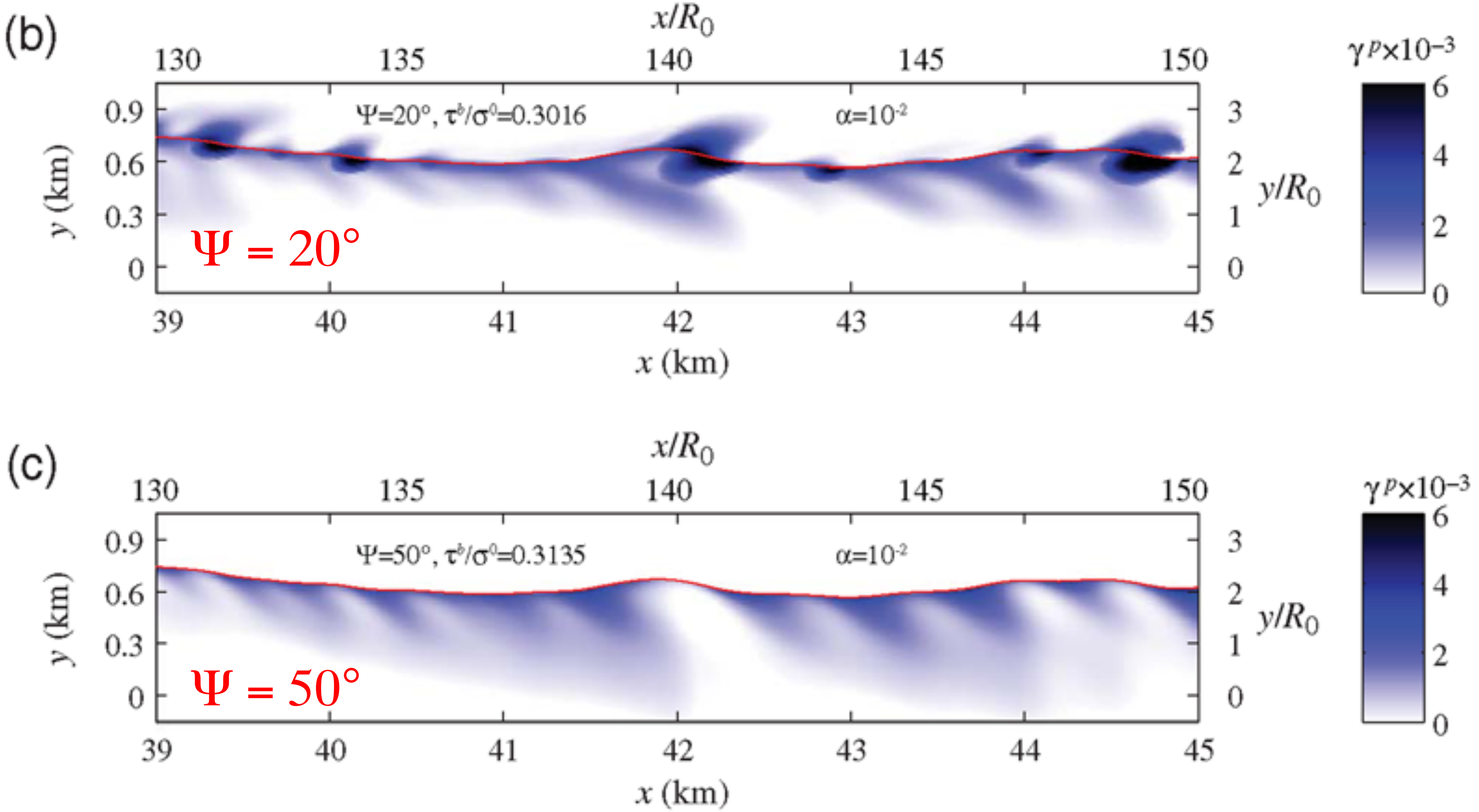


[Templeton and Rice, 2008]

Location of Plastic Strain



fault roughness modulates amplitude of plastic strain, but does not otherwise alter where it occurs



[Dunham et al., 2011]

Strike-Slip Flower Structures

plastic strain for vertical strike-slip fault with Ψ=45°:
mainly on extensional side except near free surface

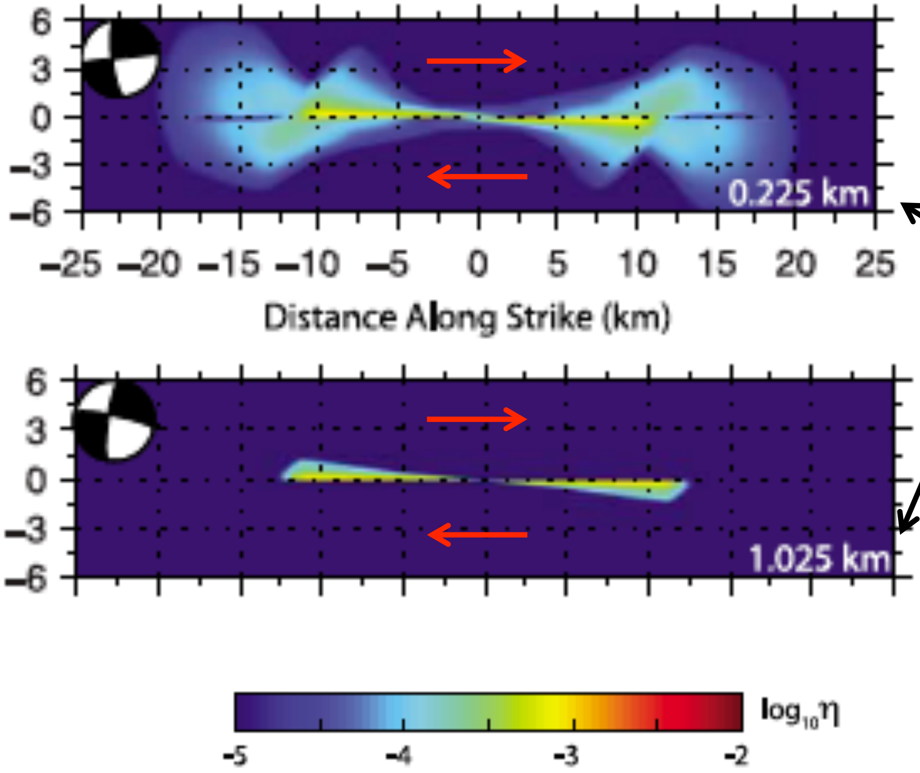
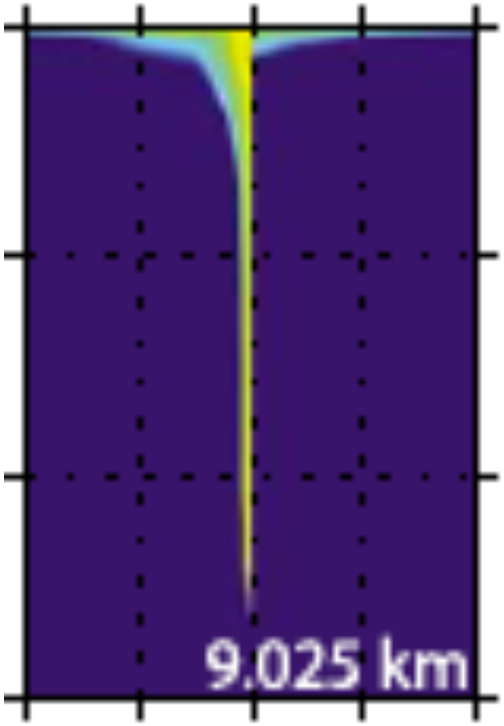


Figure 8

map view at
two depths

free surface

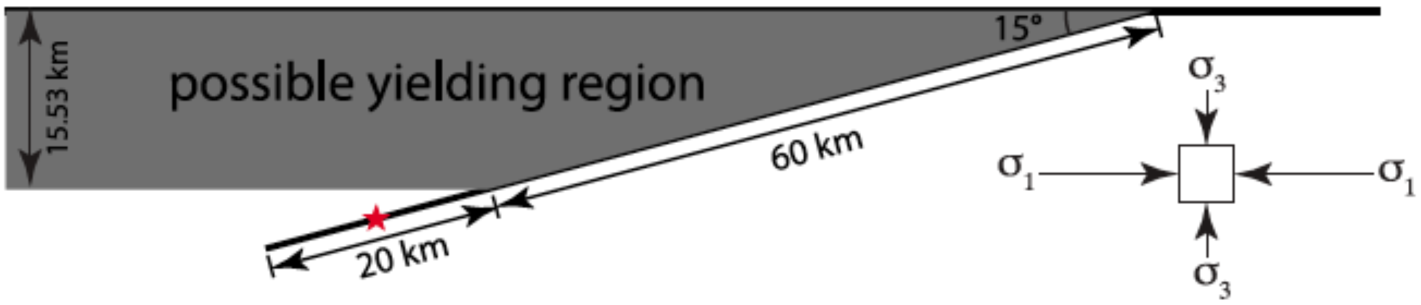
side view

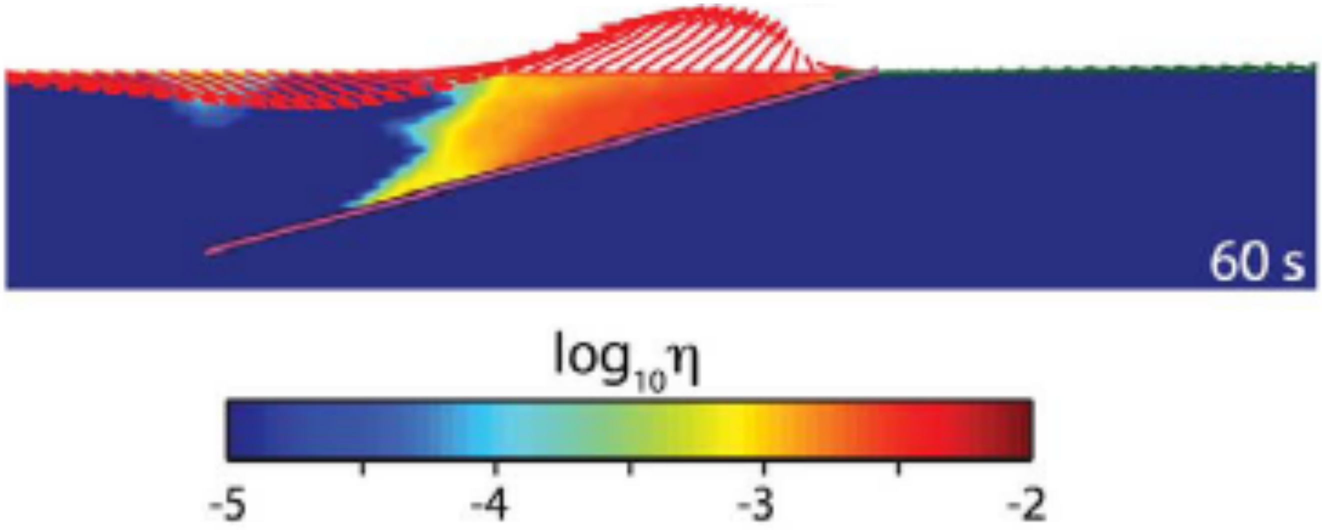


[Ma and Andrews, 2010]

Subduction Zones

shallow dip decreases Ψ and free-surface effects become important: yielding on compressional side caused by increase in deviatoric stress and reduction in mean stress from free-surface reflections

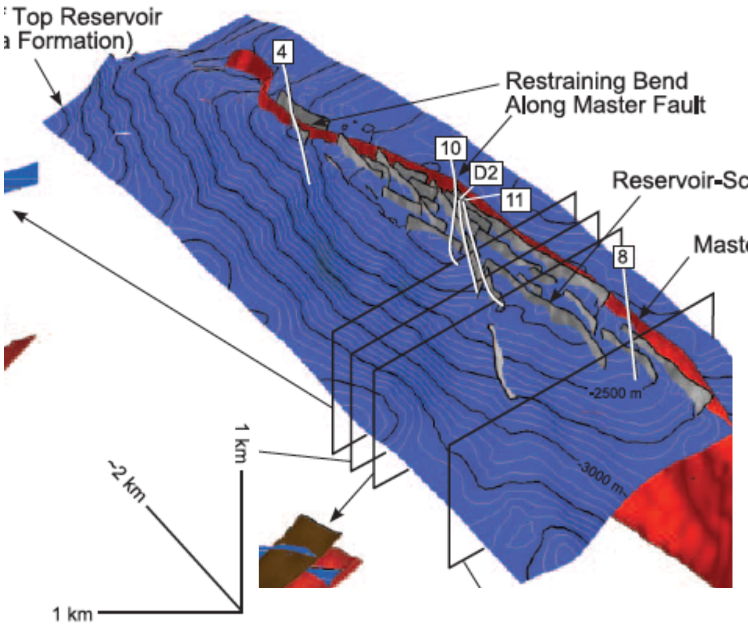




extreme amounts of plastic strain (10^{-2}!), at least when accretionary wedge has near-critical stress state, with off-fault plasticity contributing substantially (up to 50%) to overall seismic moment

[Ma, 2012]

Damage Zones and Permeability Structure



Suban gas field, Sumatra: most productive wells crossed many critically stressed fractures (seen in wellbore image logs and associated with damage zones of “reservoir-scale” faults)

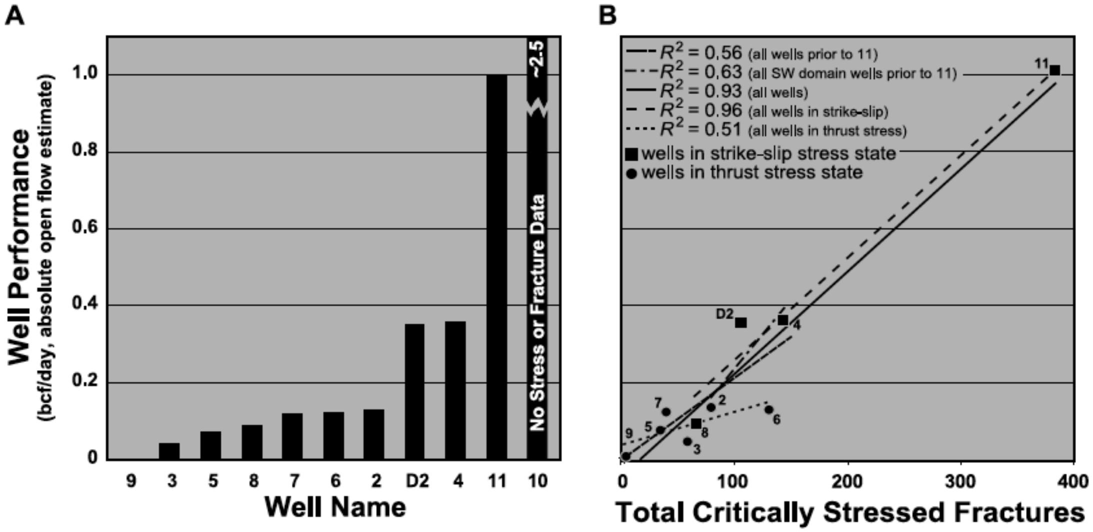
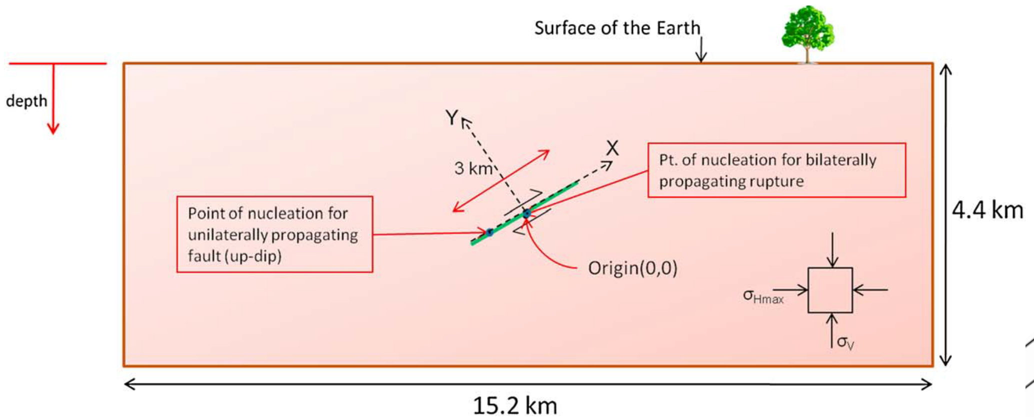


Figure 4. (A) Well performance measure, estimated absolute open flow (in billion cubic feet per day). (B) Plots of flow performance of select well groupings versus a selection of fracture characterization data from Table 1. R^2 = coefficient of determination.

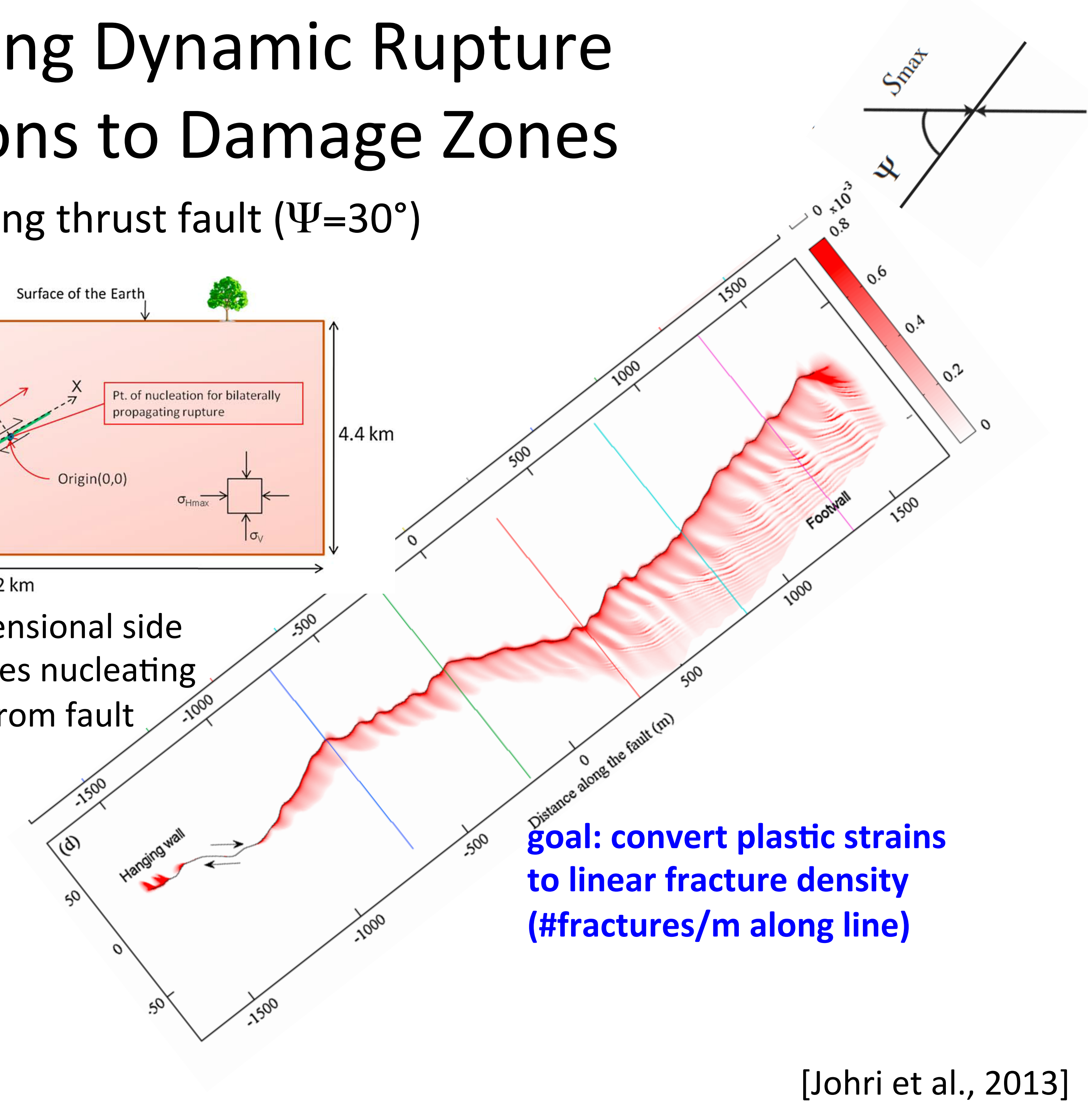
[Hennings et al., 2012]

Connecting Dynamic Rupture Simulations to Damage Zones

3-km long 30°-dipping thrust fault (Ψ=30°)



plastic strain in extensional side (*footwall* for ruptures nucleating at depth), ~100 m from fault

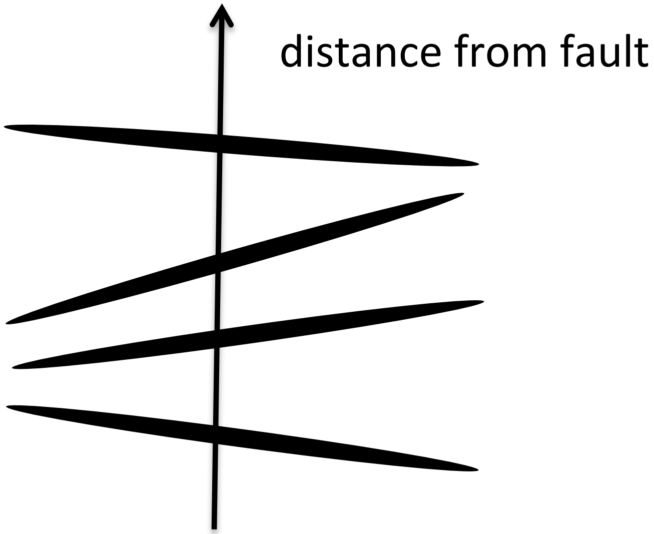


goal: convert plastic strains to linear fracture density (#fractures/m along line)

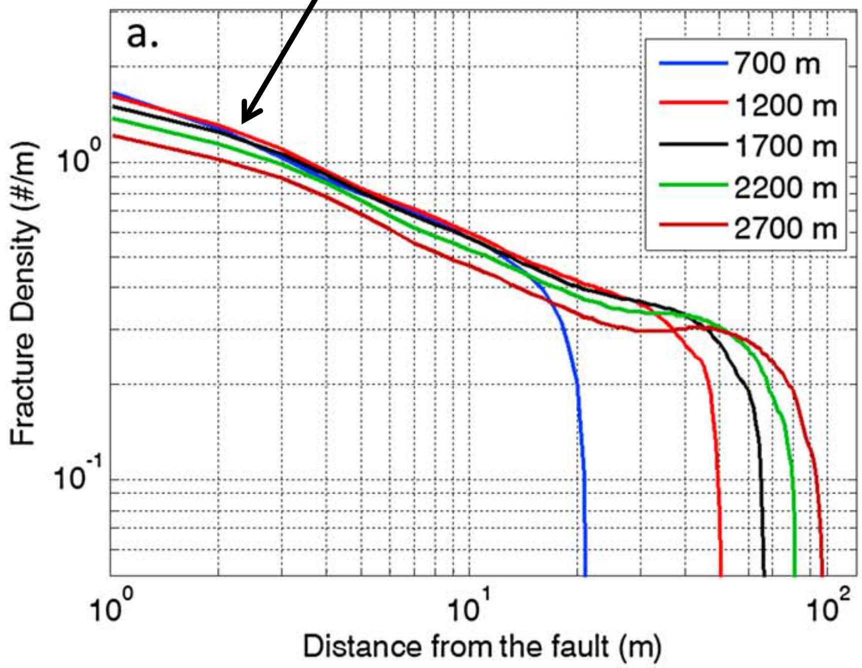
[Johri et al., 2013]

Plastic Strain → Fracture Density

assume *volumetric* plastic strain
(=$\beta\times$deviatoric plastic strain, $\beta \sim 0.3$)
expressed as fractures with 100 μm aperture
(as seen in image logs)

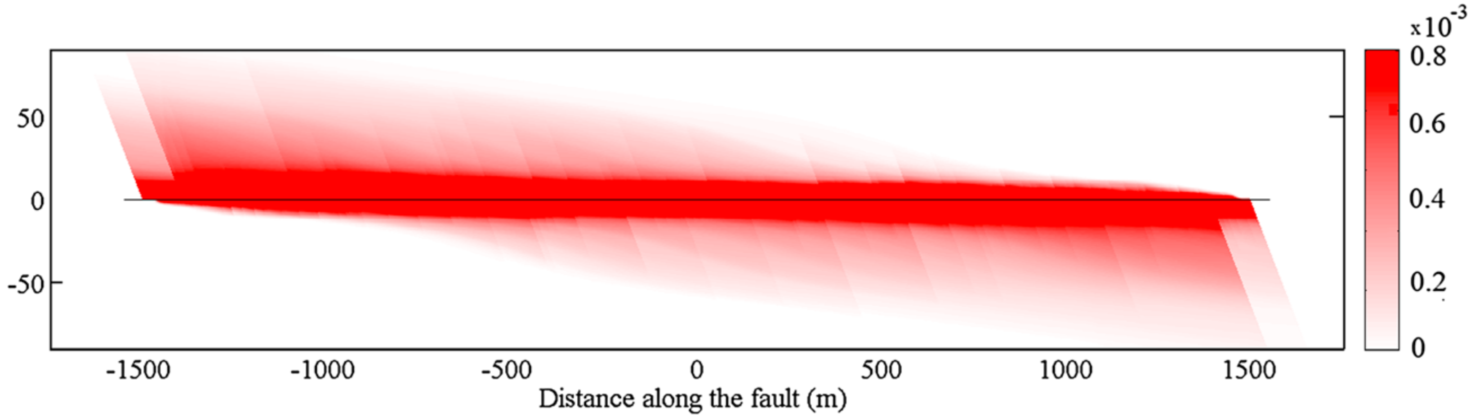


about an order of magnitude *less* than observed;
slope also inconsistent



[Johri et al., 2013]

Cumulative Effect of Multiple Ruptures

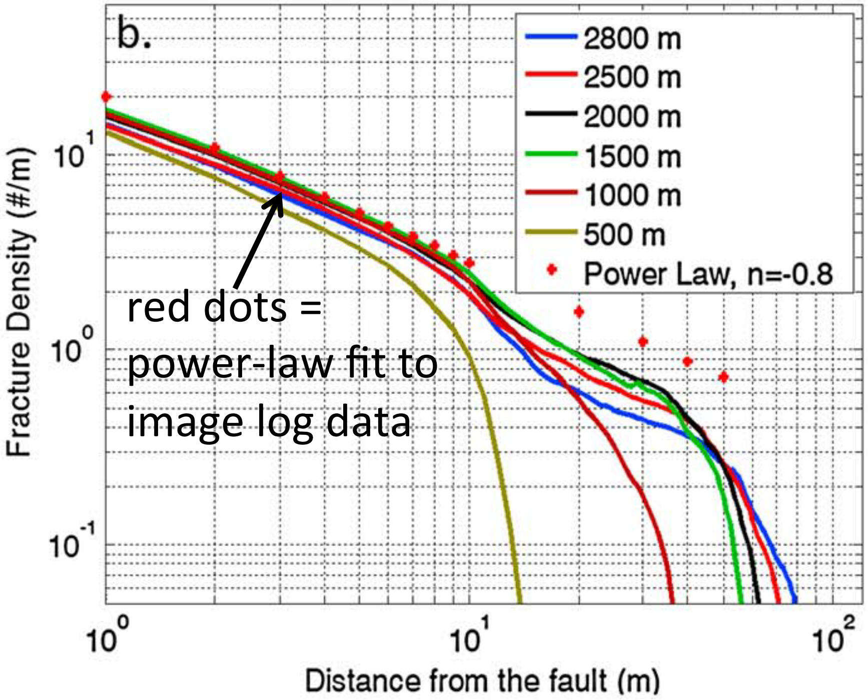


assumptions:

- Gutenberg-Richter distribution
- plastic strain from small quakes same as from large, except over smaller area (self-similarity)
- superposition is valid*

➔ increases fracture density near fault, steepens decay with distance

*ignores residual stresses from prior events!

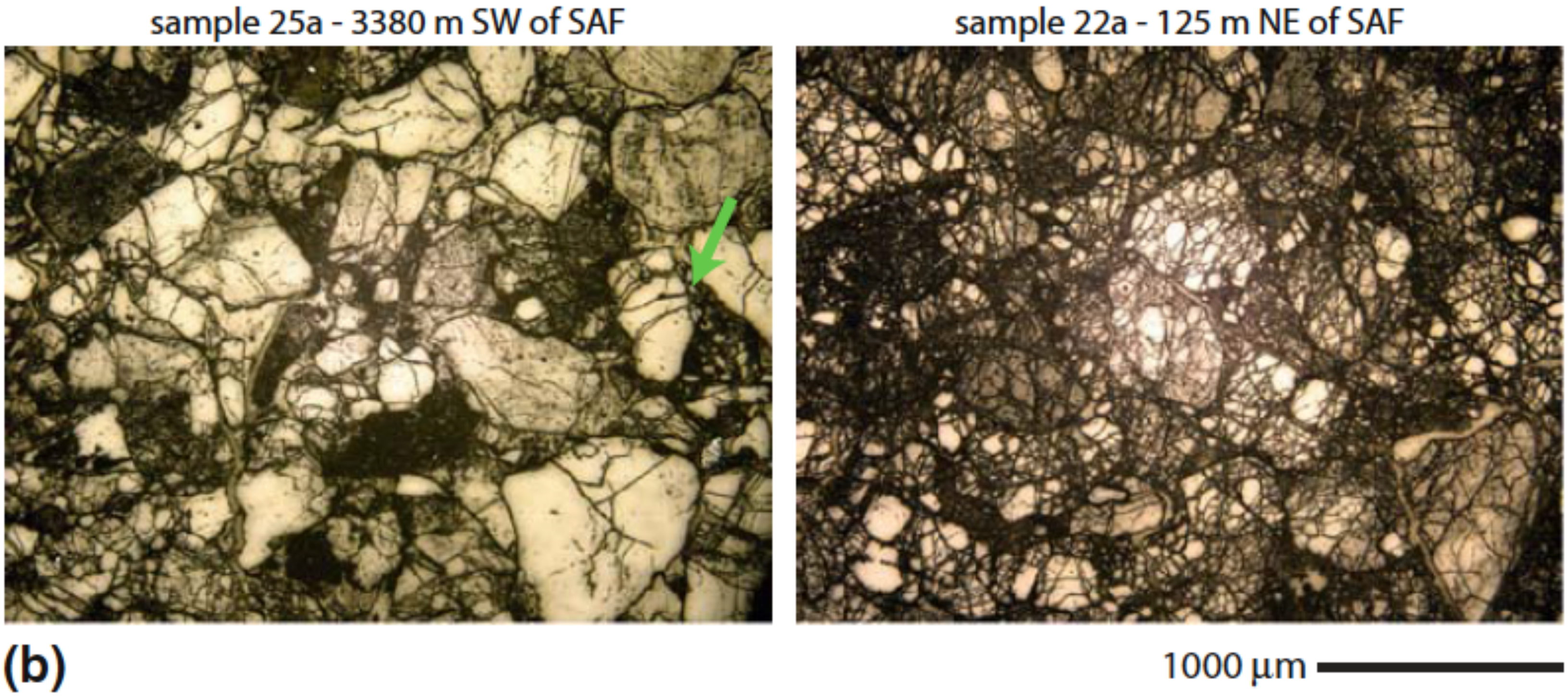


red dots = power-law fit to image log data

[Johri et al., 2013]

Will plastic strain increase indefinitely as fault hosts more ruptures?

San Andreas has hosted 1000+ earthquakes but Dor et al. [2009] report near-fault rock "displays original sedimentary fabrics and little evidence of bulk shear strain at the mesoscopic scale. The formation is, however, pervasively fractured at the microscopic scale over a zone that is about a 100 m wide"



Jim Brune (personal comm., 2013) argues plastic strain < 10^{-2}, far less than ~1 strain predicted by superposition

[Dor et al., 2009]

Shakedown

well-known effect in engineering design, where cyclically loaded structures (e.g., pressure vessels) accumulate plastic strain during first few loading cycles, but ultimately *residual stresses prevent further plasticity* → structure responds elastically

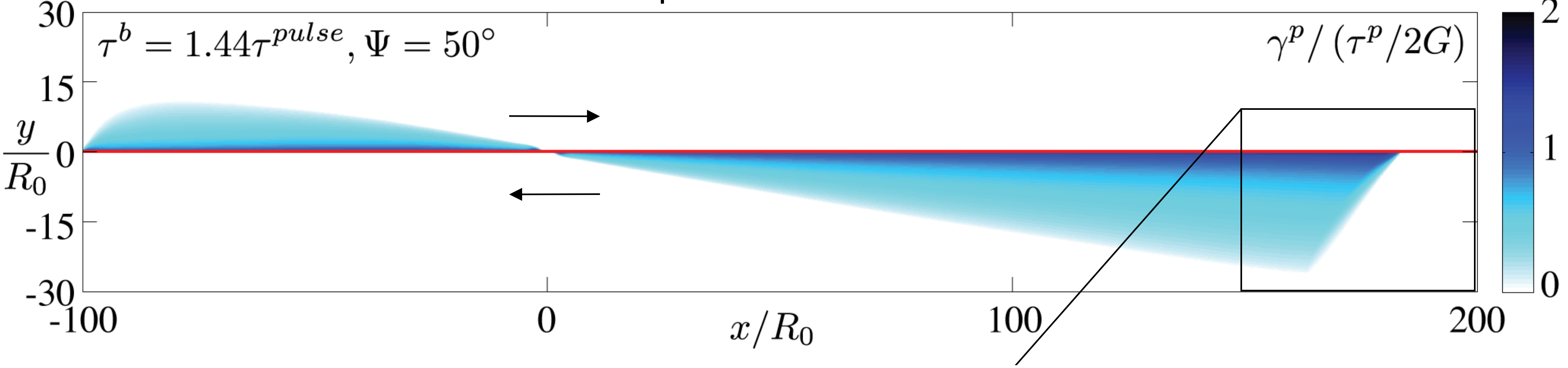
classic mechanics problem is to identify conditions leading to shakedown vs. racheting (failure from cumulative plastic strain that occurs in each cycle)

time for earthquake cycle models with plasticity!

(probably will require inertial dynamics during rupture)

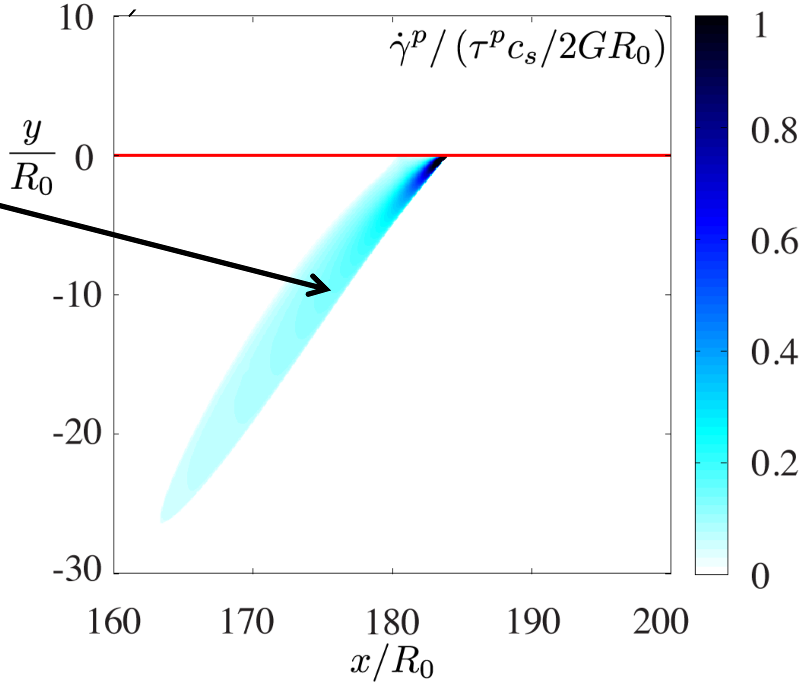
Details of ***Dynamic Plastic Straining***

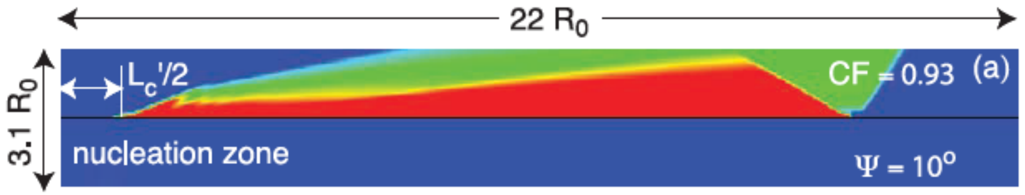
Equivalent Plastic Strain



plasticity occurs almost instantaneously along line(s) extending radially from rupture front, smeared by viscoplasticity

Equivalent Plastic Strain Rate



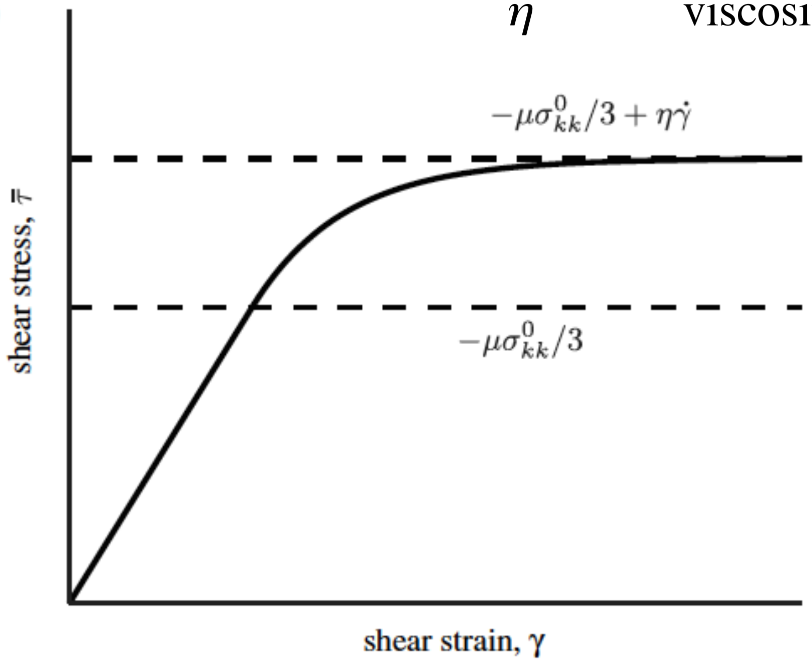


[Templeton and Rice, 2008]

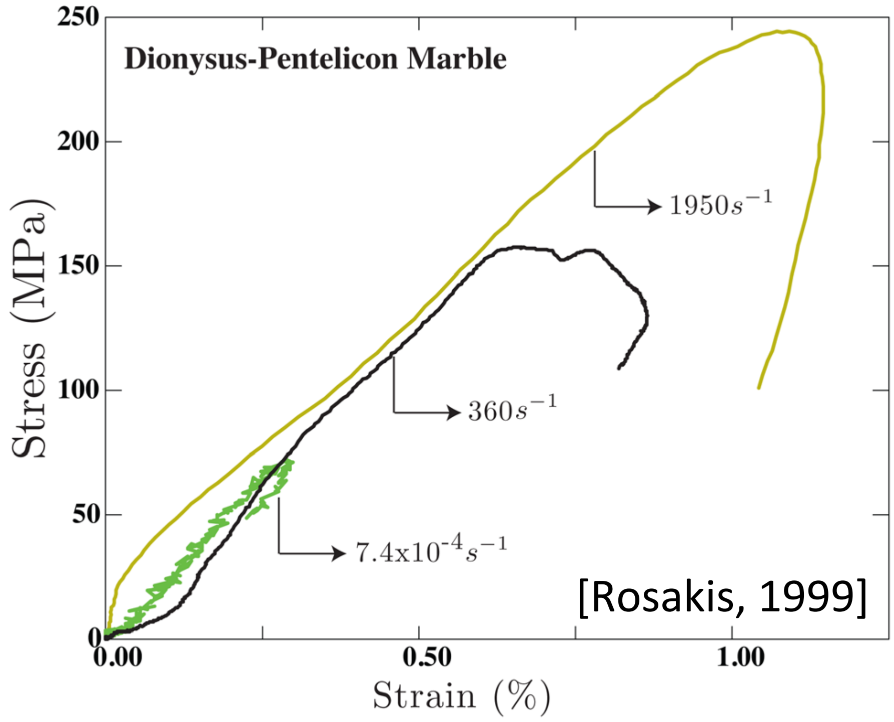
Viscoplasticity: ***Rate-Dependent*** Yielding

stresses can exceed yield
with high strain-rate loading

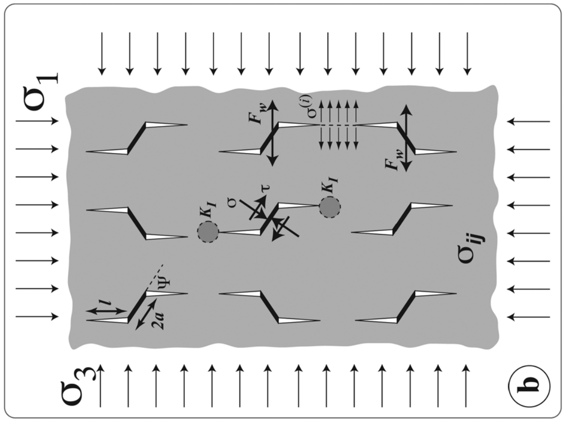
$$\text{plastic strain rate} = \dot{\gamma}^{p} = \frac{\bar{\tau} + \mu\sigma_{kk}/3}{\eta} = \frac{\text{overstress}}{\text{viscosity}}$$



[Dunham et al., 2011]



[Rosakis, 1999]

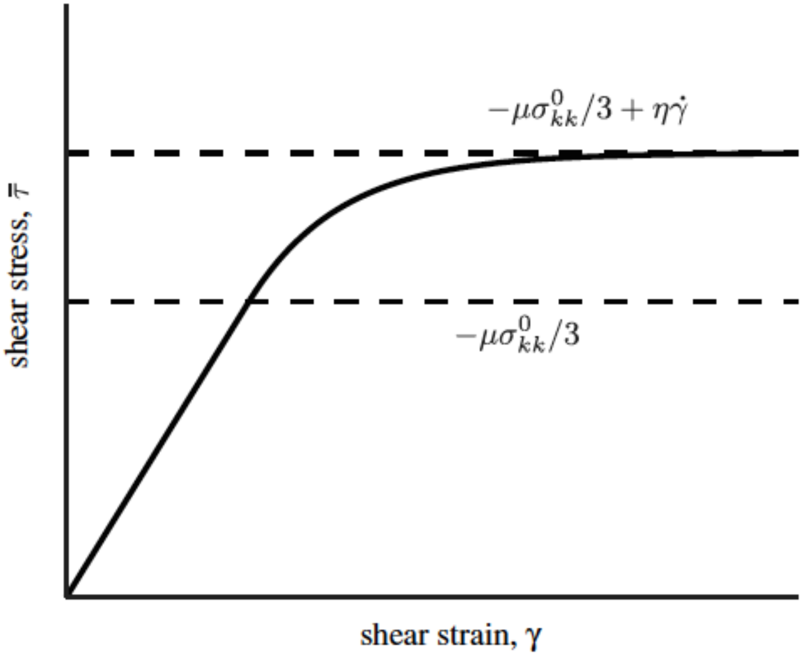


inelastic deformation limited
by rate of crack propagation

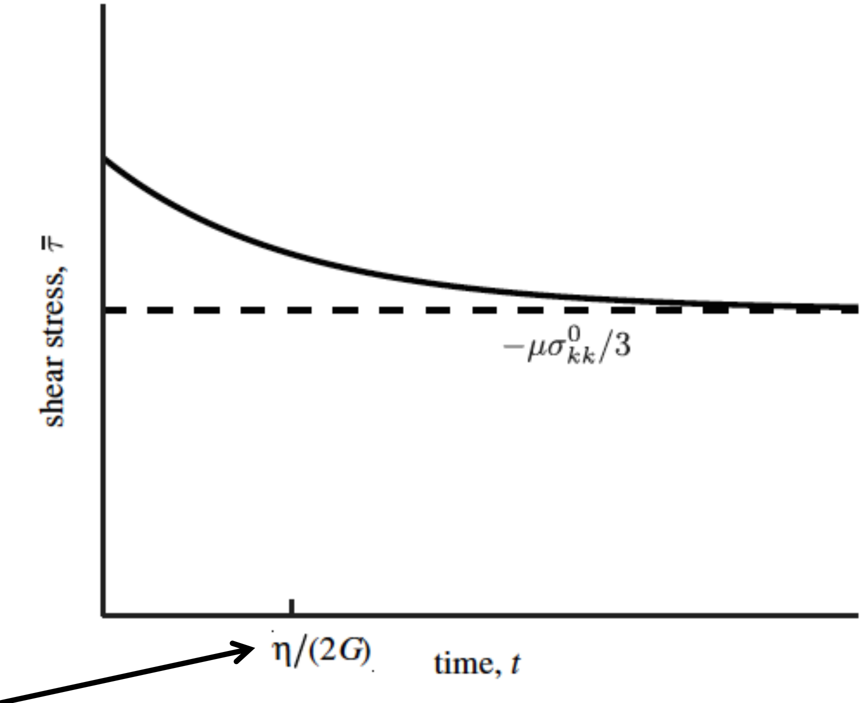
[Bhat et al., 2012]

Viscoplasticity: Rate-Dependent Yielding

stresses can exceed yield with high strain-rate loading



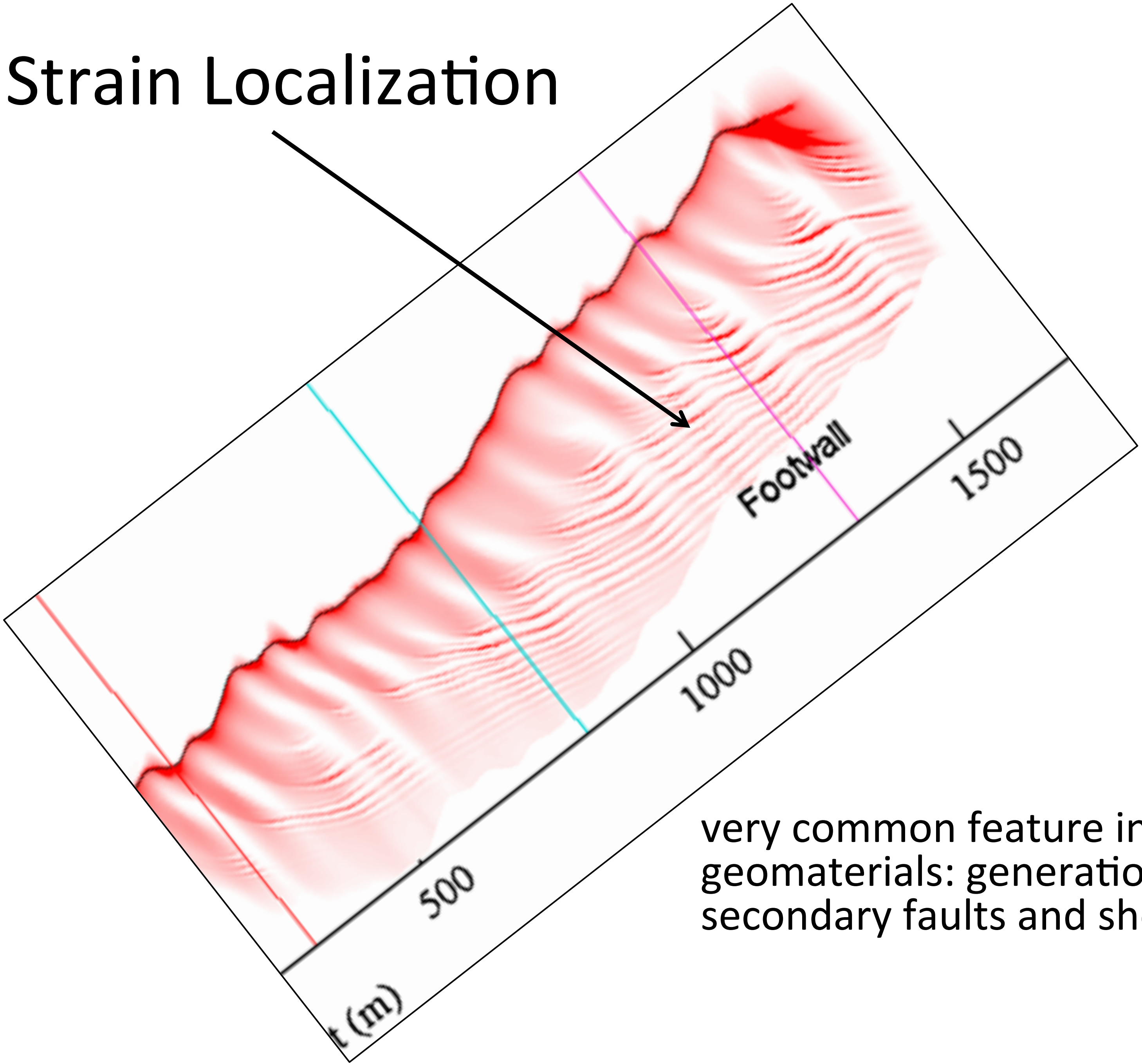
but relax back to yield in absence of additional strain



viscoplastic relaxation time (typically chosen to be few time steps in numerical simulations since actual values too small to resolve)

[Dunham et al., 2011]

Strain Localization

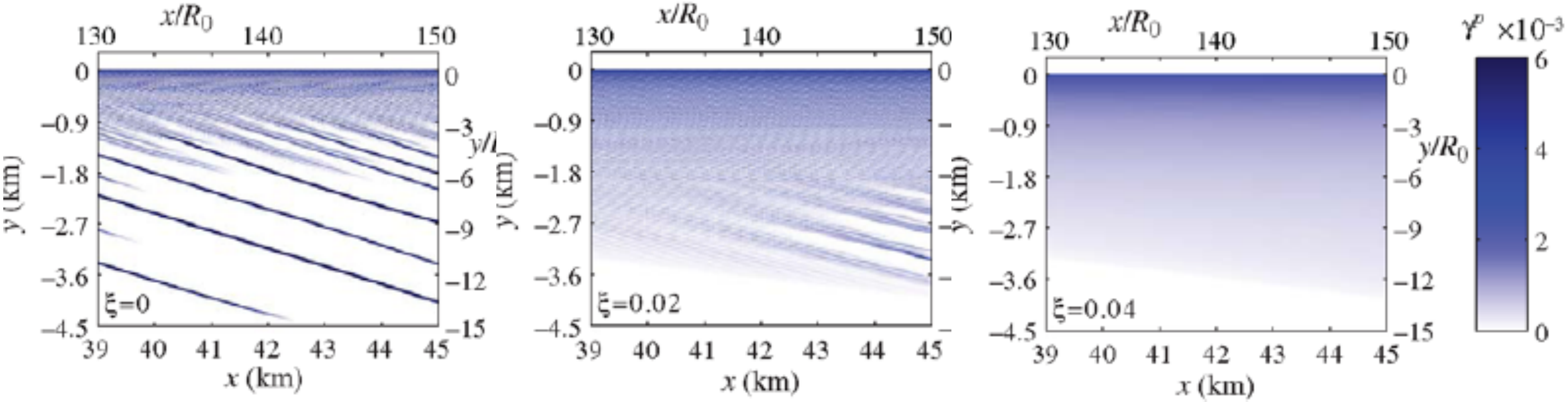


very common feature in geomaterials: generation of secondary faults and shear zones

[Johri et al., 2013]

Localization and Regularization

viscoplasticity permits localization, for sufficiently small η, but allows for mesh-convergent simulations



rate-independent plasticity

⟶ increasing η ⟶

$$\text{plastic strain rate} = \dot{\gamma}^p = \frac{\bar{\tau} + \mu \sigma_{kk}/3}{\eta} = \frac{\text{overstress}}{\text{viscosity}}$$

[Dunham et al., 2011]

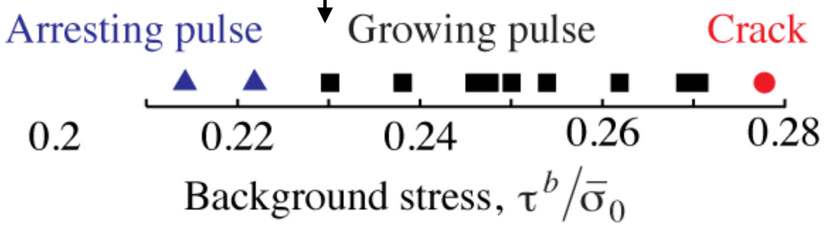
What Determines **Crustal Stress Levels**?

- deviatoric stresses bounded by *fault strength*
- likely neither static nor dynamic frictional strength, but *minimum stress required for self-sustaining rupture* (with locally higher stresses reaching static friction at isolated nucleation sites)

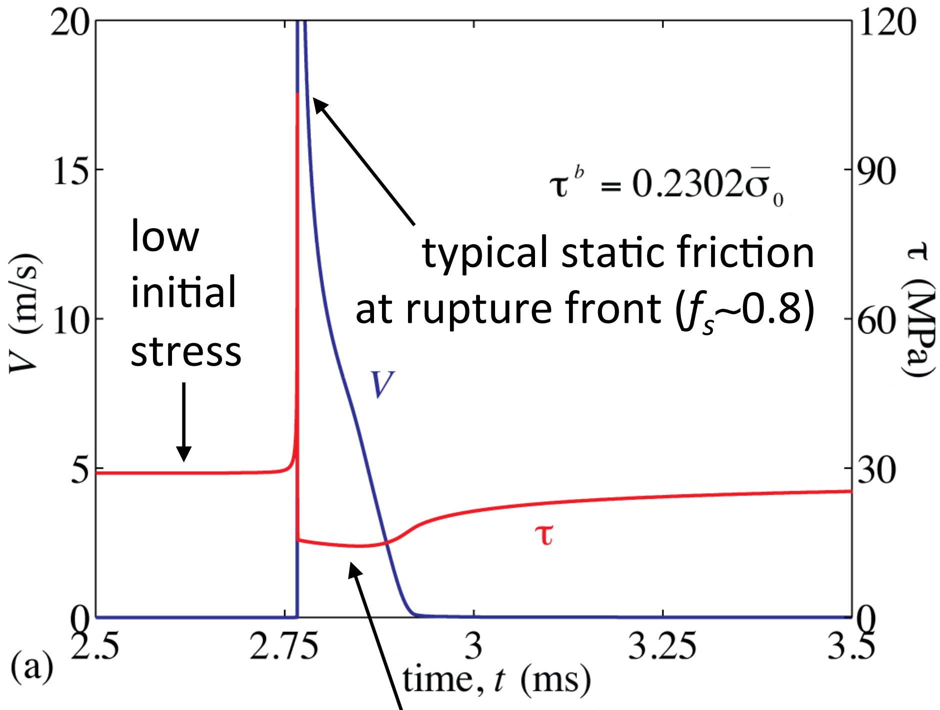
Dynamic weakening explains how *mature* faults like SAF operate at *low stresses* (and also absence of melting/heating)

simulations with dynamic weakening
(flash heating and thermal pressurization)
[Noda, Dunham, and Rice, 2009]

critical stress level τ^{pulse}



quite comparable to San Andreas stress state



low initial stress

typical static friction at rupture front (f_s~0.8)

low stress during slip

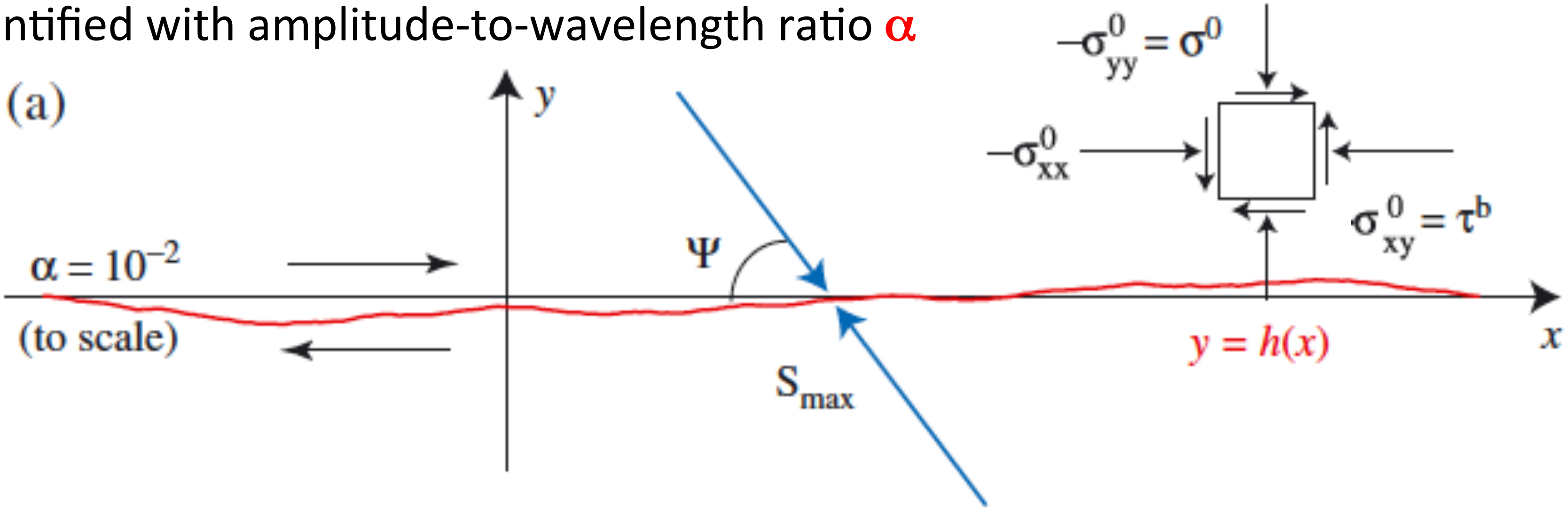
But most other faults operate at $\tau/(\sigma - p) \sim 0.6$!

Why???

(simplest explanation = dynamic weakening unique to mature faults, but I'll argue something quite different involving plasticity)

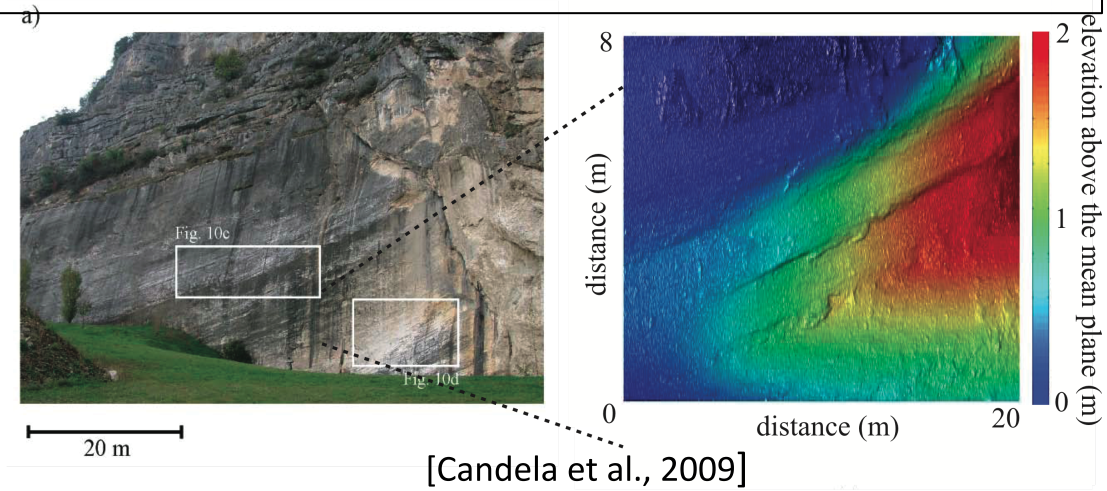
What makes mature faults different?

structural complexity: idealized here as roughness of single fault surface, quantified with amplitude-to-wavelength ratio α



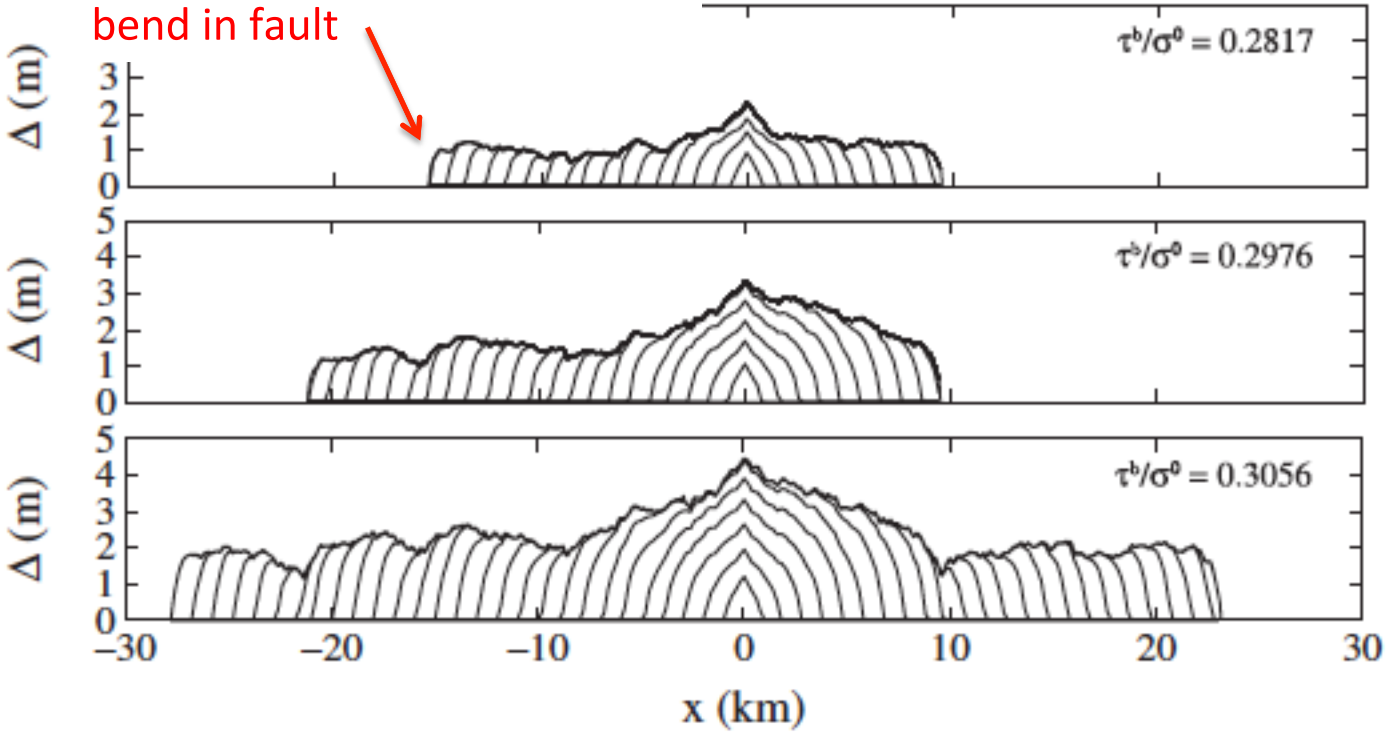
key idea: roughness introduces resistance to slip, in addition to frictional resistance, and that "*roughness drag*" is dominant resistance for all but smoothest faults

quantify roughness drag using dynamic rupture simulations with homogeneous initial stress in medium, uniform frictional properties, but rough fault (self-similar fractal roughness)



[Candela et al., 2009]

No unique threshold stress for rupture on rough faults



rupture arrests at unfavorable bend in fault

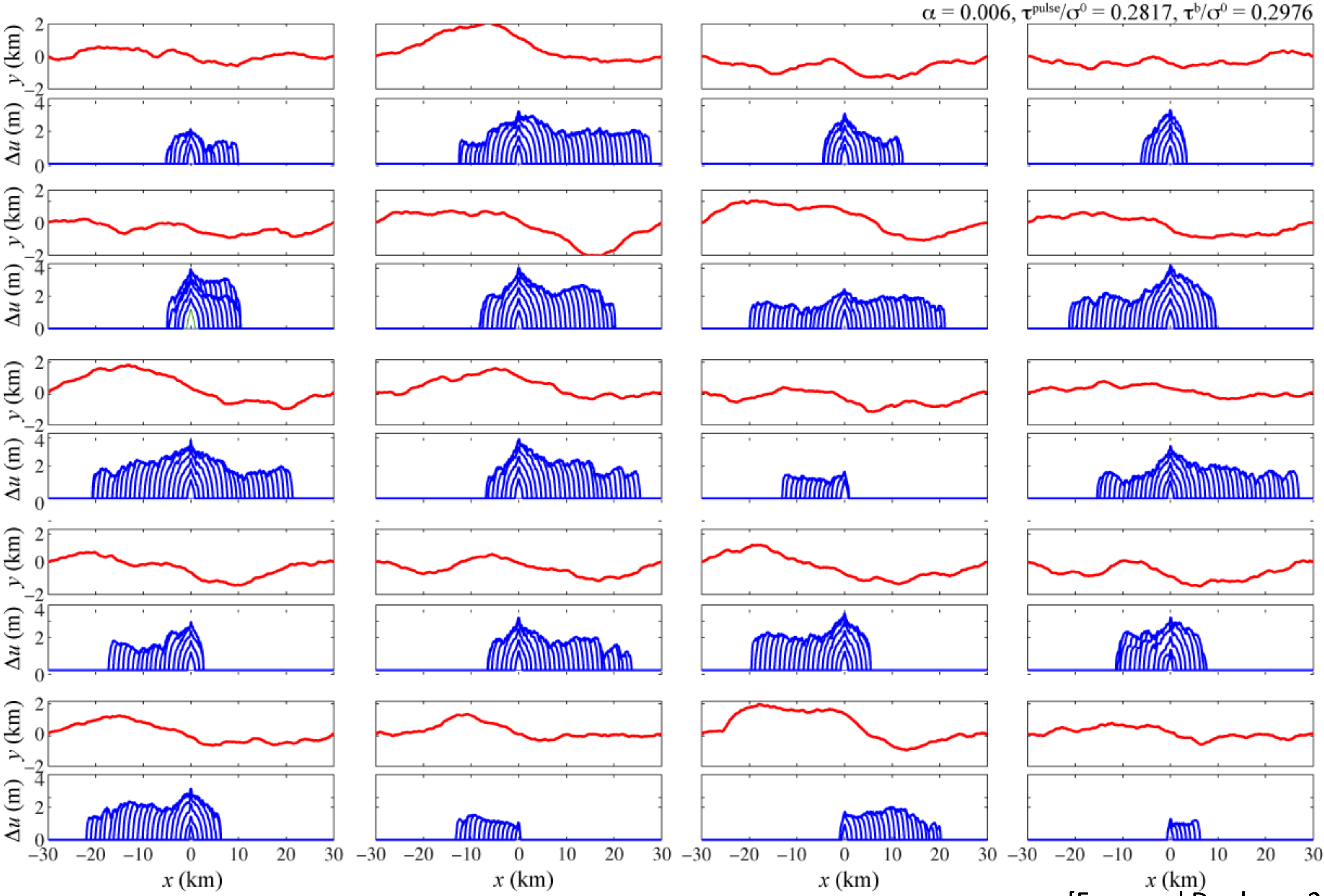
increasing shear / effective normal stress

Figure 4. Sequences of cumulative slip Δ every 0.28 s for ruptures occurring on the same fault but at three different τ^b levels. The extent of rupture and the amount of fault slip increase with background stress.

[Fang and Dunham, 2013]

variability is quite pronounced, quantifiable as *probability* of rupture exceeding some magnitude as function of stress and roughness

same initial stresses and level of fault roughness, but different hypocenter



[Fang and Dunham, 2013]

Quantifying Roughness Drag, τ_{drag}

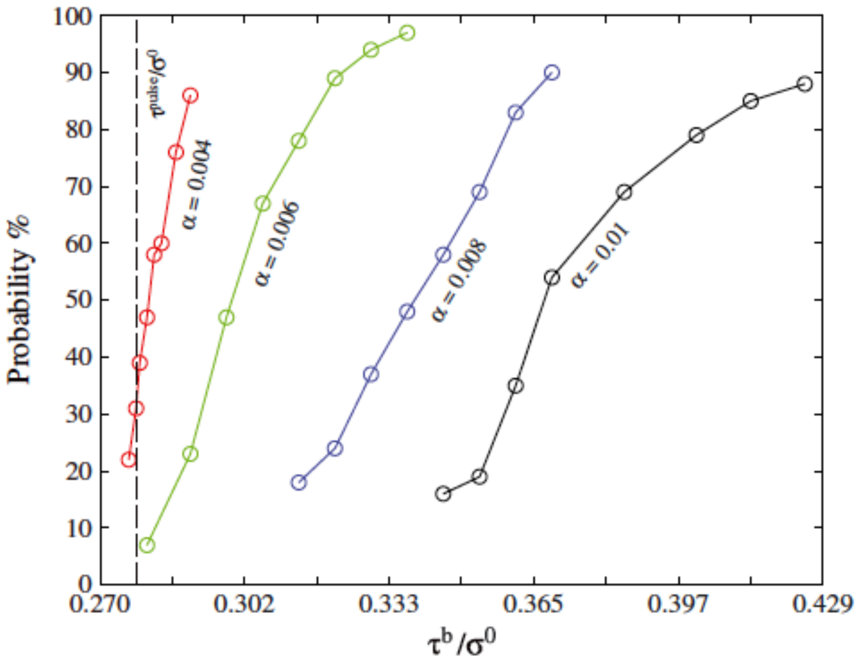
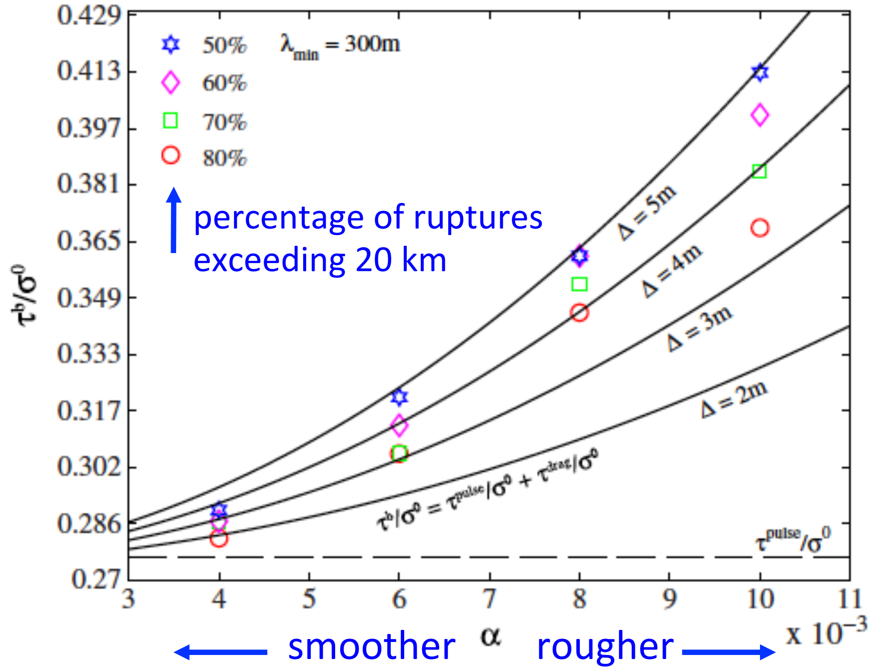


Figure 6. Probabilities of rupture to reach an extent of 20 km (in either direction) from the hypocenter as a function of background stress level τ^b. Rougher faults require larger τ^b to reach the same extent.



percentage of ruptures exceeding 20 km

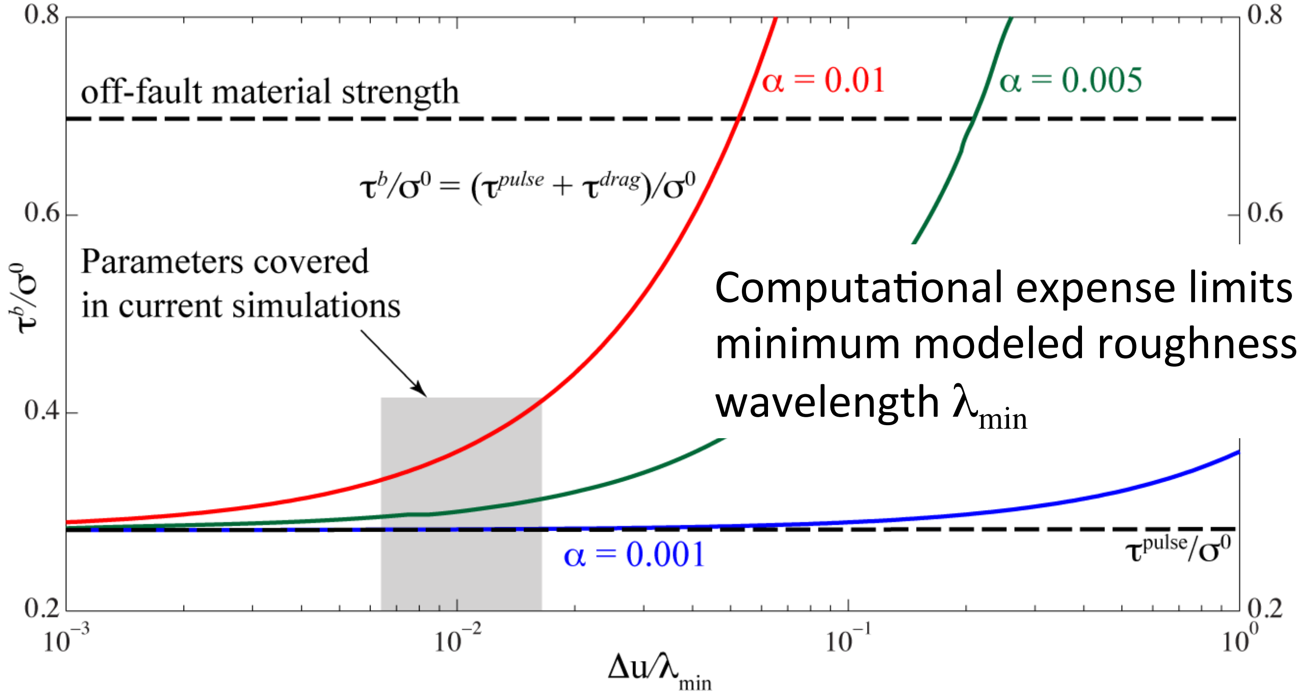
smoother rougher

Figure 7. Background stress levels τ^b required for 50%, 60%, 70%, and 80% of ruptures to propagate beyond 20 km in at least one direction. Solid lines are predictions using the theoretical expression for roughness drag in equation (5).

Projection of O(α) stress perturbations onto nonplanar fault results in an O(α^2) *resistance to slip in addition to friction* (roughness drag):

$$\tau_{drag} = 8\pi^3\alpha\frac{G}{1-\nu}\frac{\alpha\Delta u}{\lambda_{\min}} \sim 10\text{ MPa}\left(\frac{\alpha}{10^{-3}}\right)^2\left(\frac{\Delta u}{\lambda_{\min}}\right)$$

[Fang and Dunham, 2013]



Computational expense limits minimum modeled roughness wavelength λ_{min}

Hypothesis: Minimum background stress level τ^b required for self-sustaining rupture propagation on rough faults is

$$\boldsymbol{\tau^b \approx \tau^{drag} + \tau^{pulse}}$$

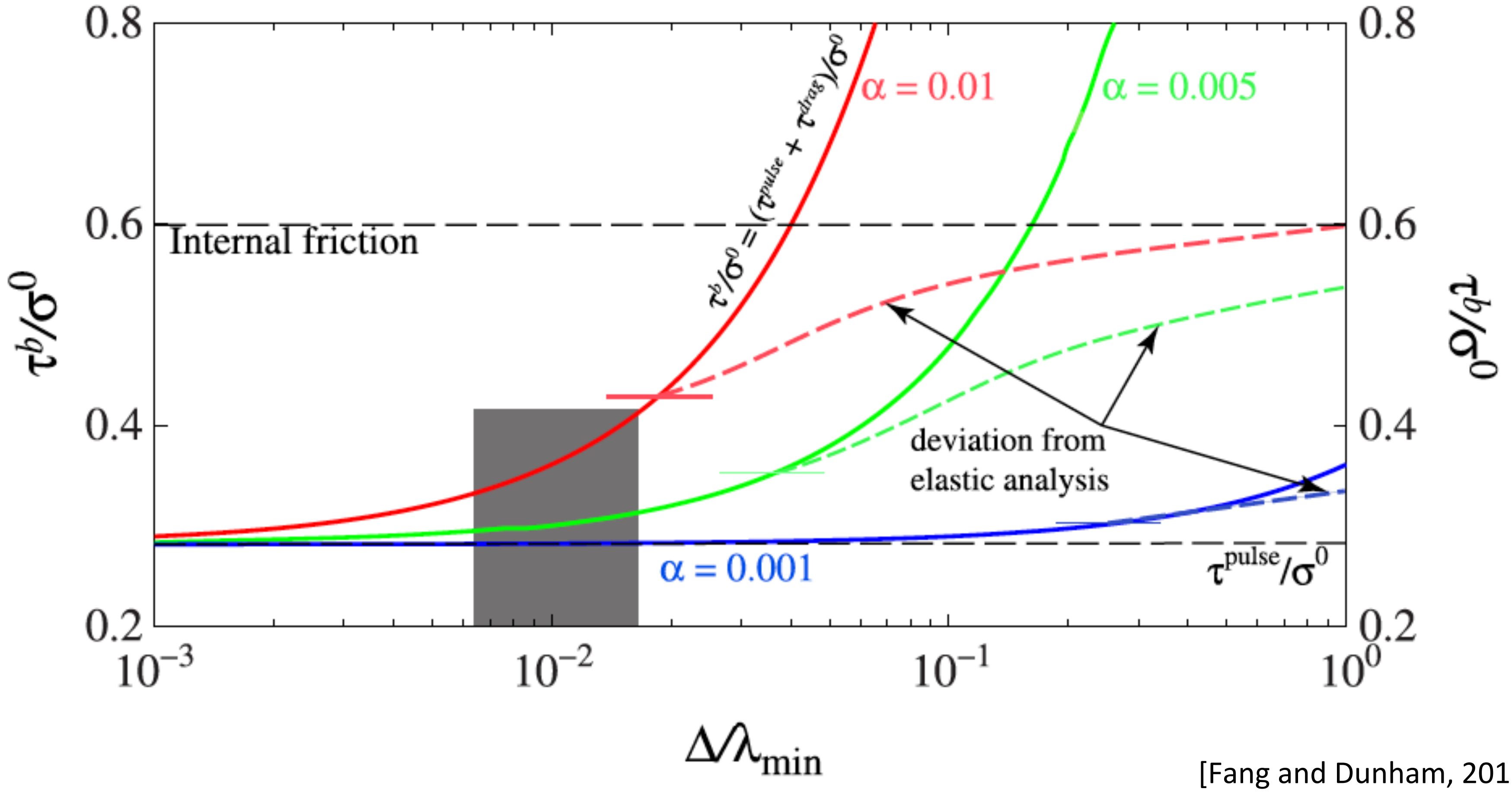
Limiting cases:

Mature faults: $\tau^{drag} << \tau^{pulse}$ so that $\tau^b \approx \tau^{pulse} \sim 0.2\text{-}0.3\sigma^{eff}$ (like SAF)

Immature faults: inelastic off-fault response ultimately bounds τ^{drag}, so that $\tau^b \approx \tau^{drag} + \tau^{pulse} \approx f_{internal}\sigma^{eff} \sim 0.6\sigma^{eff}$ (*regardless of frictional resistance!*)

[Fang and Dunham, 2013]

Extrapolation of Simulations to Nature



[Fang and Dunham, 2013]

- Stress ultimately bounded by strength of off-fault material
  - Explains success of Mohr-Coulomb theory, with "Byerlee friction coefficients" of 0.6-0.9, in predicting fault activity—but 0.6-0.9 is *NOT* frictional strength of faults
- Geometrical resistance to slip causes immature faults to operate at overall stress levels 0.6-0.9σ_{eff}, but with negligible heat production due to dynamic weakening

Conclusions

Damage zones and long-term evolution of fault systems:

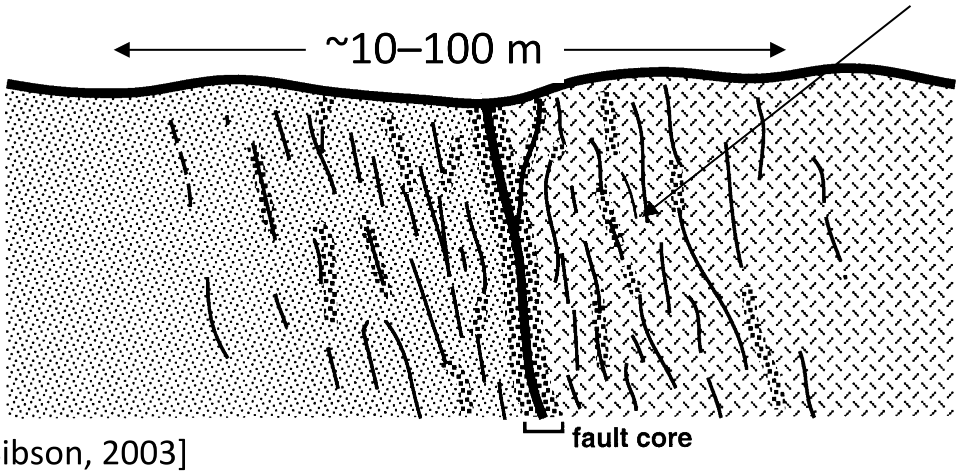
- what happens over 10,000+ year time scales?
- will plastic deformation saturate? (shakedown)
- how do fault systems develop and evolve?

→ finite strain simulations with localization

Crustal stress levels:

- resistance to slip from geometric complexities might be as or more important than friction

→ spun-up simulations of dynamic ruptures on realistic fault geometries



Plastic strain represents frictional motion of distributed set of microcracks in damage zone

[Sibson, 2003]