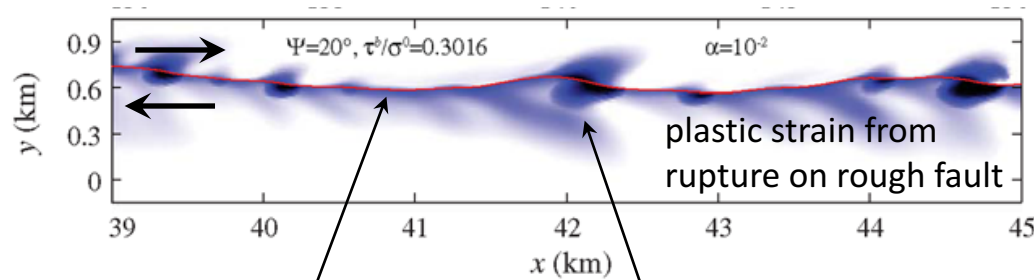


Earthquake Energy Balance, Stress Levels, and Heat Production in Rough Fault Simulations

Eric M. Dunham, Stanford

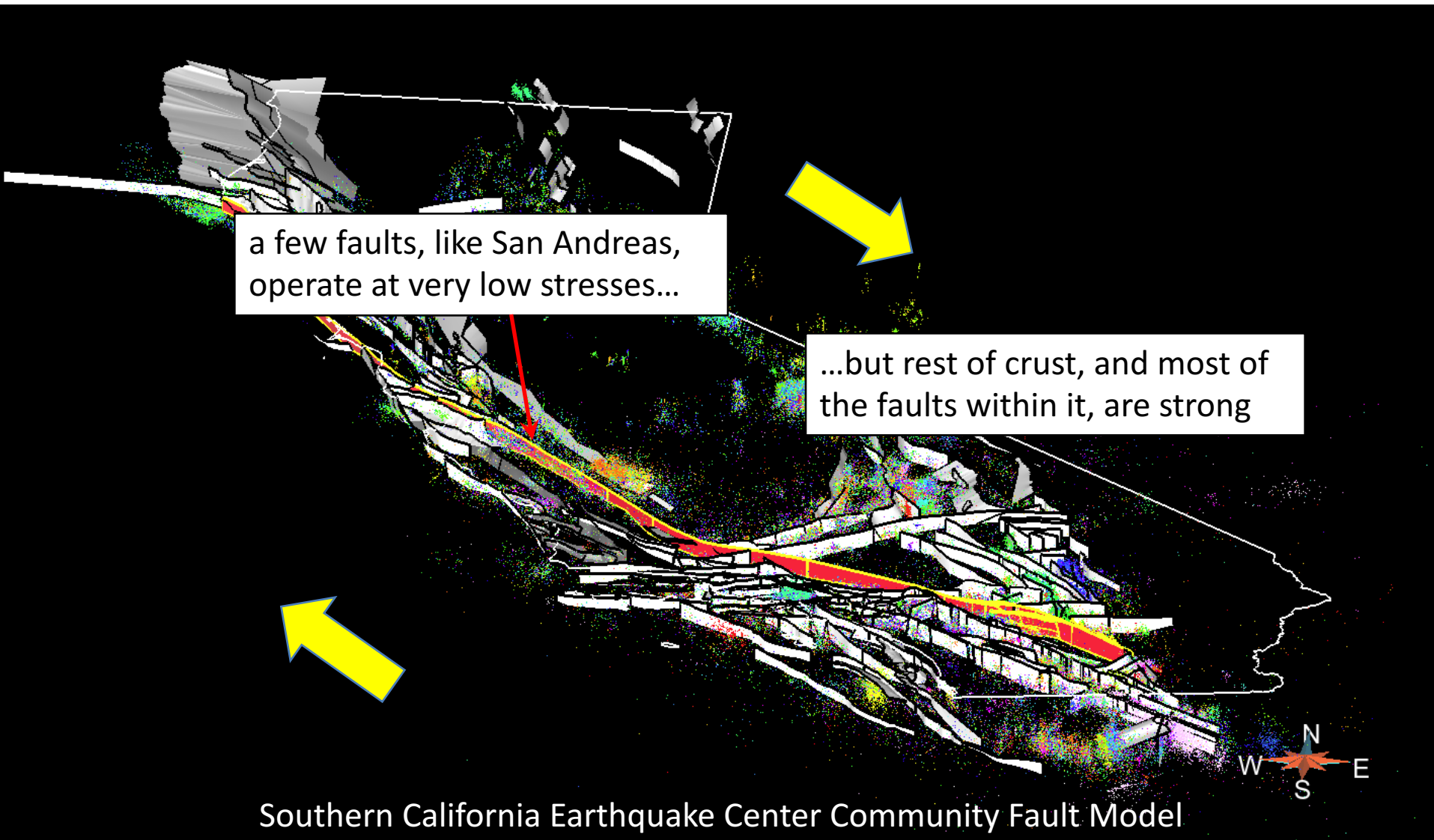


frictional strength τ on main fault reduced to nearly zero by dynamic weakening during coseismic slip

resistance to slip comes primarily from geometric complexity
→ load transferred to secondary faults and microfractures in off-fault material (causing plastic strain), which remains strong because resolved shear rates are too small for dynamic weakening (but off-fault heat production also remains small)

Or, how faults can host earthquakes at “high” background stresses $\tau_b \approx 0.6(\sigma - p)$ with negligible heat production

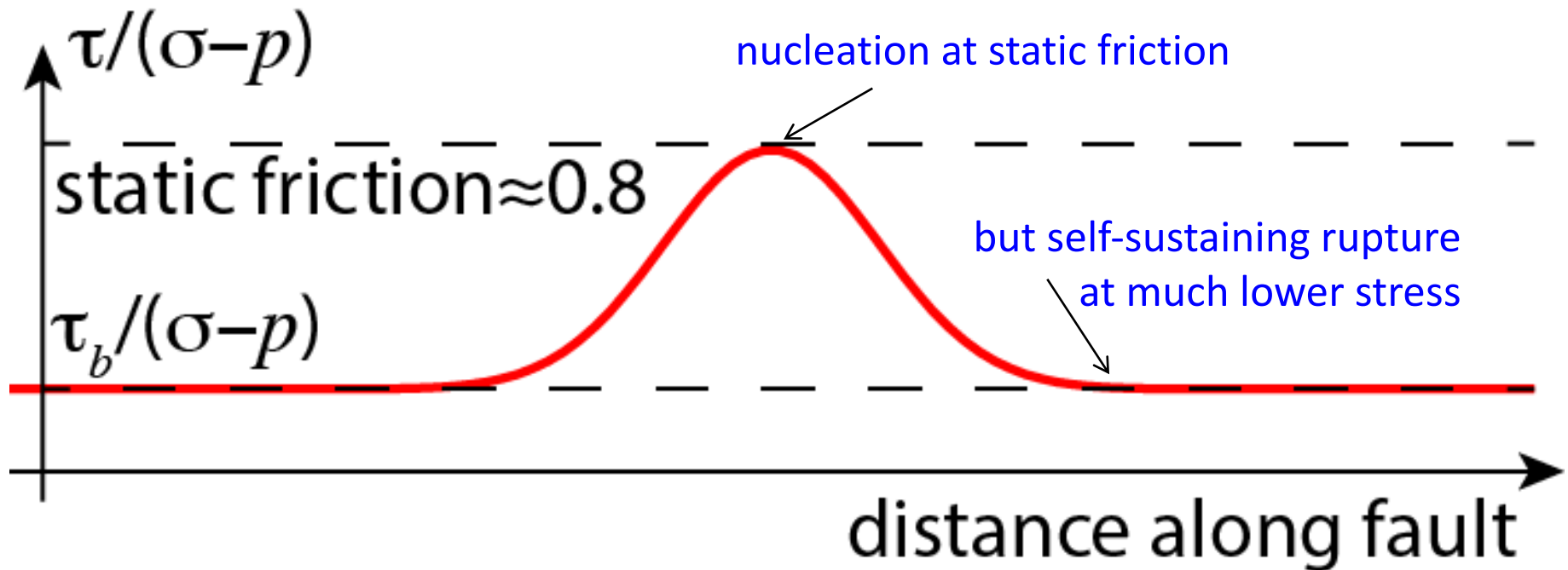
State of Stress in Earth's Crust



Why are stress levels on SAF and other faults so different?

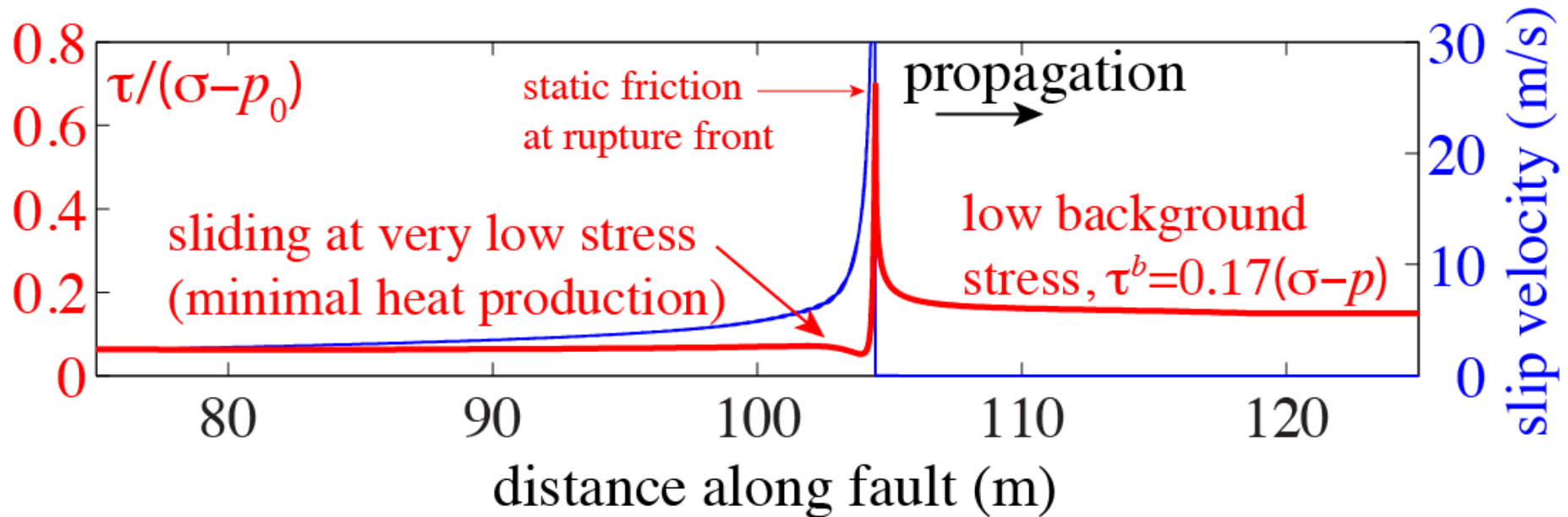
We first have to carefully define two related, but subtly different stresses:

- local tractions on fault surface, τ
- overall or average stress driving slip, τ_b (remote tectonic stress)



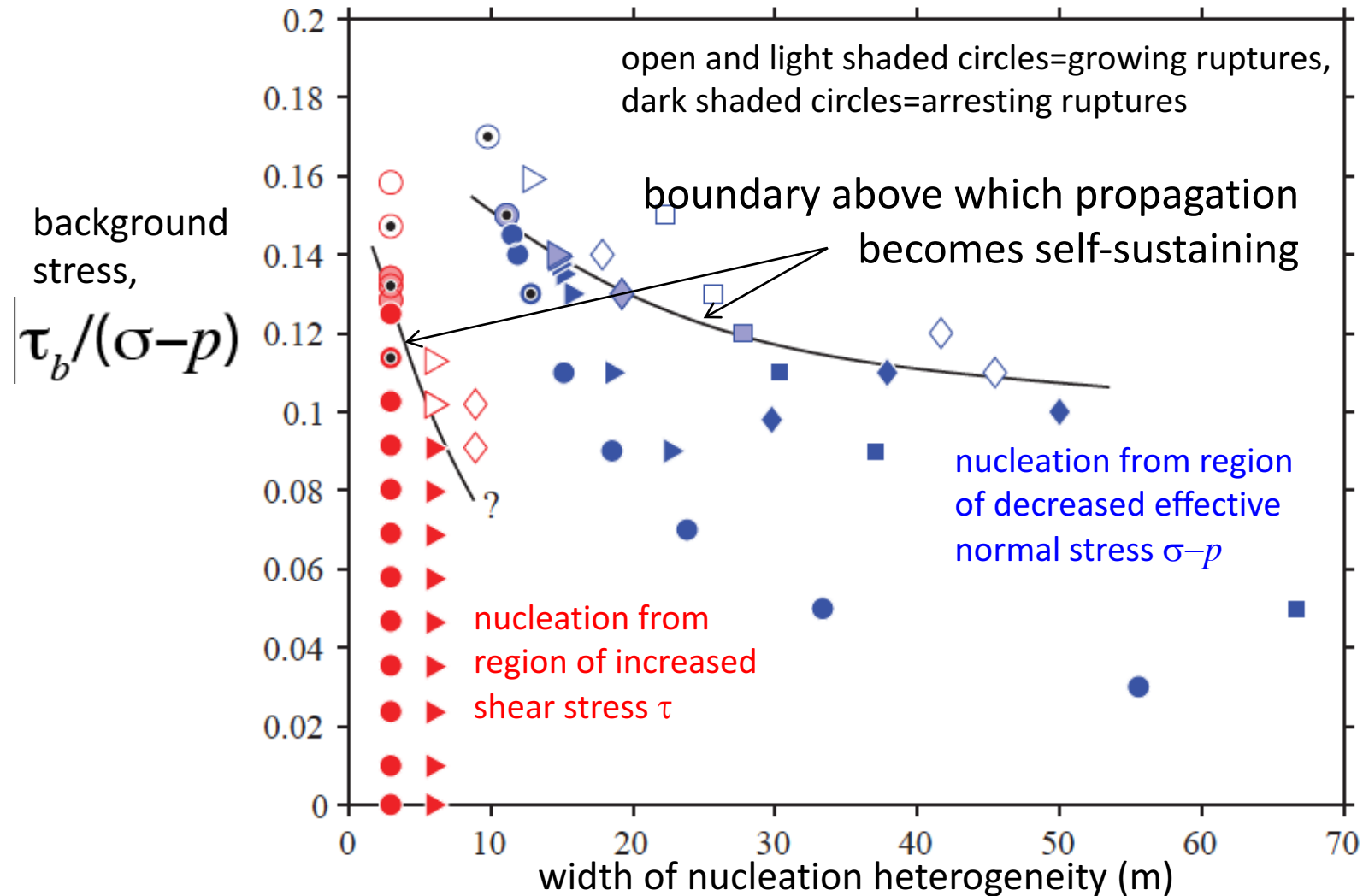
Dynamic weakening* permits **self-sustaining propagation** at very low stress and minimal heating

as illustrated in *dynamic rupture simulation with thermal pressurization on planar fault in elastic medium*



*dynamic weakening=extreme reduction in fault strength during coseismic sliding (slip rates ~ 1 m/s) from thermal pressurization, decomposition reactions, flash heating, etc.

Ruptures with *Thermal Pressurization* on *Planar Faults in Elastic Medium*



Dynamic weakening permits **self-sustaining propagation at very low stress and minimal heating**

Average stress doing work on fault (i.e., generating heat) in our simulations is

$$\tau_{heat} = \frac{\int \tau V dt}{\int V dt} = \frac{\text{work/area done on fault}}{\text{slip}} \approx 10 \text{ MPa}$$

with even smaller values expected for larger events due to additional pressurization.

Thus, heat production from frictional sliding of fault satisfies constraints from heat flow:

If most of the fault motion is accomplished by periodic earthquakes, the lack of an anomaly both at Hollister and other locations along the San Andreas fault, establishes an upper limit of about 100 bars for the average frictional stress operating during faulting. — 10 MPa

[Brune et al., 1969; see also
Lachenbruch and Sass, 1980]

This is how the San Andreas (and other mature faults) appear to operate; thus, dynamic weakening potentially resolves “stress / heat flow paradox”

Why do other faults require $\tau_b \approx 0.6(\sigma - p)$ for rupture?

Two possibilities, both with identical background stress levels, but quite different dynamics:

HEAT PRODUCTION

1. ***dynamic weakening is unique to mature faults*** having well-developed cores prone to shear localization, heating, and thermal weakening

high (from sliding at elevated τ), though distributed shear can prevent melting

2. dynamic weakening eliminates frictional resistance, but ***some other mechanism provides resistance to slip in addition to friction***

low (from sliding at negligible τ , and minimal off-fault heat production during plastic strain)

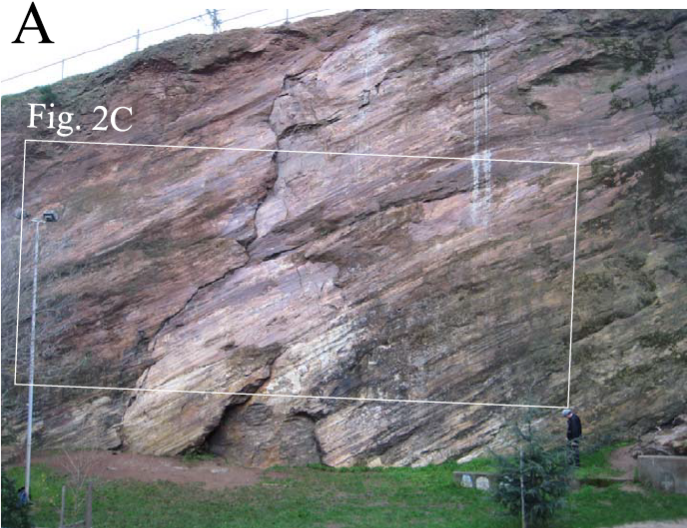
Second explanation appealing because dynamic weakening is ubiquitous in experiments and localization develops rapidly in sheared gouge.

Additional Resistance from Structural Complexities

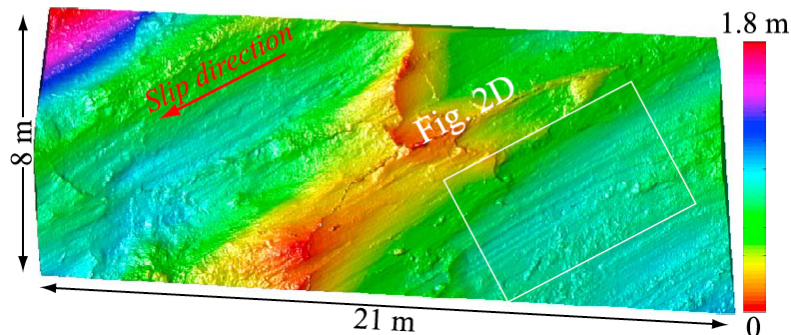
like surface roughness, segmentation, branching, etc.

This geometric complexity introduces resistance to slip, even when faults are frictionless.

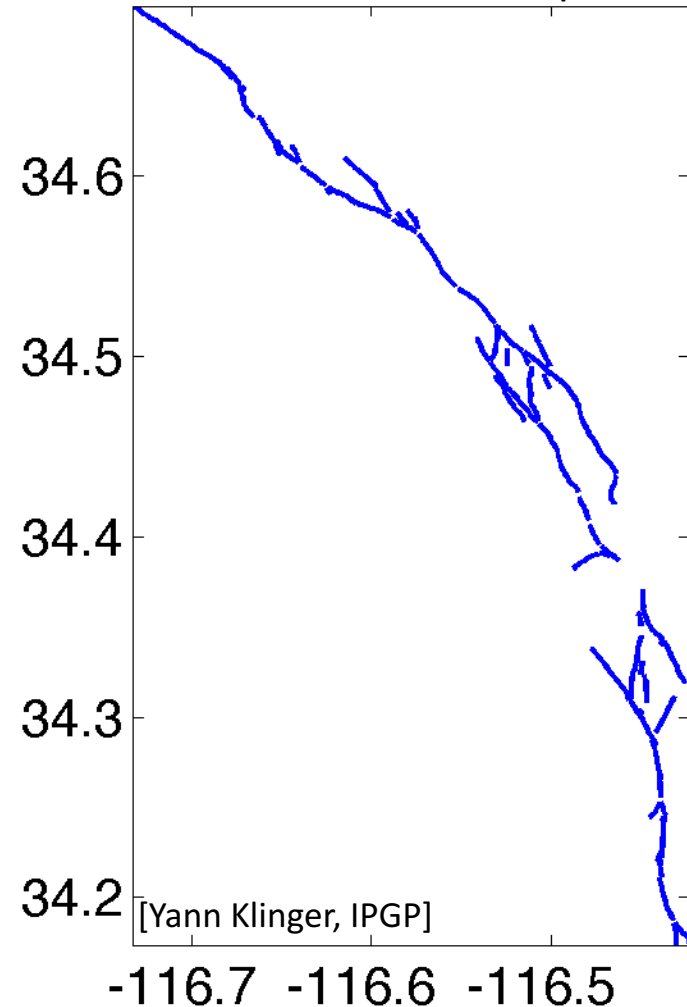
Corona Heights fault, San Francisco
(former quarry, front face stripped away)



C [Candela et al., 2012]



1992 Landers earthquake



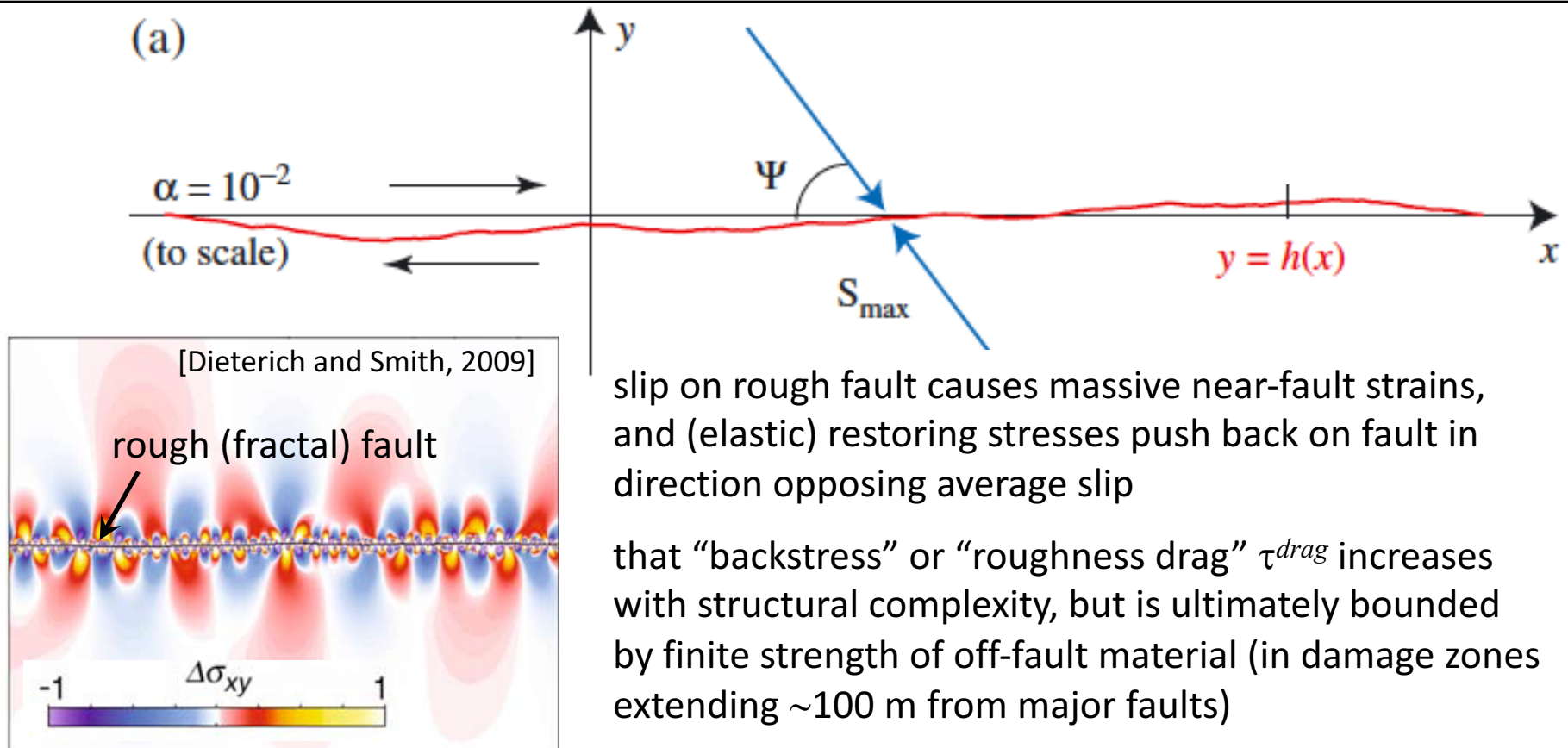
Dynamic Ruptures on Geometrically Complex Faults with Dynamic Weakening

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

$\alpha \sim 10^{-2}$ for immature faults, $\alpha \sim 10^{-3}$ for mature faults

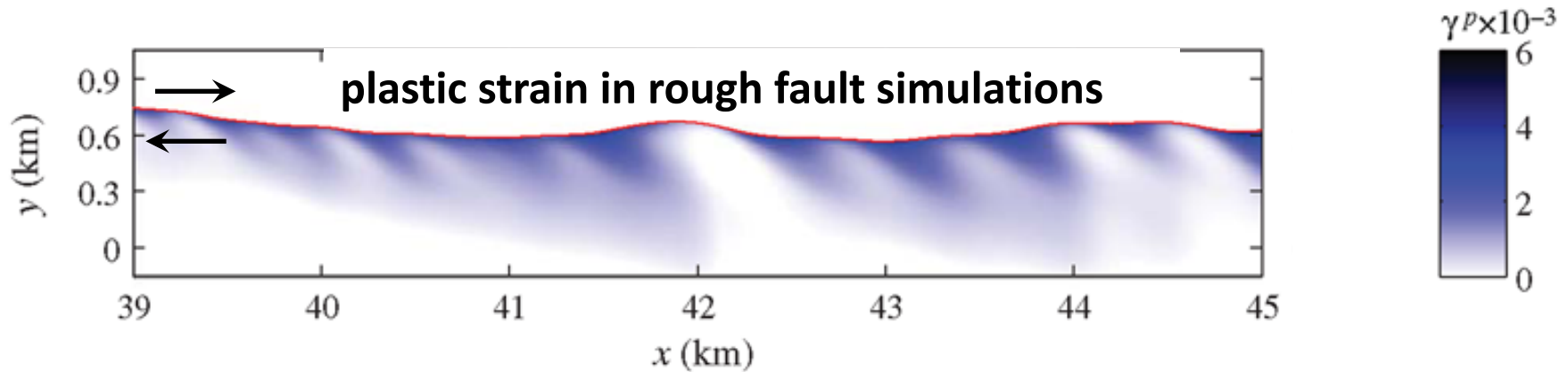
[Power and Tullis, 1991; Brodsky et al., 2011; Candela et al., 2013]

hypothesis: roughness introduces resistance to slip, in addition to friction, and “roughness drag” τ^{drag} is dominant resistance for all but smoothest faults



Inelastic Deformation using Drucker-Prager Plasticity

(very similar to Mohr-Coulomb)



plasticity essential to prevent otherwise unrealistically large stresses in vicinity of fault

...but *plastic strain also produces heat* (frictional sliding on secondary faults and microcracks), and we must check that this additional heating doesn't violate heat flow constraints

If earthquake nucleates at some $\tau_b/(\sigma-p)$, will it become large?

roughness drag substantially increases threshold stress for self-sustaining rupture

...but note that stress levels have not yet reached observed $\tau_b/(\sigma-p) \approx 0.6$ (because we only model roughness wavelengths >100 m)

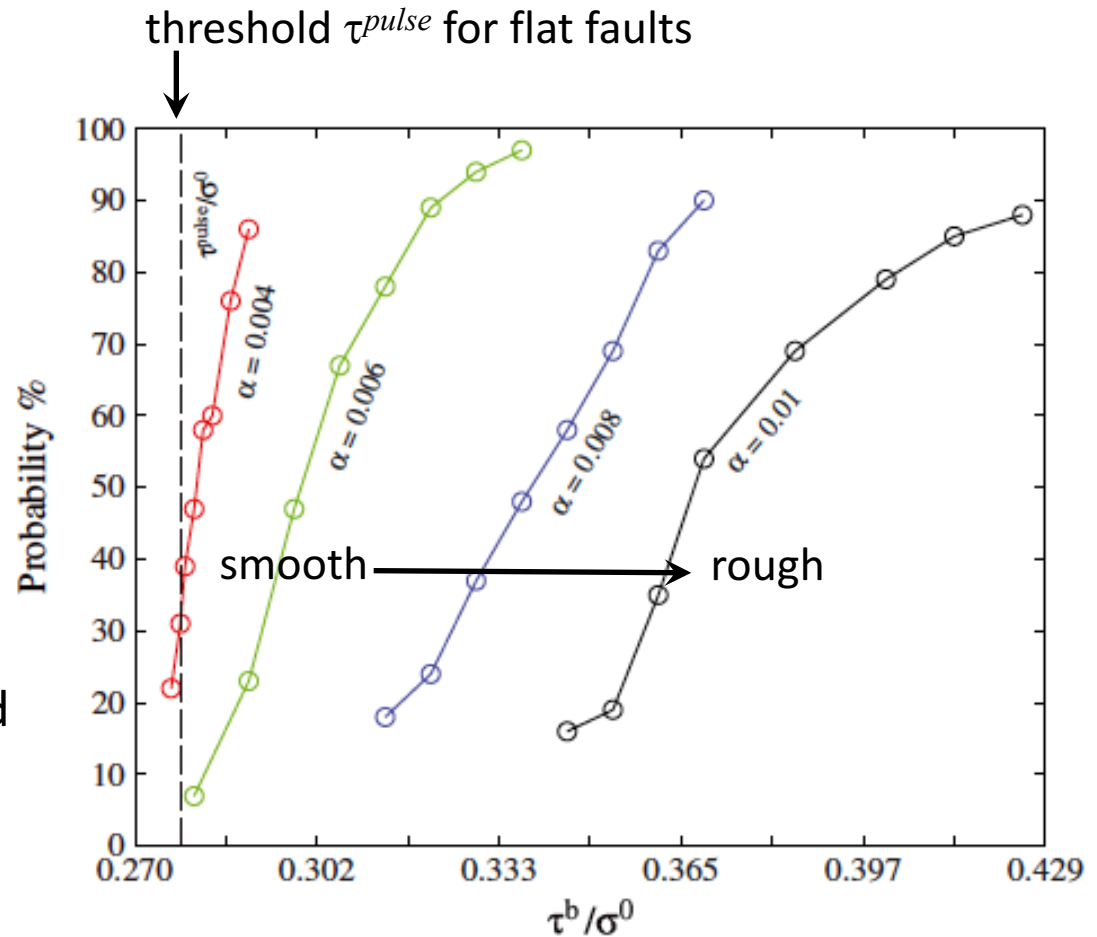
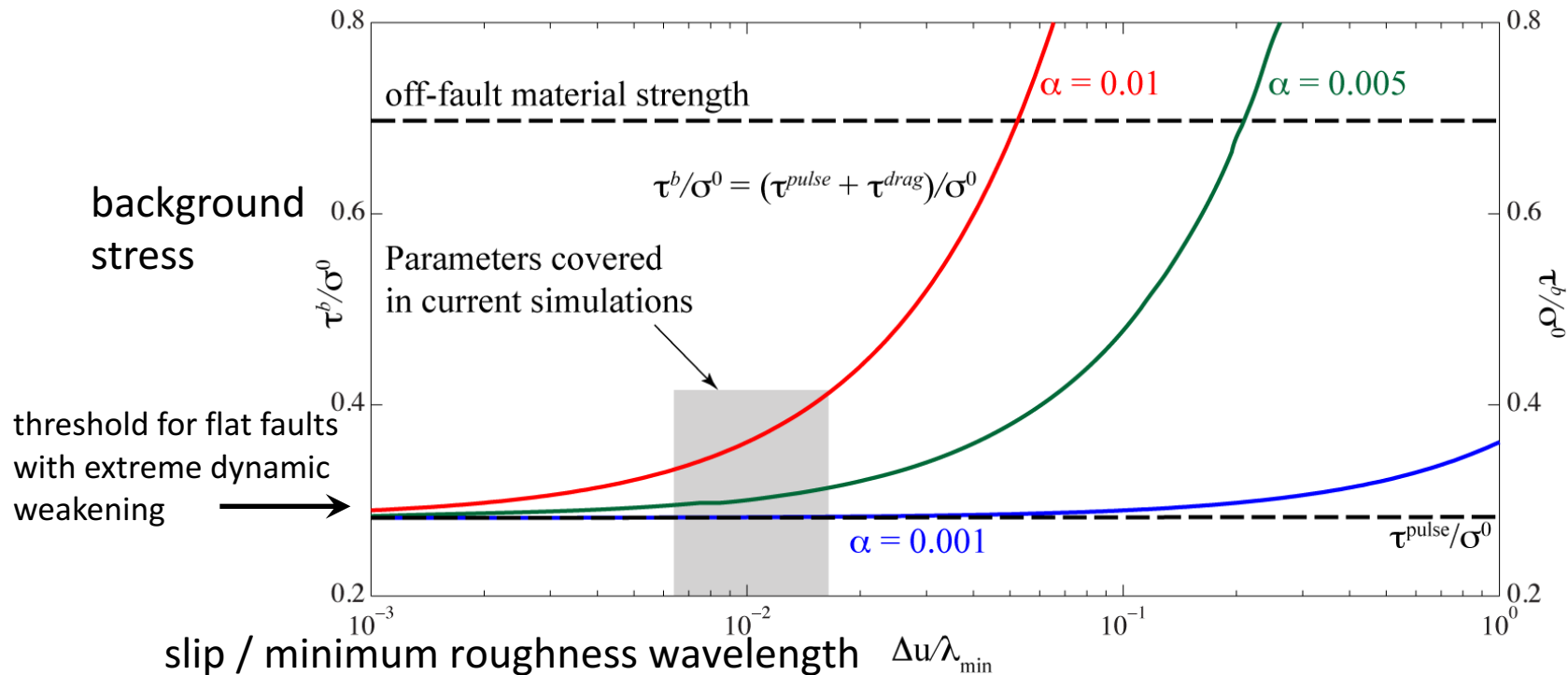


Figure 6. Probabilities of rupture to reach an extent of 20 km (in either direction) from the hypocenter as a function of background stress level τ^b . Rougher faults require larger τ^b to reach the same extent.

Bringing Simulations Closer to Reality (by accounting for shorter roughness wavelengths)

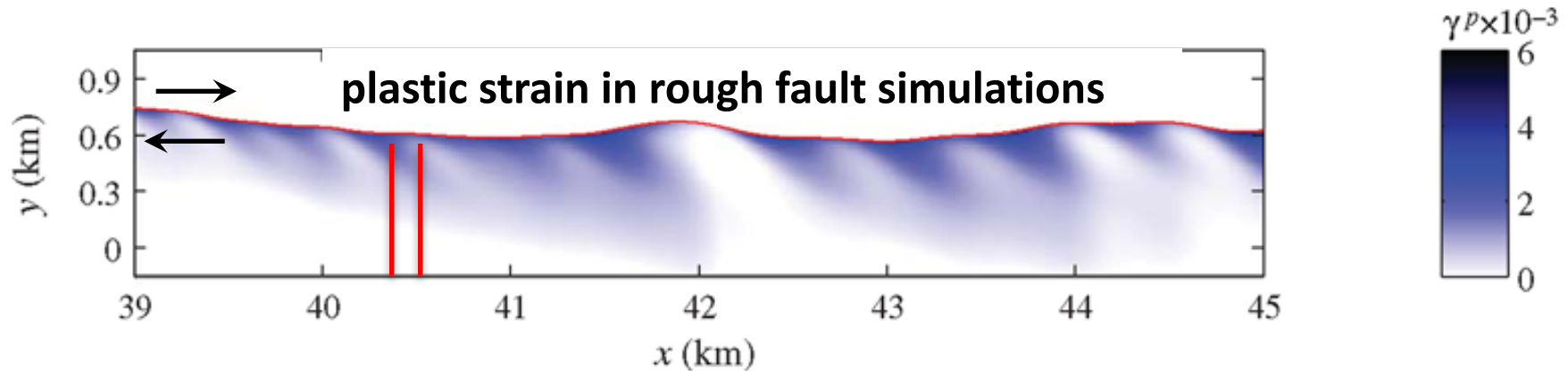
predicted threshold stresses τ^b based on analytical estimate [Fang and Dunham, 2013] of τ^{drag} and hypothesis that $\tau^b \approx \tau^{pulse} + \tau^{drag}$



smooth faults: τ^{drag} negligible, so $\tau^b \approx \tau^{pulse} \approx 0.25(\sigma - p)$ (like SAF)

rough faults: τ^{drag} dominates resistance, ultimately bounded by finite strength of off-fault material, so $\tau^b \approx 0.6(\sigma - p)$

Heat Production by Off-Fault Plastic Deformation



$$\text{work/volume done by plastic strain} = \int \sigma_{ij} \dot{\epsilon}_{ij}^p dt$$

$$\sim (\text{deviatoric stress})(\text{plastic strain}) \sim (100 \text{ MPa})(10^{-3}) = 0.1 \text{ MJ/m}^3$$

or, integrating over off-fault dimension, **$\sim 3 \text{ MJ/m}^2$** , consistent with seismically inferred fracture energy for events of this size [e.g., Abercrombie and Rice, 2005]

$$\text{temperature change} = \frac{\int \sigma_{ij} \dot{\epsilon}_{ij}^p dt}{\rho c} \sim \frac{0.1 \text{ MJ/m}^3}{3 \text{ MJ/m}^3 \text{K}} \sim 0.03 \text{ K}$$

(and contribution to total heat production is about 3 to 10 times *less* than Brune et al. [1969] upper bound)

Taken at face value, these results present a dilemma:

A fault operating at high stress (~ 40 MPa), and experiencing a small stress drop (~ 4 MPa), should have a huge amount of energy flowing into it.

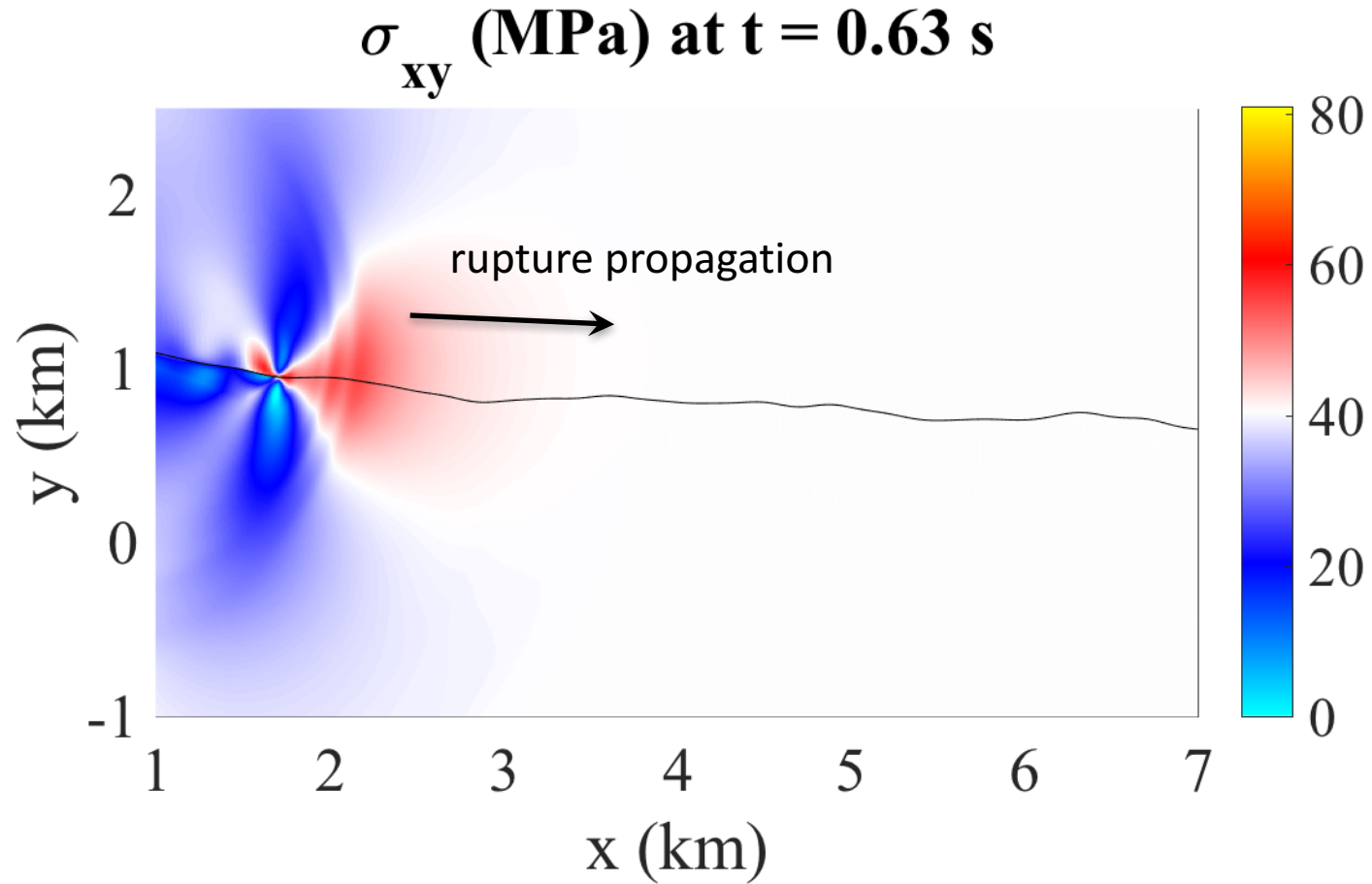
I've also suggested that

- not much is dissipated as heat during frictional sliding on fault
- even less is dissipated as heat during plastic straining

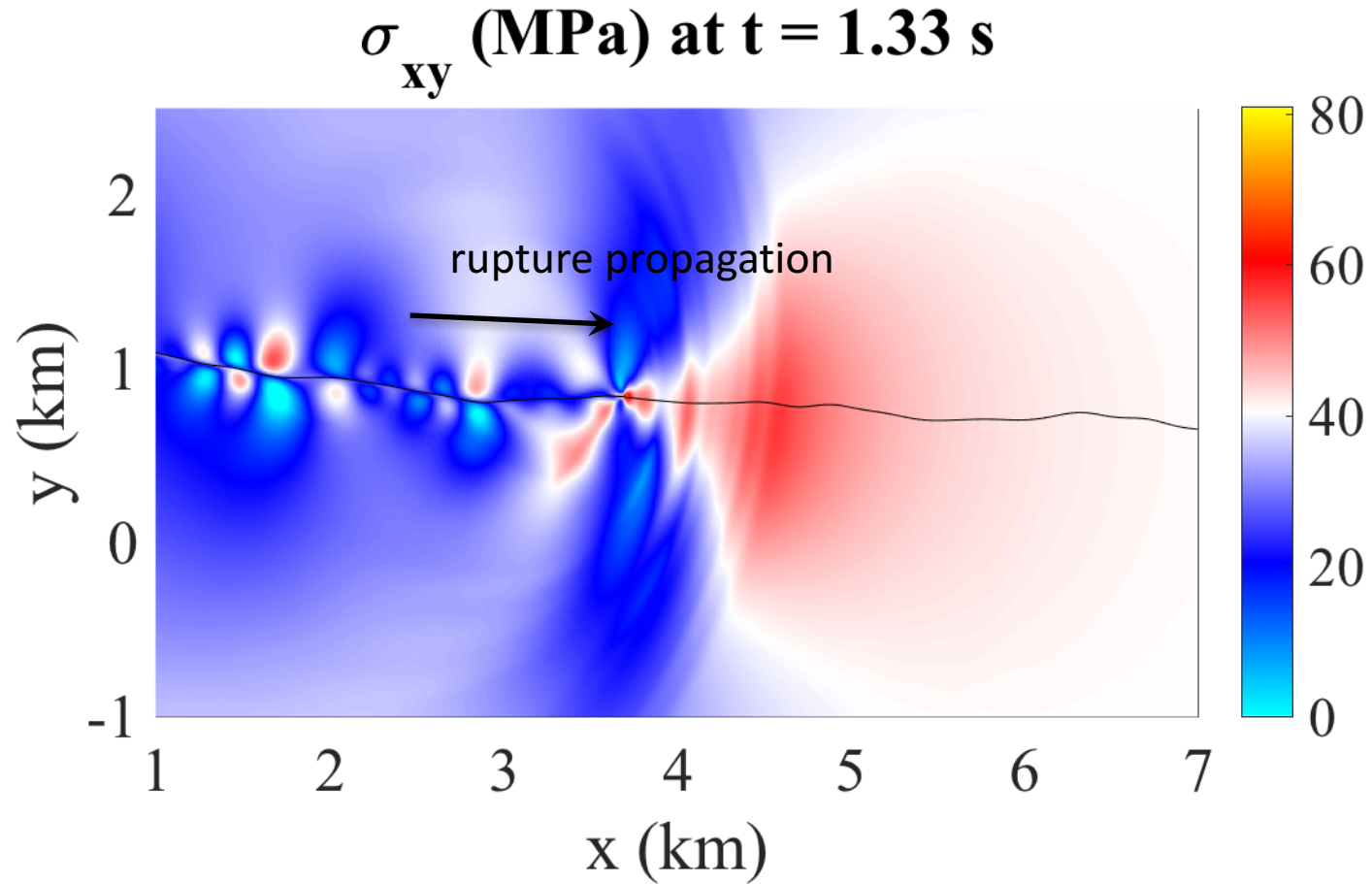
So where is the energy going?

let's examine one simulation in more detail

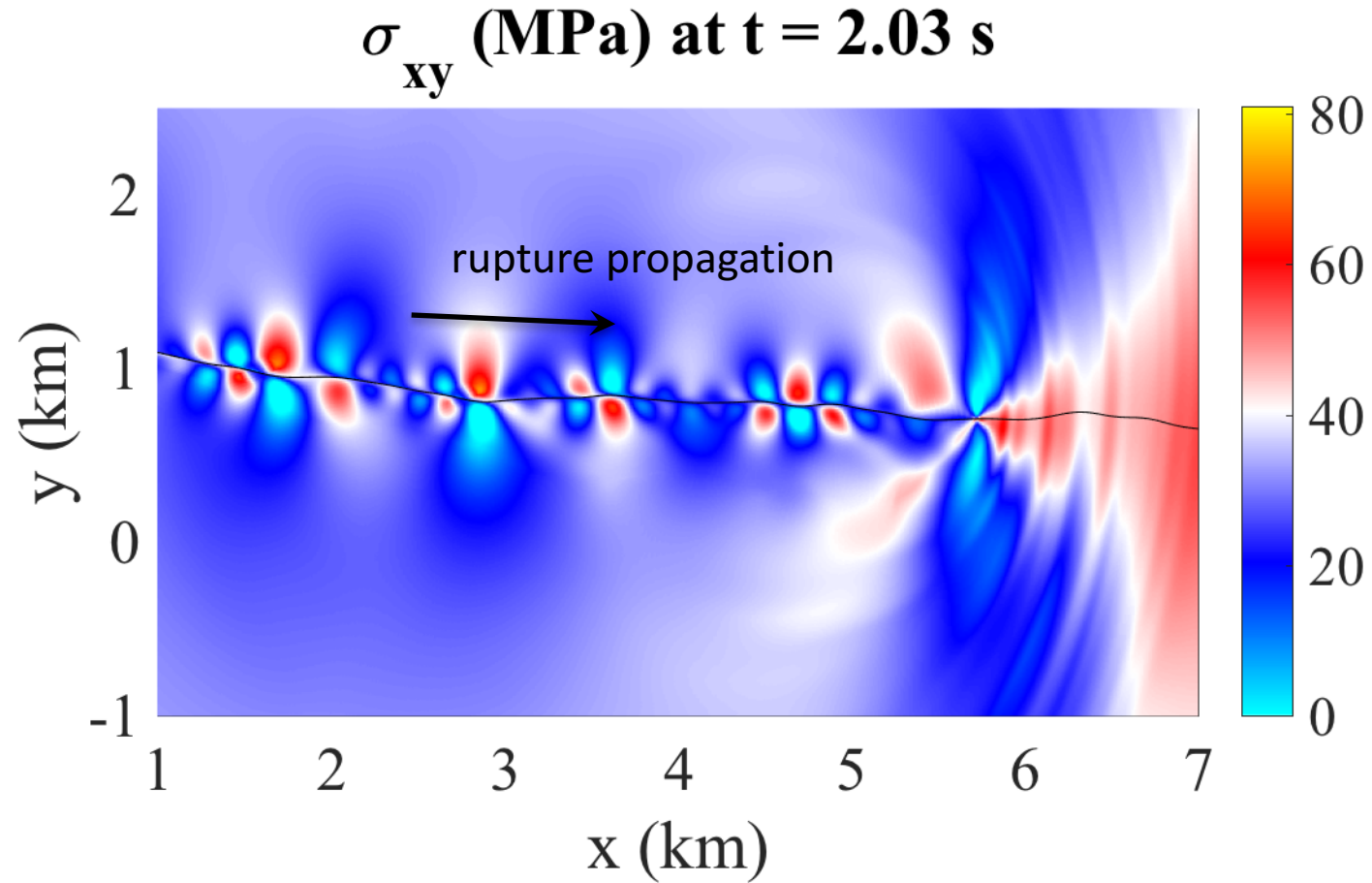
What do we mean by “stress drop”?



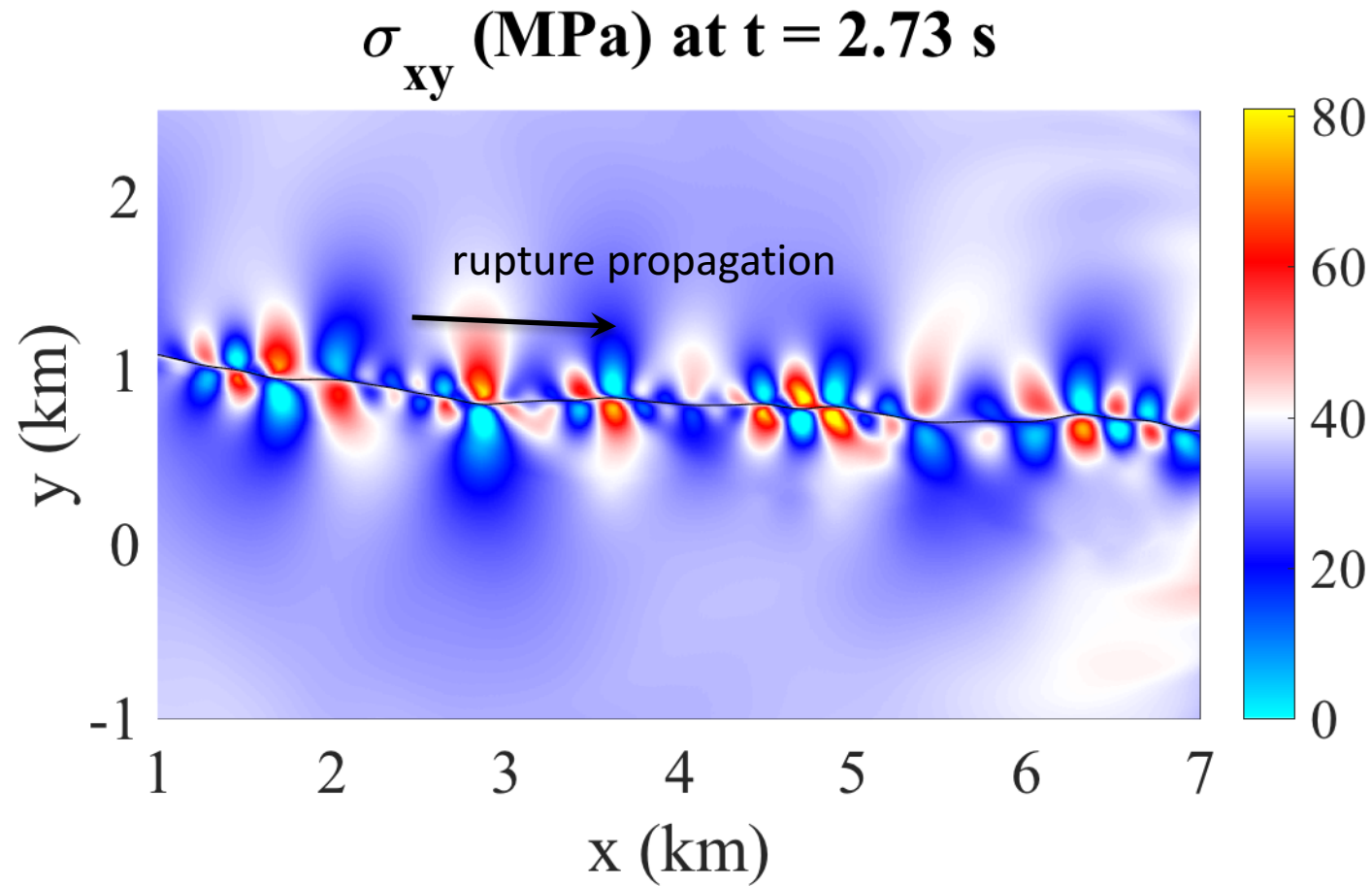
What do we mean by “stress drop”?



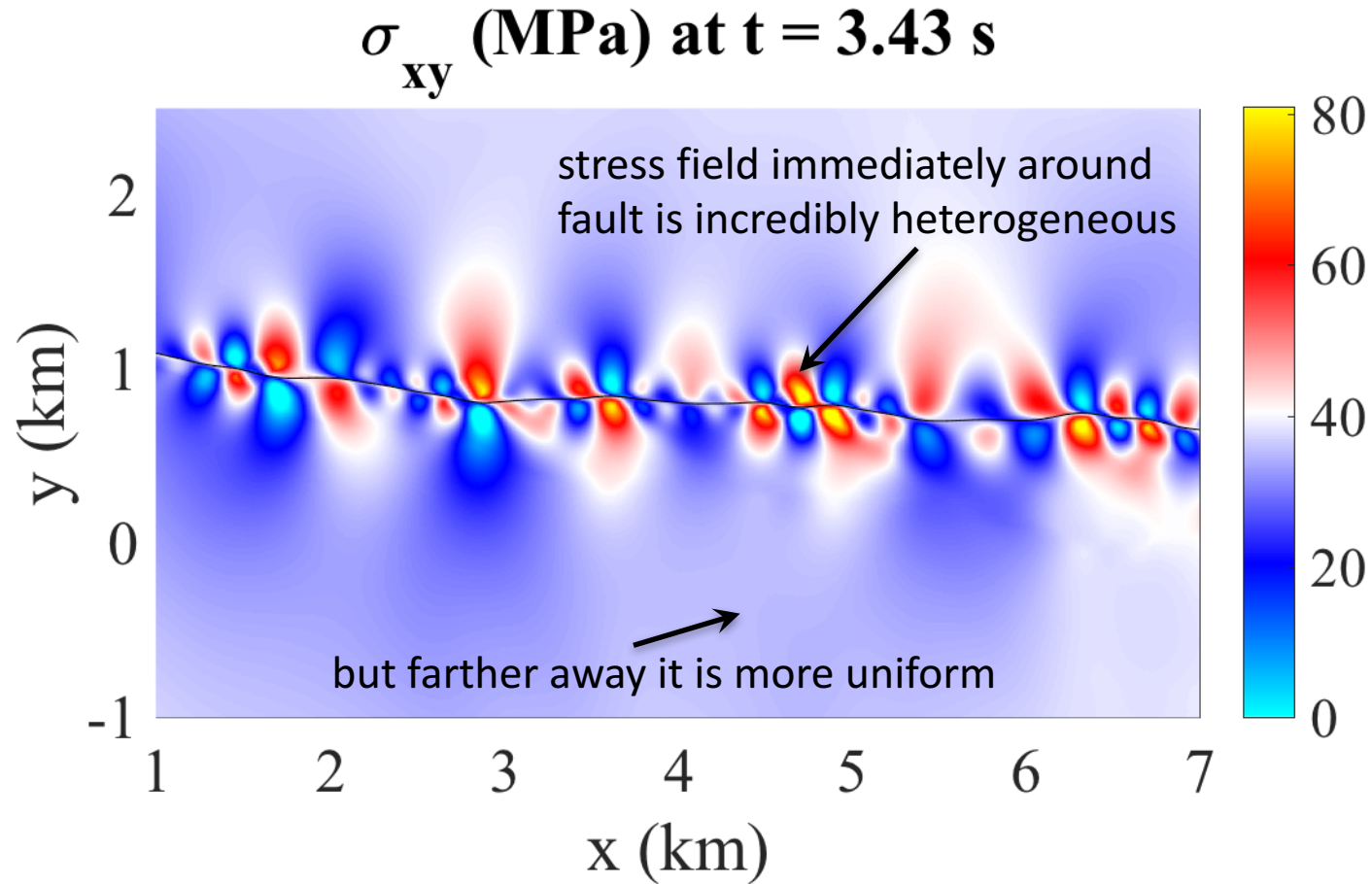
What do we mean by “stress drop”?



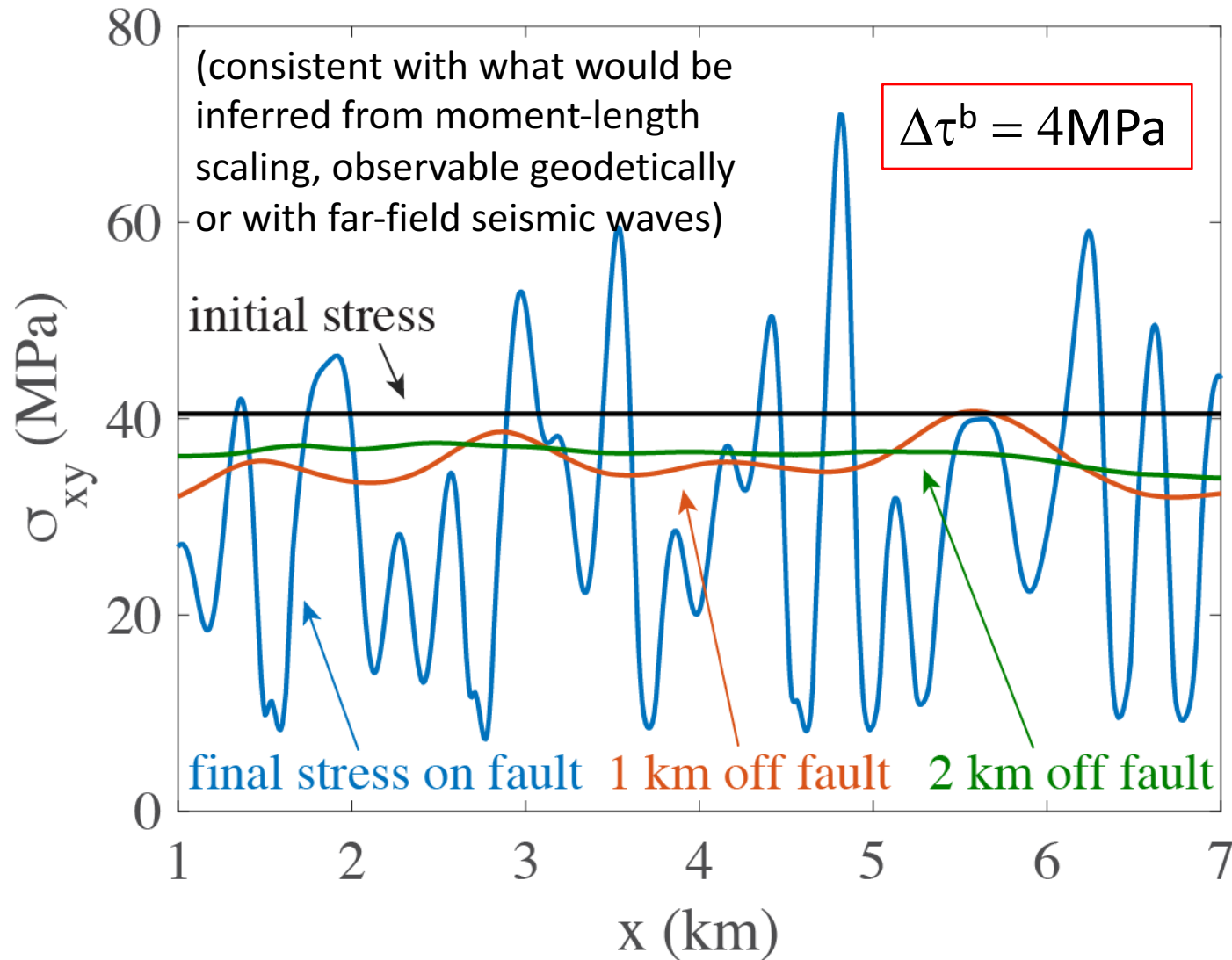
What do we mean by “stress drop”?



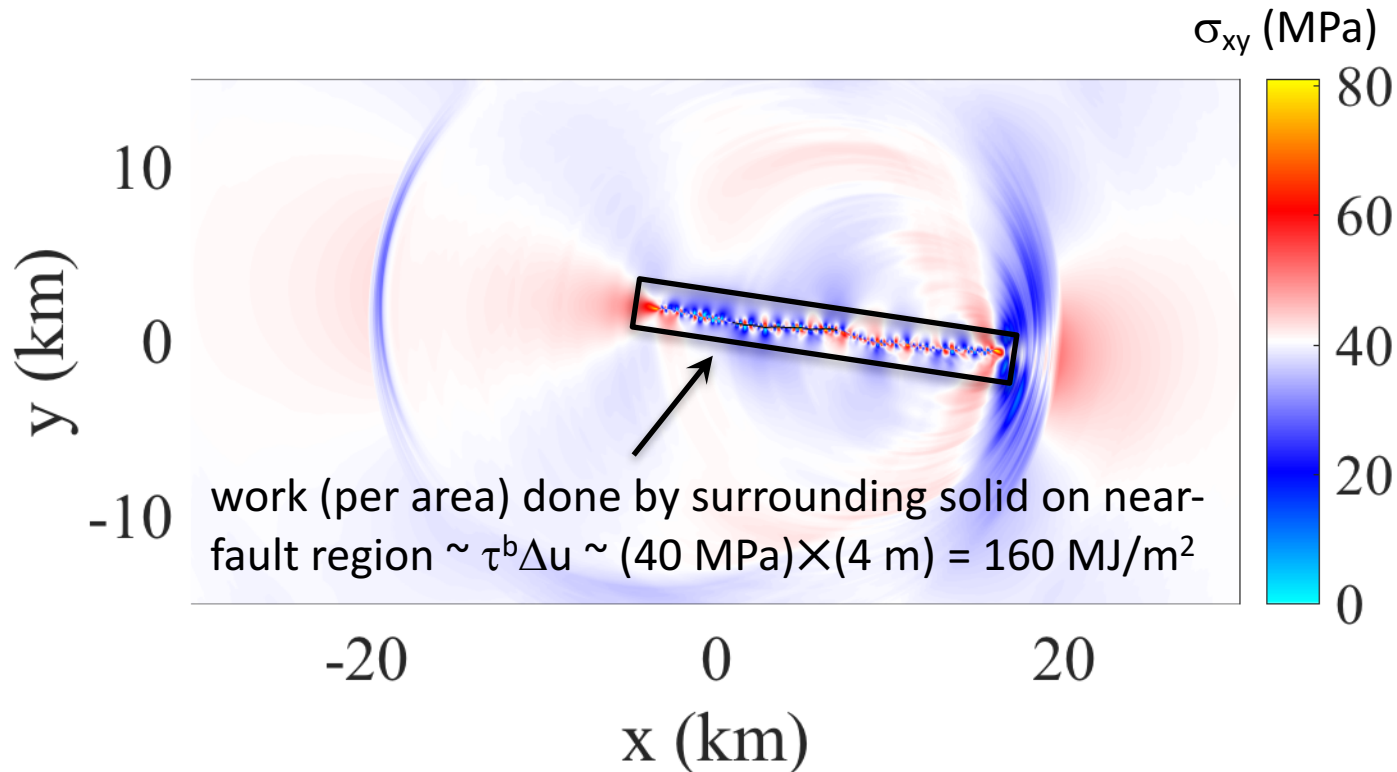
What do we mean by “stress drop”?



We can define stress drop in terms of background stress τ^b using values of σ_{xy} outside of near-fault region of heterogeneous stress.



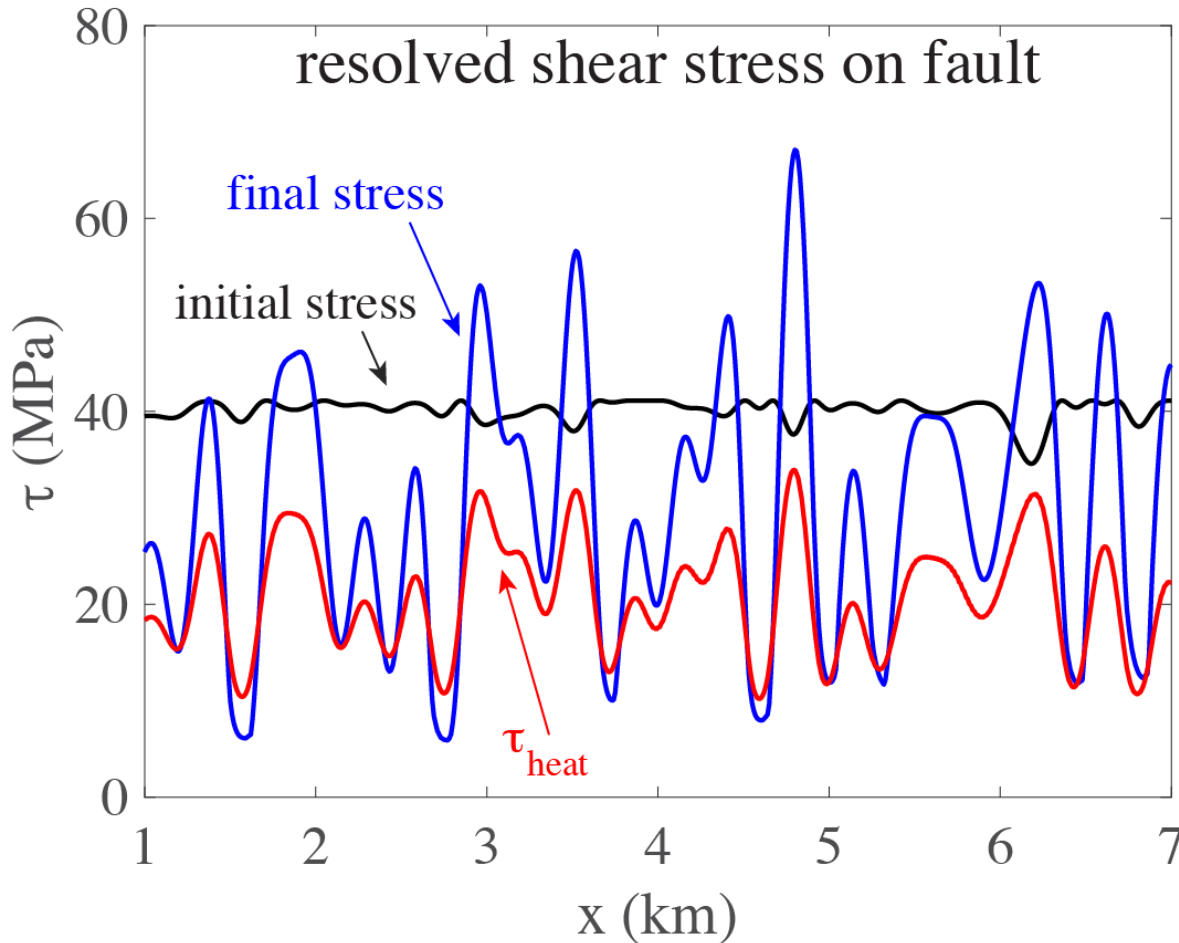
Do the usual earthquake energy balance, but expand the “fault” to include the near-fault region, too.



I'll discuss this in terms of stress doing work on near-fault region $\sim \tau^b \sim 40 \text{ MPa}$

stress doing work on near-fault region $\sim \tau^b \sim 40$ MPa
(quantifies flux of strain + kinetic energy into region)

Where does this energy go?



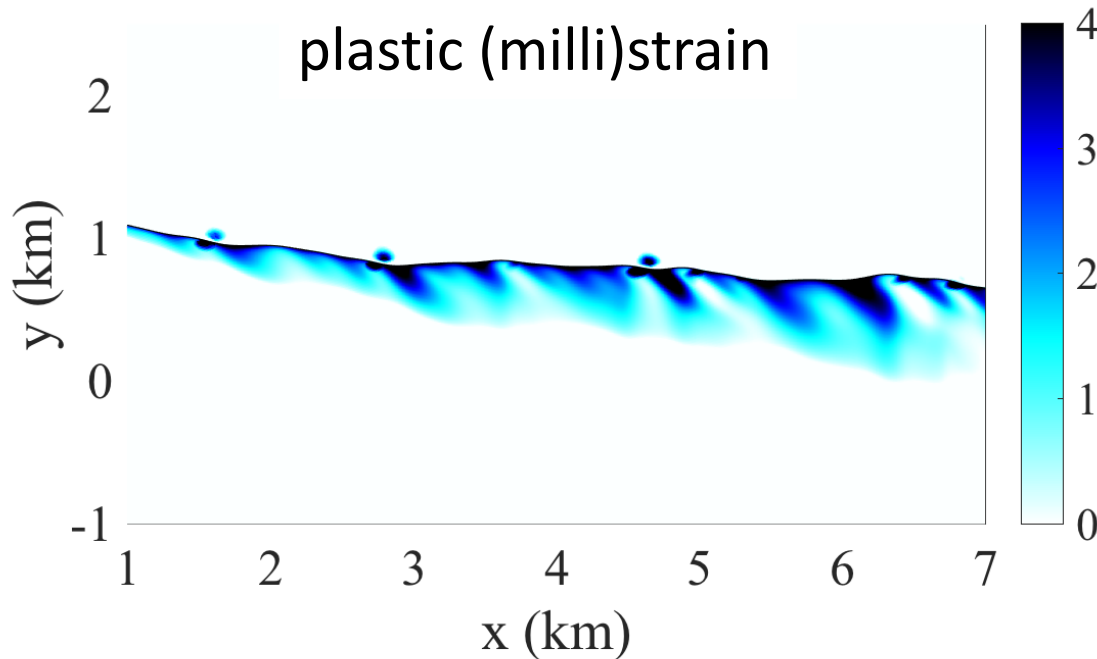
frictional heat on fault:

$\tau_{\text{heat}} \sim 20$ MPa in this example
(but can be made *arbitrarily small* by appealing to more extreme dynamic weakening)

$$\tau_{\text{heat}} = \frac{\int \tau V dt}{\int V dt}$$

stress doing work on near-fault region $\sim \tau^b \sim 40$ MPa
(quantifies flux of strain + kinetic energy into region)

Where does this energy go?



frictional heat on fault:

$\tau_{\text{heat}} \sim 20$ MPa in this example
(but can be made *arbitrarily small* by appealing to more extreme dynamic weakening)

heat from plastic straining:

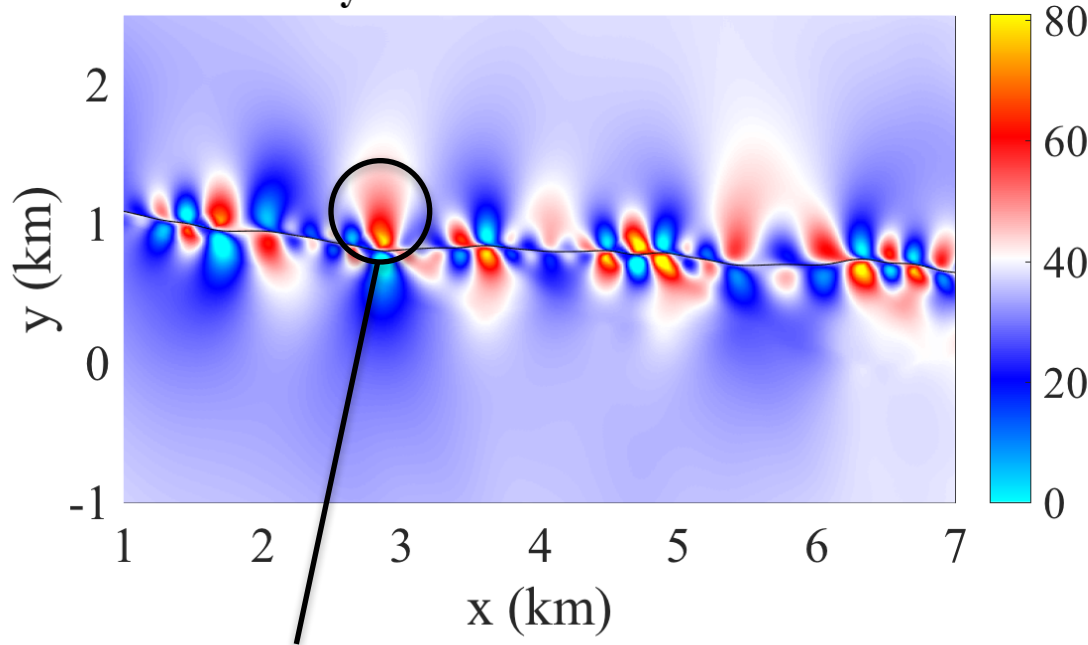
stress-equivalent dissipation*
 ~ 10 MPa in this example
(relatively insensitive to dynamic weakening)

*stress equivalent dissipation =
dissipated energy/volume,
integrated over off-fault distance,
divided by slip

stress doing work on near-fault region $\sim \tau^b \sim 40$ MPa
(quantifies flux of strain + kinetic energy into region)

Where does this energy go?

σ_{xy} (MPa) at $t = 3.43$ s



...but these stresses trigger earthquakes (aftershocks and background seismicity) on secondary faults, which are themselves fractal surfaces, repeating this process at ever smaller scales – with some additional energy loss via radiation

frictional heat on fault:

$\tau_{\text{heat}} \sim 20$ MPa in this example
(but can be made *arbitrarily small* by appealing to more extreme dynamic weakening)

heat from plastic straining:

stress-equivalent dissipation*
 ~ 10 MPa in this example
(relatively insensitive to dynamic weakening)

strain energy in near-fault stress concentrations:

~ 10 MPa in this example
(relatively insensitive to dynamic weakening)

Conclusions

Faults can host earthquakes at “high” background stresses $\tau_b \approx 0.6(\sigma - p)$ with negligible heat production if

- dynamic weakening reduces frictional resistance τ to nearly zero (eliminating on-fault heat production)
- structural complexity introduces additional resistance, elevating threshold background stress for rupture to $\tau_b \approx 0.6(\sigma - p)$, a value set by strength of off-fault material (i.e., frictional strength of secondary faults and microcracks at low slip/shear rates)
- off-fault heat production during off-fault plastic strain also within bound placed by lack of heat flow anomaly

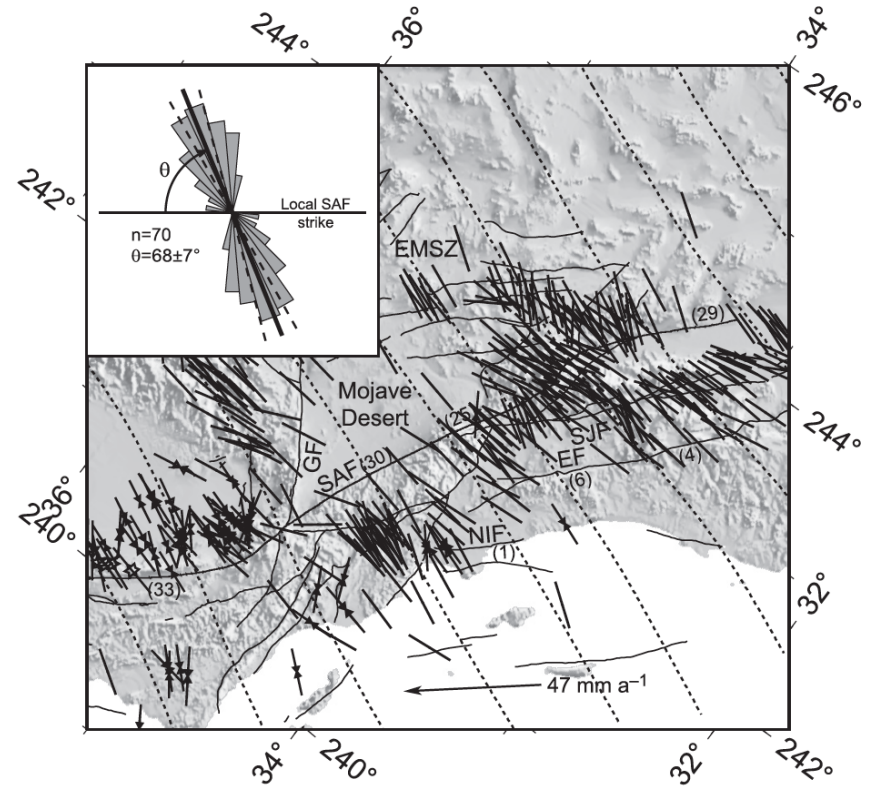
Alternative explanation, distributed shear without dynamic weakening, predicts higher levels of heat production (not observed in drilling measurements from Chi-Chi, Wenchuan, Tohoku, etc.)

Extra Slides

And that's how the San Andreas (and other mature faults) appear to operate – “stress / heat flow paradox”

maximum compressive stress
at high angle to San Andreas,
requiring $\tau_b/(\sigma-p) < 0.3$

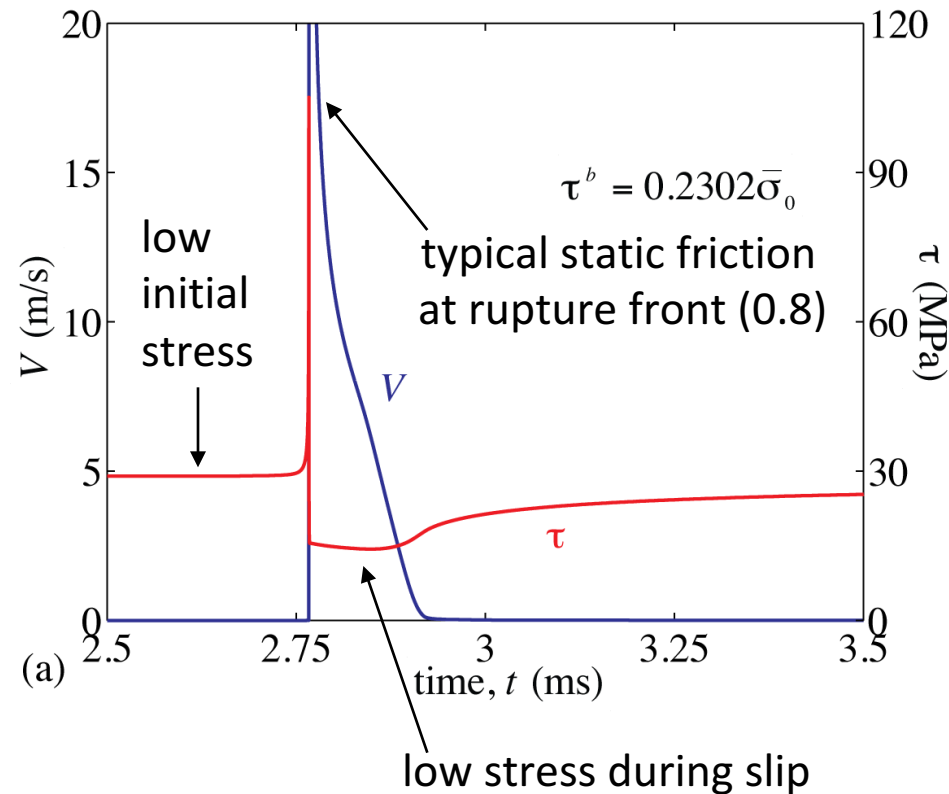
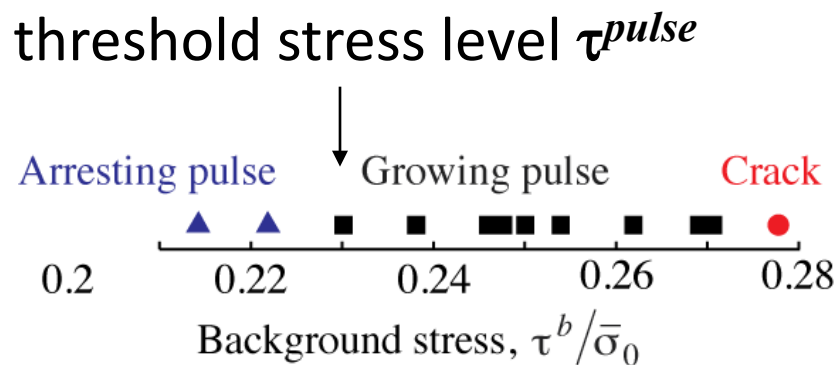
absence of heat flow anomaly
requires low dynamic friction



[Townend, 2006; see also ongoing work
in Community Stress Model project]

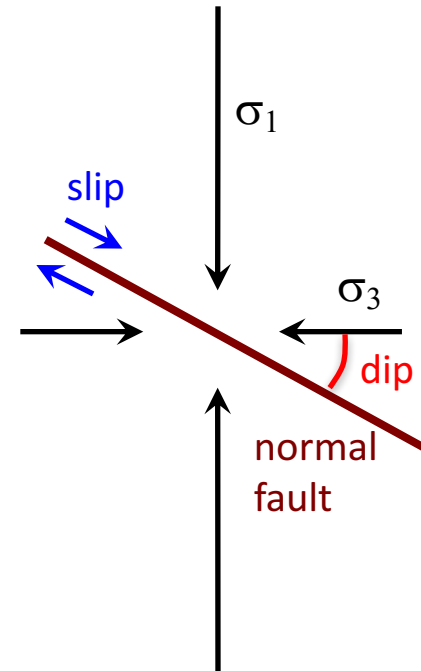
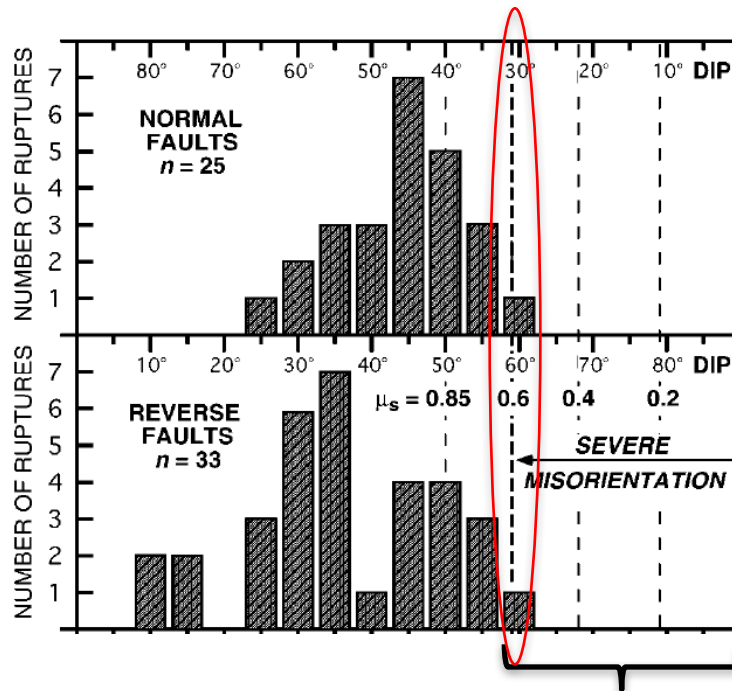
And that's how the San Andreas (and other mature faults) appear to operate – “stress / heat flow paradox”

dynamic rupture simulations on planar faults with thermal pressurization and flash heating [Noda, Dunham, Rice, 2009] show self-healing slip pulses at low τ_b



...but almost all other faults operate at higher stress

Collettini and Sibson [2001] compilation of active (M_w 5.5-6) dipping faults, **showing fault operation at $\tau_b/(\sigma-p) \approx 0.6$** , based on Sibson [1985] lock-up angle concept

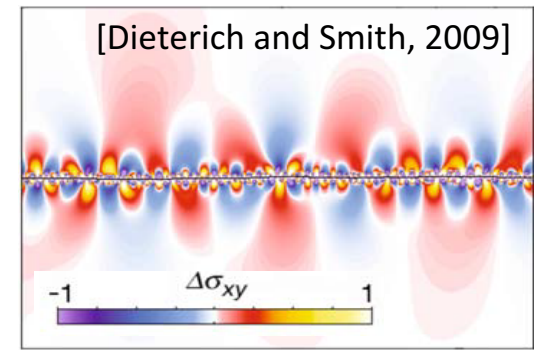


at these dip angles, resolved $\tau_b/(\sigma-p)$ is insufficient for self-sustaining rupture, even for arbitrarily large

+ many other lines of evidence, σ_1/σ_3 including stress measurements in deep boreholes [Townend and Zoback, 2001]

Possible Discriminants

geometric resistance model predicts:

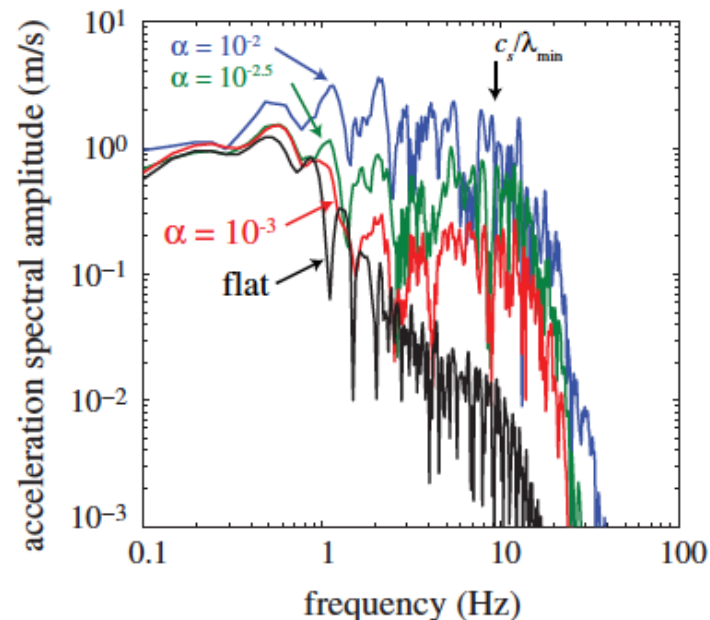


local near-fault stress changes \sim absolute stress (~ 100 MPa)

→ *diversity of aftershock focal mechanisms* [Smith and Dieterich, 2010]
as observed in Loma Prieta, Landers, and other events

(but seismically inferred stress drop, linking moment and fault dimension and controlling ground motion amplitude, is only ~ 3 MPa \ll absolute stress)

rough faults produce realistically flat acceleration spectra at high frequencies [Dunham et al., 2011];
see also comparison to GMPEs from 3D simulations [Shi and Day, 2013]



Earthquake Energy Balance

local energy balance for elastic-plastic material:

$$\frac{\partial}{\partial t} \left(\frac{1}{2} \rho \mathbf{v}^2 + U \right) + \nabla \cdot (\boldsymbol{\sigma} \cdot \mathbf{v}) = -\dot{W}^p$$

$$U = \frac{1}{2} (\sigma_{ij}^0 + \sigma_{ij}) \varepsilon_{ij} \text{ (elastic strain energy density)}$$

$$\dot{W}^p = \sigma_{ij} \dot{\varepsilon}_{ij}^p \geq 0 \text{ (plastic work rate per unit volume)}$$

Vary roughness, measure threshold stress for self-sustaining rupture

...but no unique threshold stress for rupture on rough faults

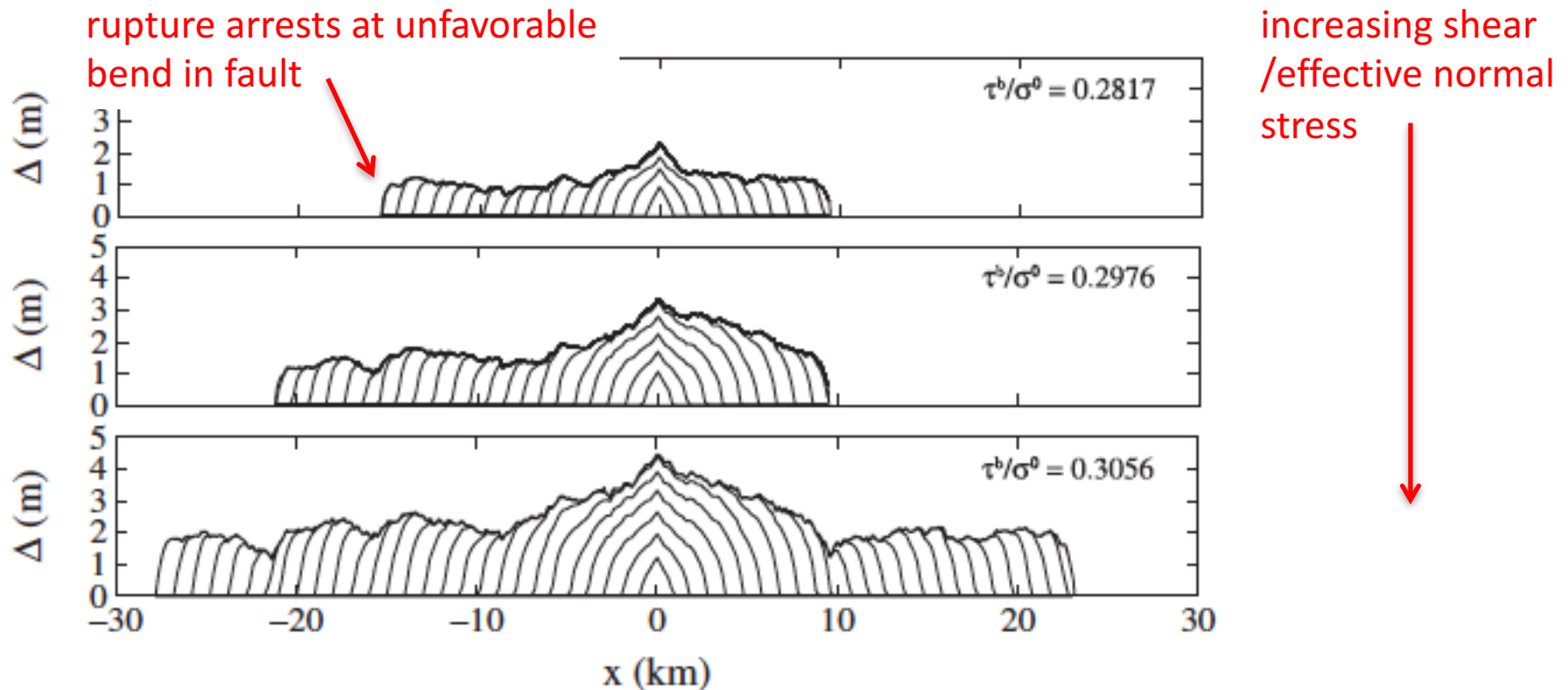


Figure 4. Sequences of cumulative slip Δ every 0.28 s for ruptures occurring on the same fault but at three different τ^b levels. The extent of rupture and the amount of fault slip increase with background stress.

Remarkable variability, despite statistically identical fault surfaces (same roughness α) and same background stress τ_b

red=fault profile, blue=slip snapshots

$\alpha = 0.006$, $\tau^{\text{pulse}}/\sigma^0 = 0.2817$, $\tau^b/\sigma^0 = 0.2976$

