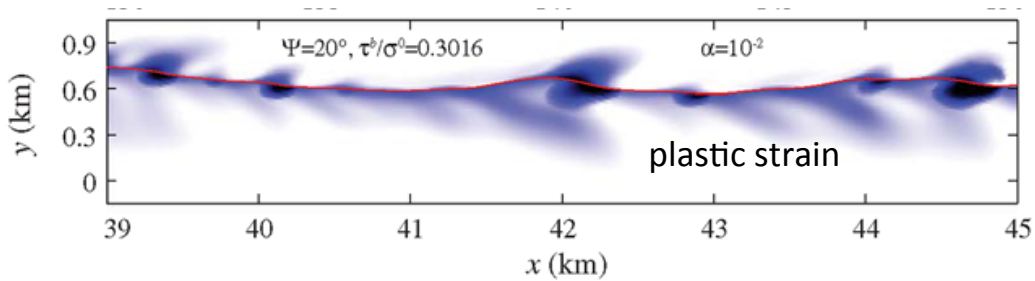
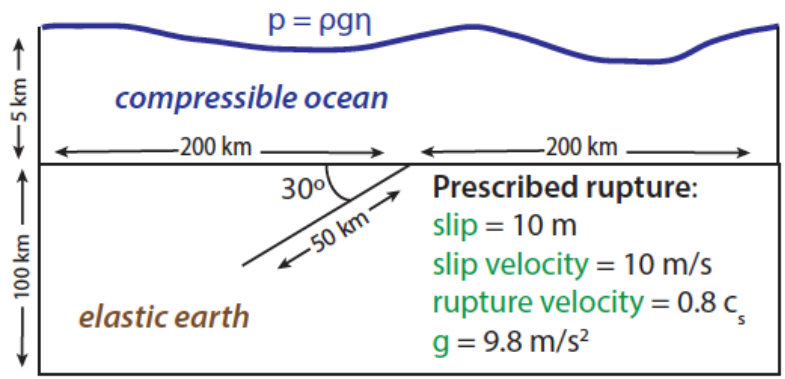
Beyond Elasticity: New Directions in Earthquake Modeling

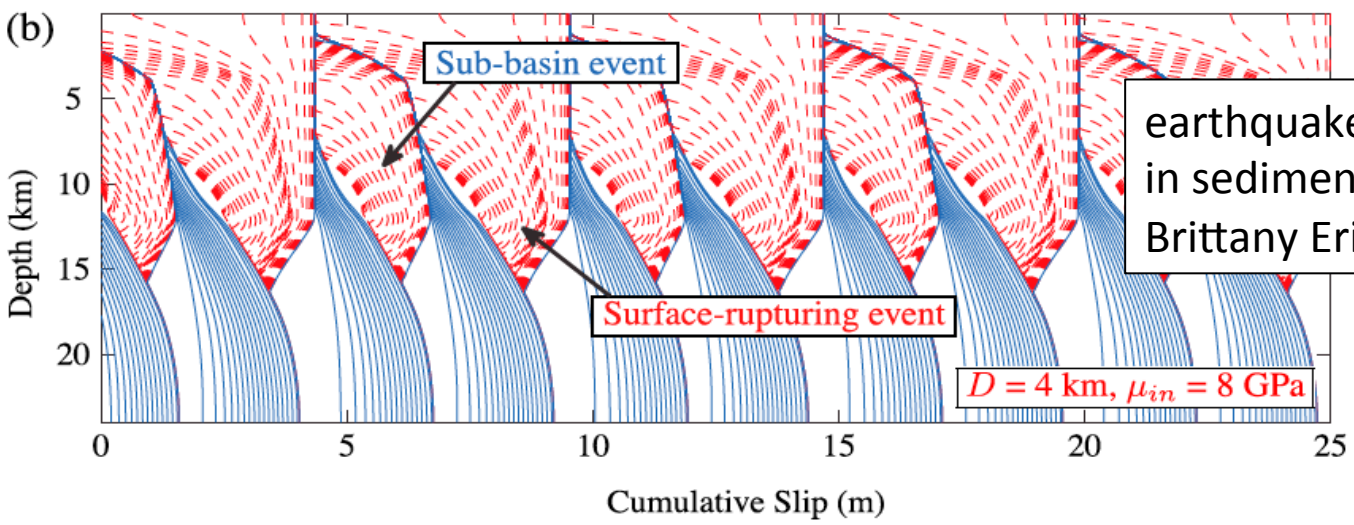
Eric M. Dunham, Stanford



ruptures on geometrically complex faults:
Zijun Fang and Lucile Bruhat



earthquake+tsunami simulations: Gabe Lotto

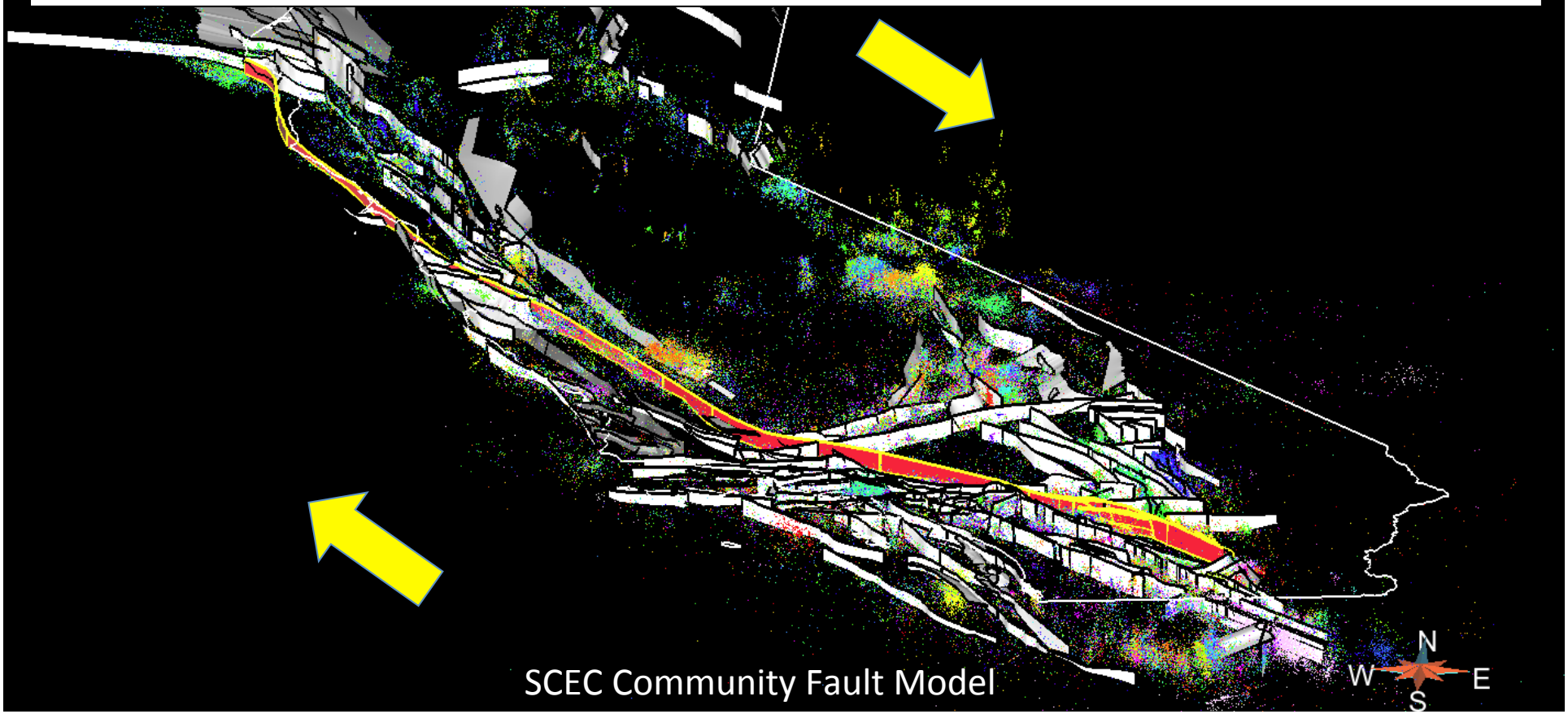


earthquake sequence simulations in sedimentary basins:
Brittany Erickson, Kali Allison

State of Stress in Earth's Crust

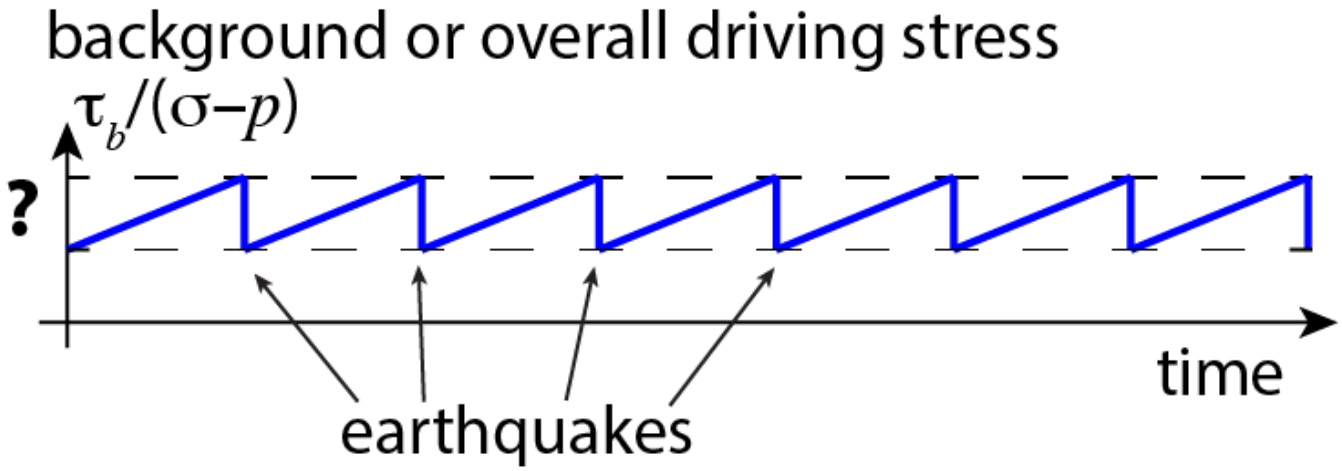
Motivating questions:

- At what stress levels do faults become capable of hosting earthquakes?
- How can we have weak faults (like San Andreas) in a strong crust, if that crust is also riddled with faults, and dynamic weakening acts on all faults?
- What is the origin of complexity in faulting process (variability in rupture size, branching, jumping, rupture velocity)?
- Can we quantify the likelihood of different earthquakes?



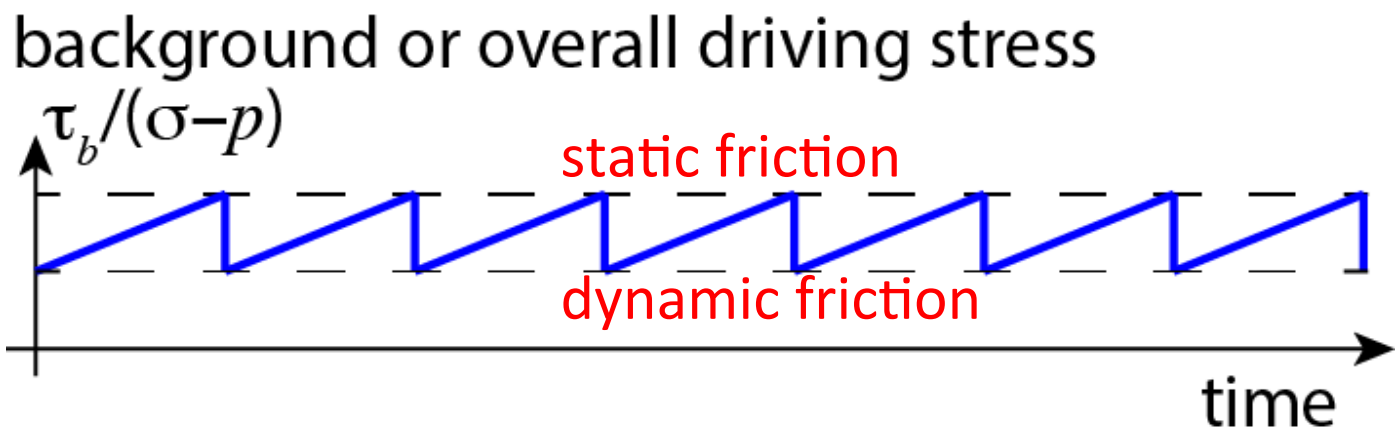
SCEC Community Fault Model

Stress in the Earthquake Cycle



- what sets upper and lower limits on stress?
- what is absolute stress?

Simplest View



Could this work?

Effective stress $(\sigma-p) \sim 100$ MPa (lithostatic−hydrostatic at seismogenic depth)

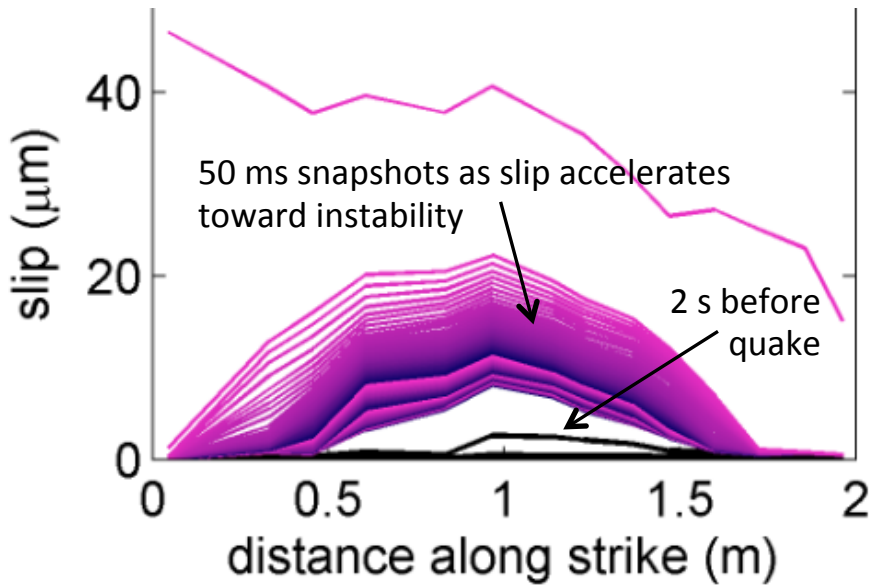
From experiments, static friction ≈ 0.8*

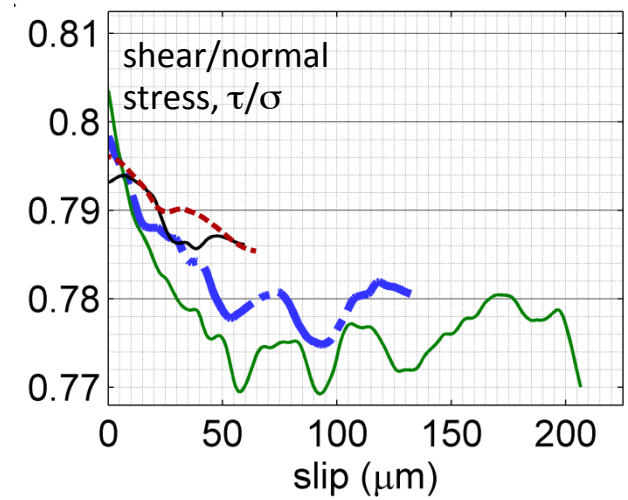
…but dynamic friction more complicated

*with a few exceptions like clayey gouge in SAFOD and JFAST drilling of Japan Trench

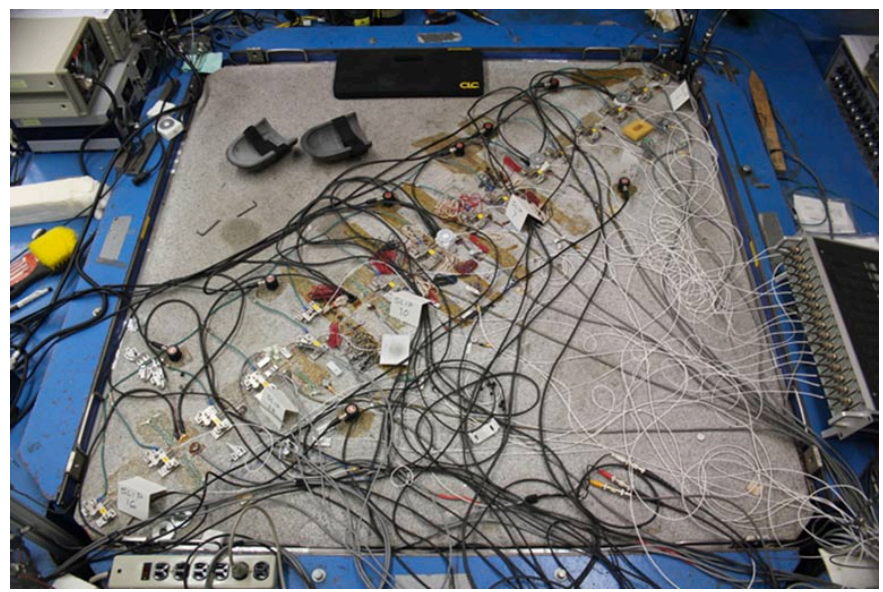
Constraints from Lab Experiments

experiments by Greg McLaskey with 2 m granite block biaxial apparatus at USGS



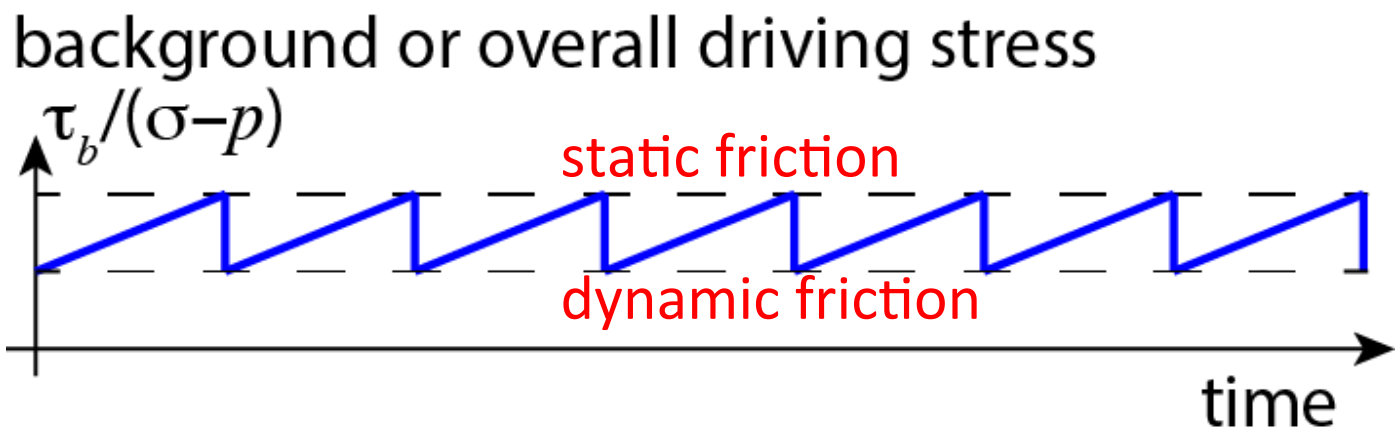


static friction ≈ 0.8
dynamic friction ≈ 0.77



experiments at σ≈6 MPa

Simple View



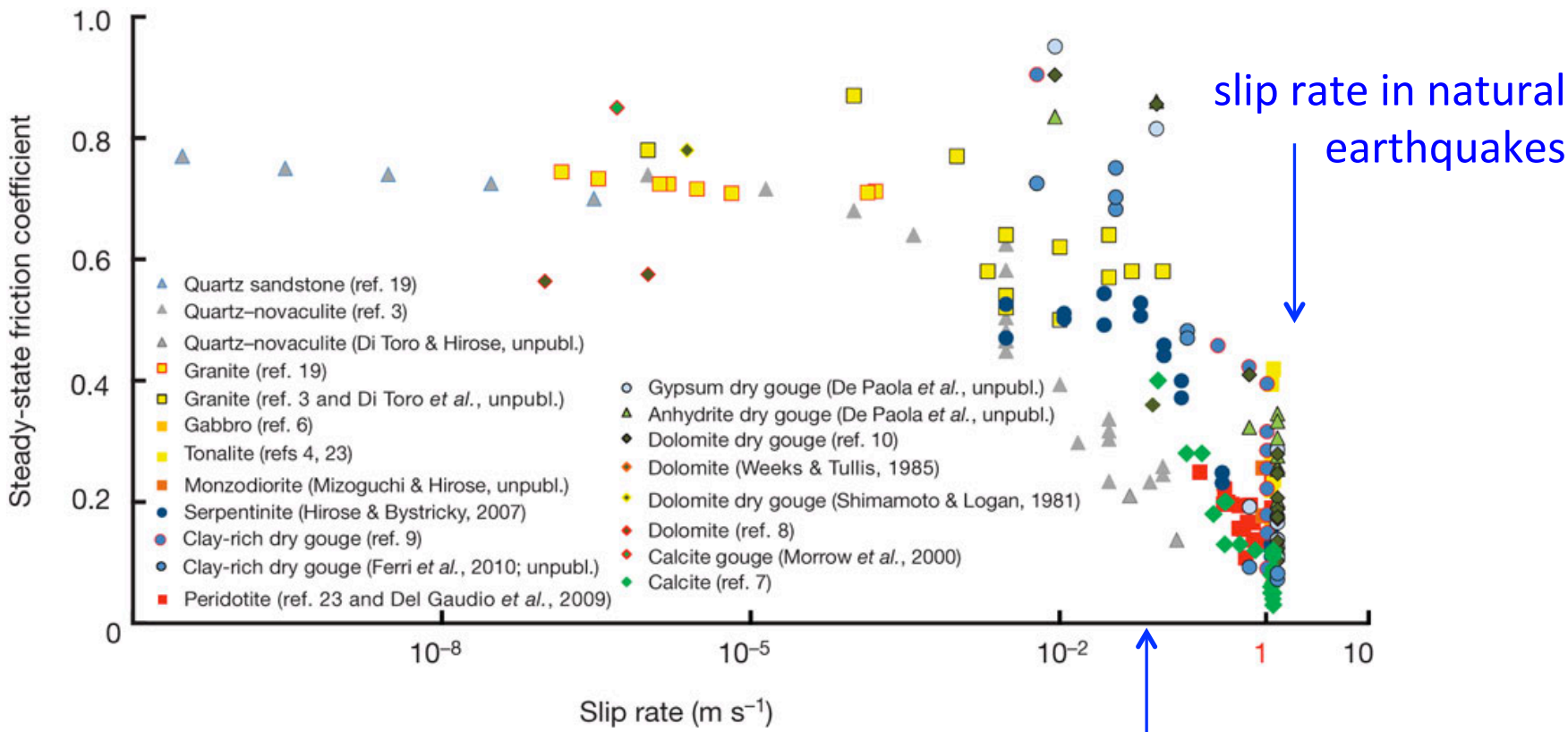
Could this work?
Effective stress $(\sigma-p)$ ~ 100 MPa (lithostatic−hydrostatic at seismogenic depth)
From experiments, static friction ≈ 0.8, dynamic friction ≈ 0.77

→ stress drops ~ (0.8−0.77)×100 MPa ~ 3 MPa, exactly as observed, and slip velocities ~ 1 m/s (producing realistic ground motion)

The Catch: Dynamic Weakening

dramatic reduction of frictional resistance at coseismic slip rates

from thermal pressurization, flash heating, thermal decomposition, and many other processes

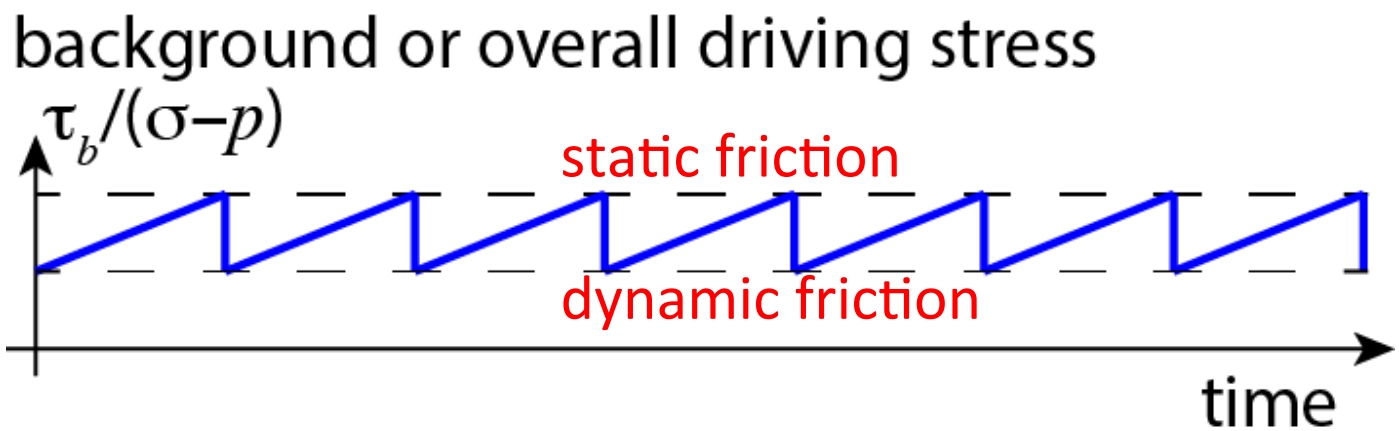


slip rate in natural earthquakes

slip rate reached in experiments shown in previous slide (due to low σ)

[Di Toro et al., 2011]

Simple View



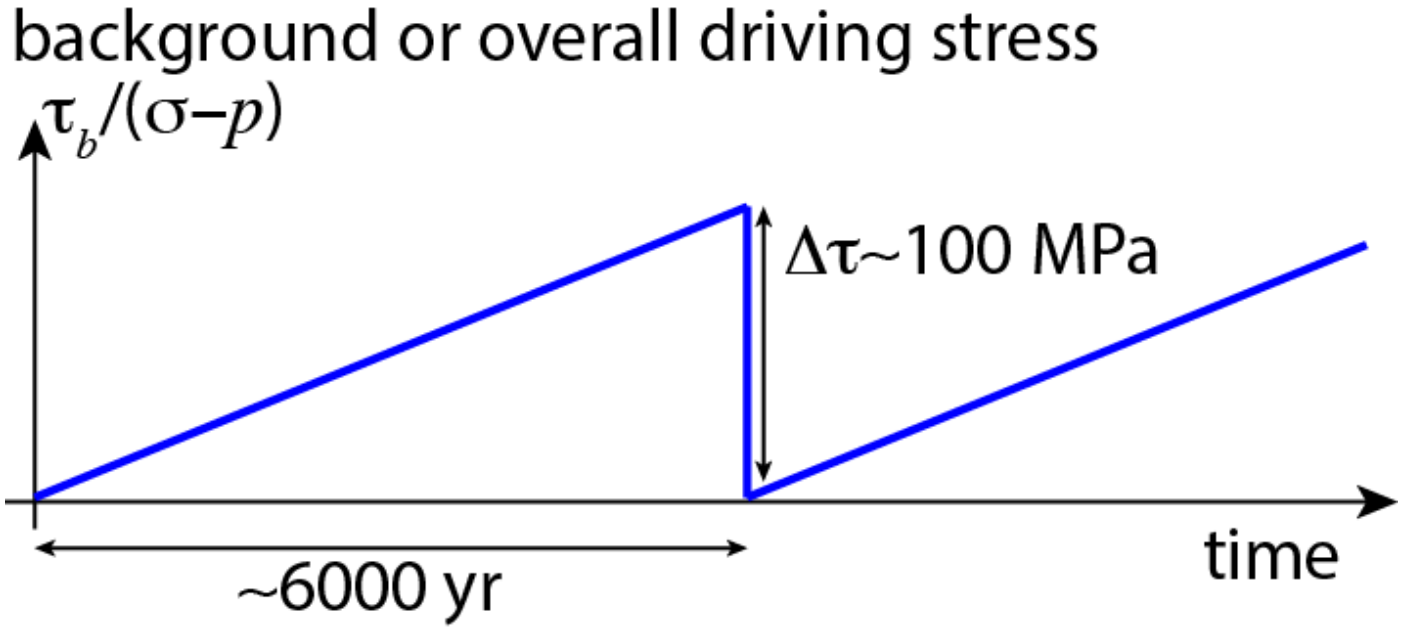
Could this work?

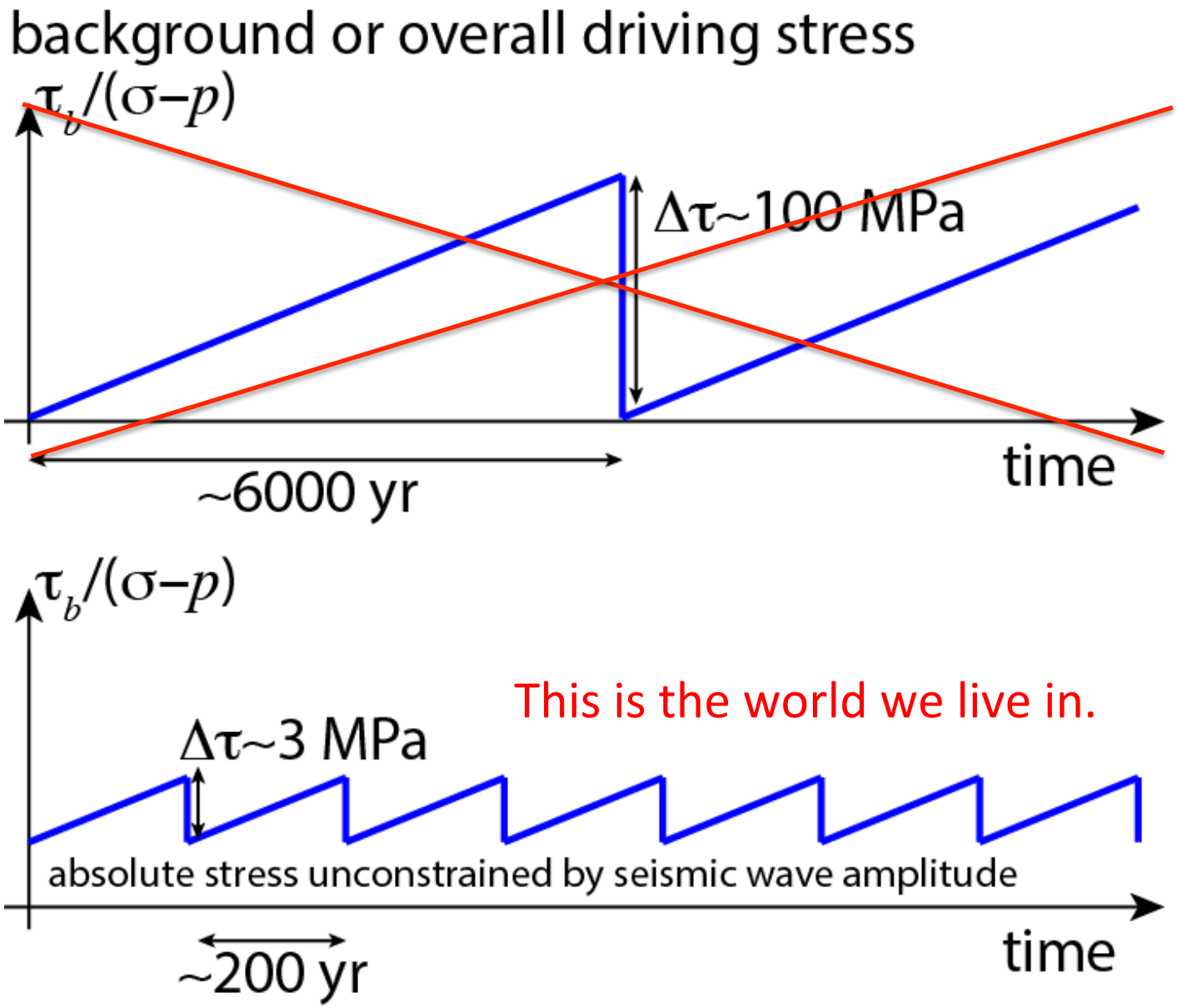
Effective stress $(\sigma-p)$ ~ 100 MPa (lithostatic−hydrostatic at seismogenic depth)

From experiments, static friction ≈ 0.8, dynamic friction ≈ 0

→ stress drops ~ 80 MPa, not observed in large earthquakes,

and slip velocities ~ 30 m/s (ground motion we don't want to imagine)


background or overall driving stress
$\tau_b/(\sigma-p)$
$\Delta\tau$~100 MPa
~6000 yr
time

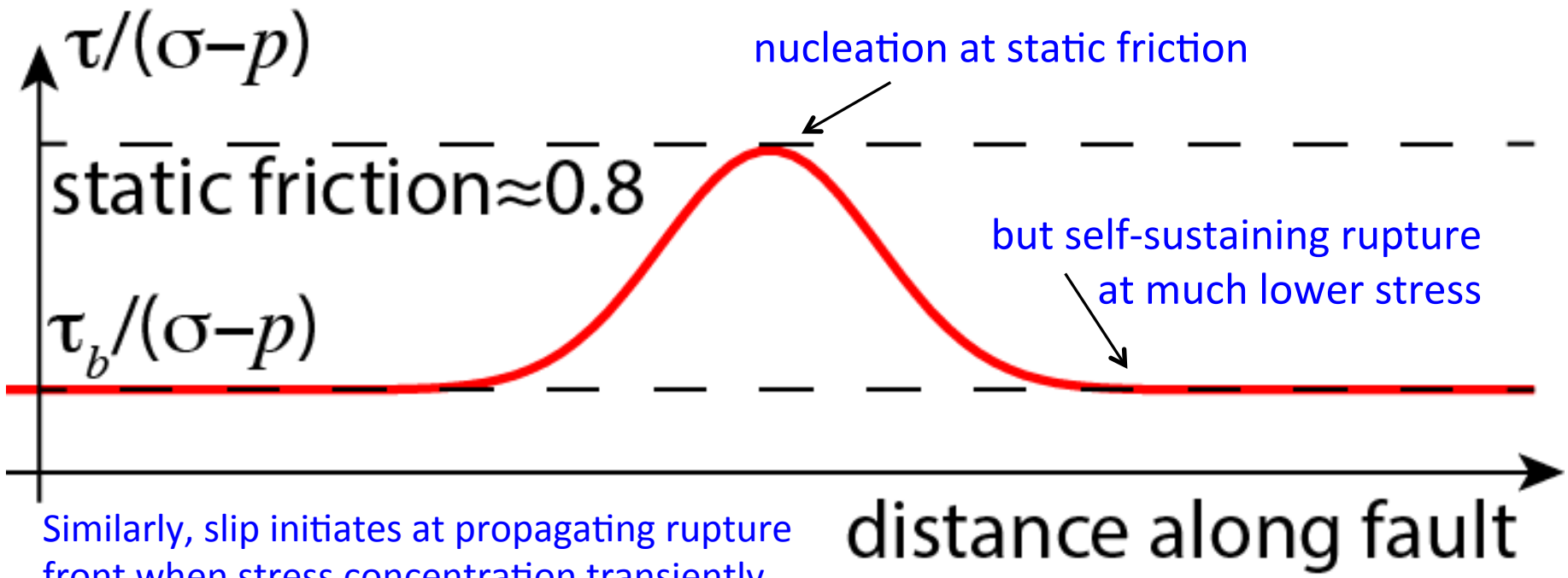

background or overall driving stress
$\tau_b/(\sigma-p)$
$\Delta\tau$~100 MPa
~6000 yr
time
$\tau_b/(\sigma-p)$
This is the world we live in.
$\Delta\tau$~3 MPa
absolute stress unconstrained by seismic wave amplitude
~200 yr
time

How Can We Resolve This?

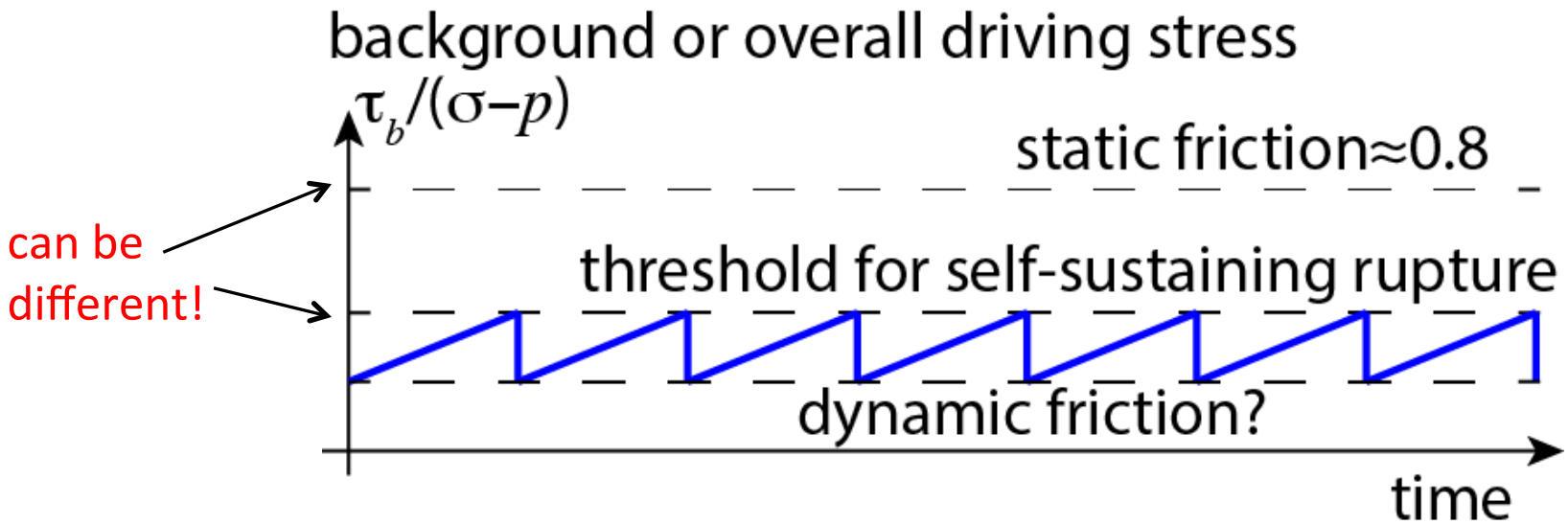
We first have to recognize that we are discussing two related, but subtly different stresses:

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

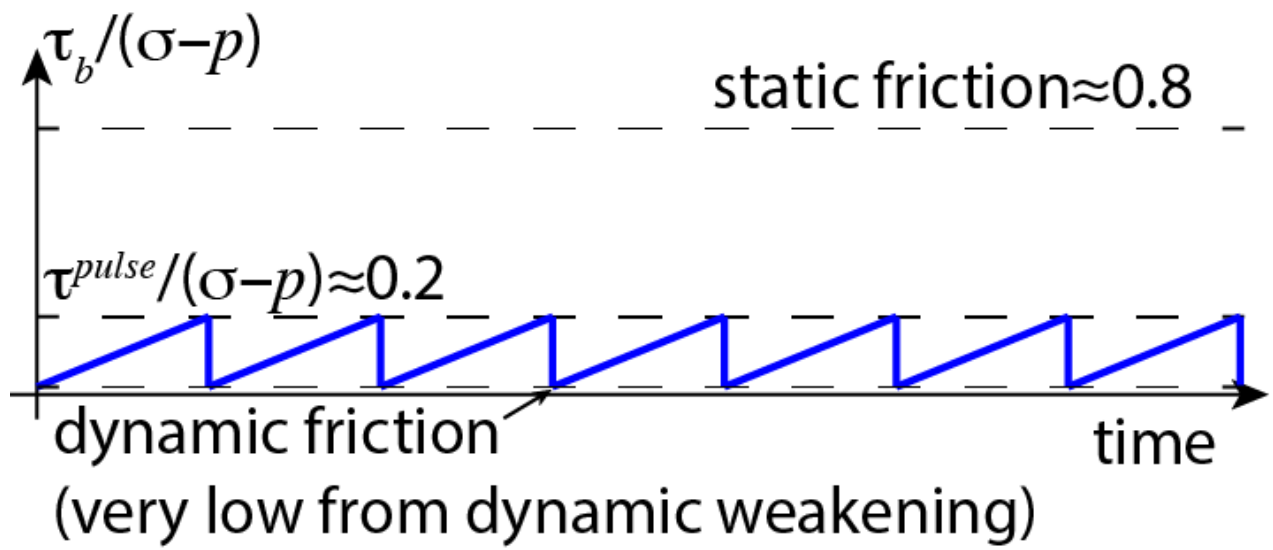
These coincide only for planar faults with spatially uniform loading and slip.



Similarly, slip initiates at propagating rupture front when stress concentration transiently raises fault to static friction.



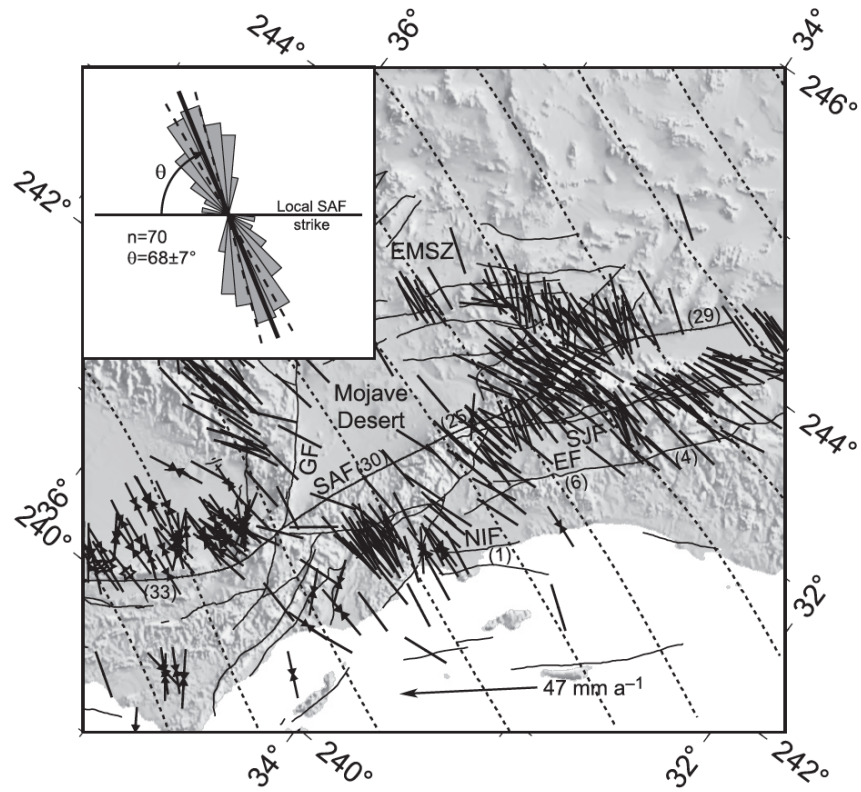
Next, suppose lower limit is dynamic friction (≈ 0 from dynamic weakening).
To obtain reasonable stress drops, *faults must operate at very low stress levels*.



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

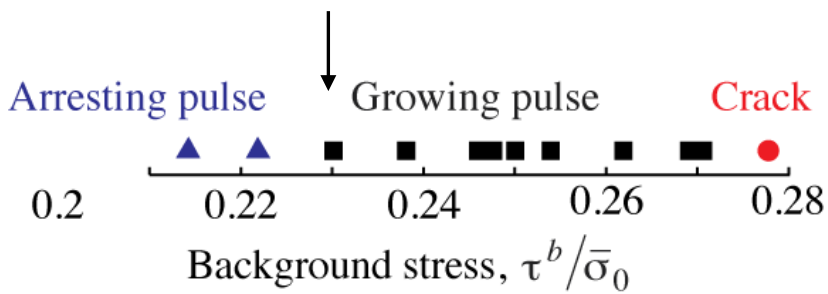


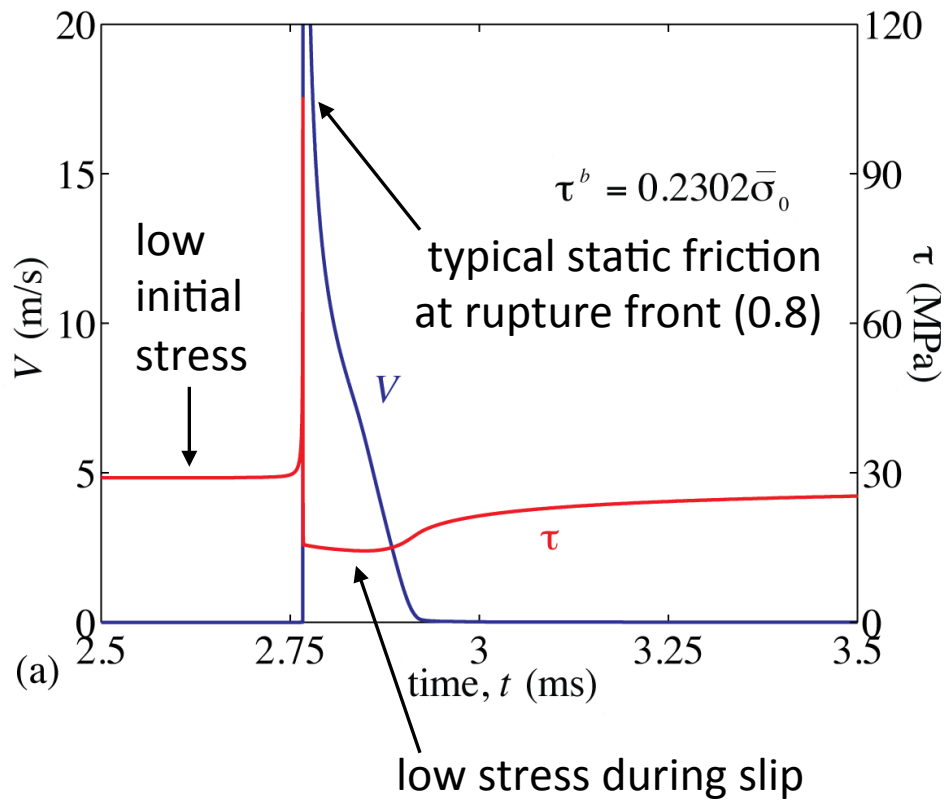
[Townend, 2006; see also ongoing work in Community Stress Model project]

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

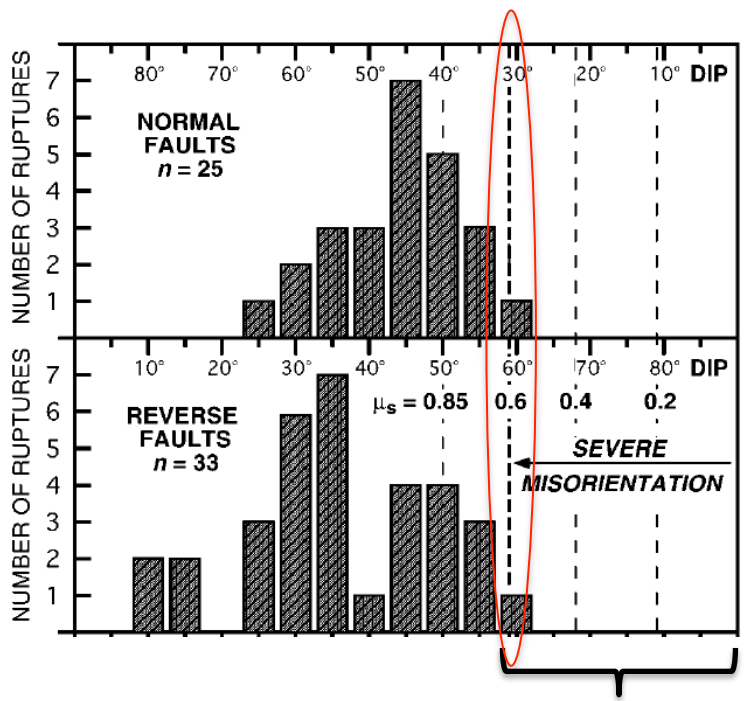
threshold stress level τ^{pulse}

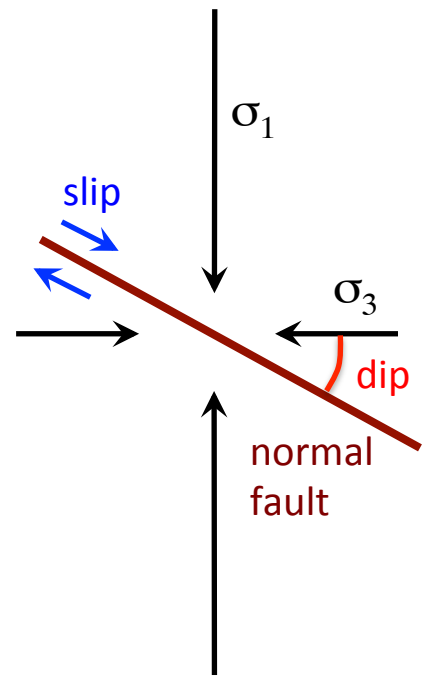




…but almost all other faults operate at higher stress

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



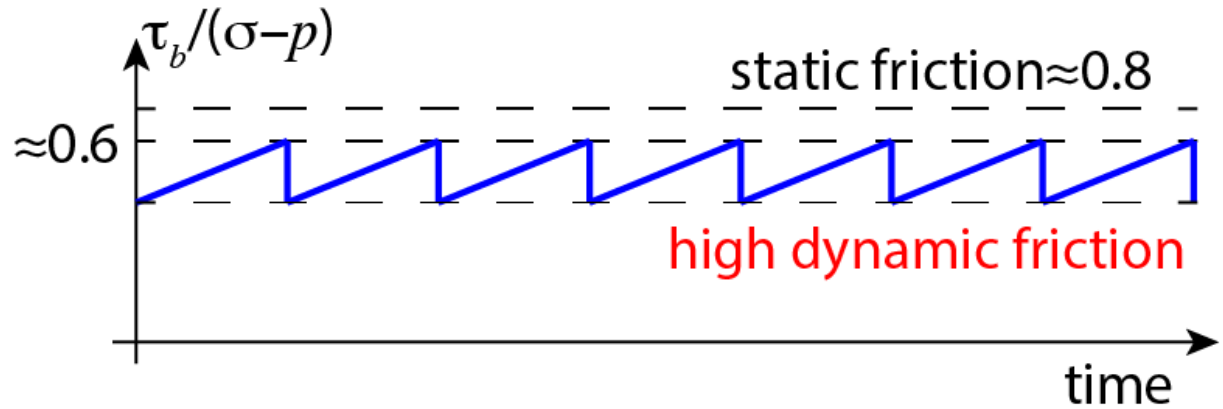


at these dip angles, resolved $\tau_b/(\sigma-p)$ is insufficient for self-sustaining rupture, even for arbitrarily large σ_1/σ_3

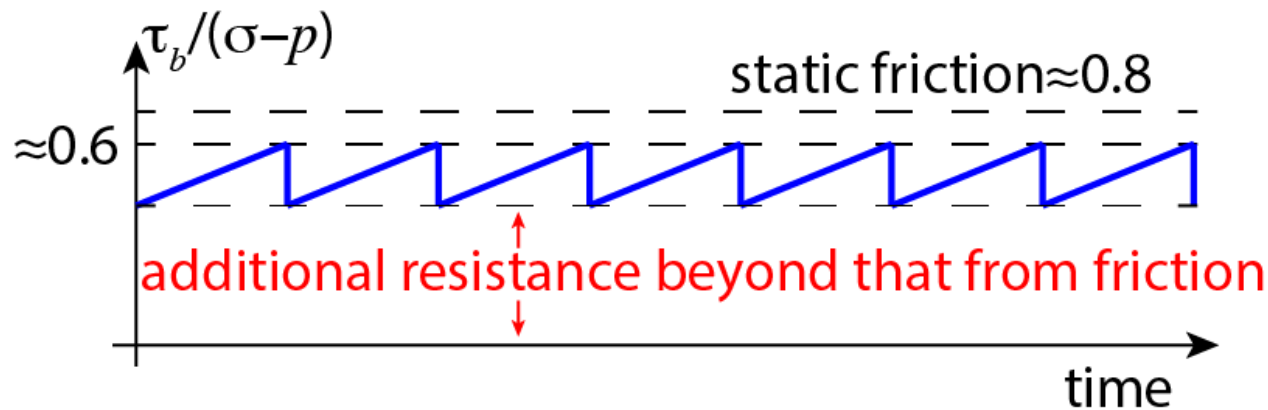
+ many other lines of evidence, including stress measurements in deep boreholes [Townend and Zoback, 2001]

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

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



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



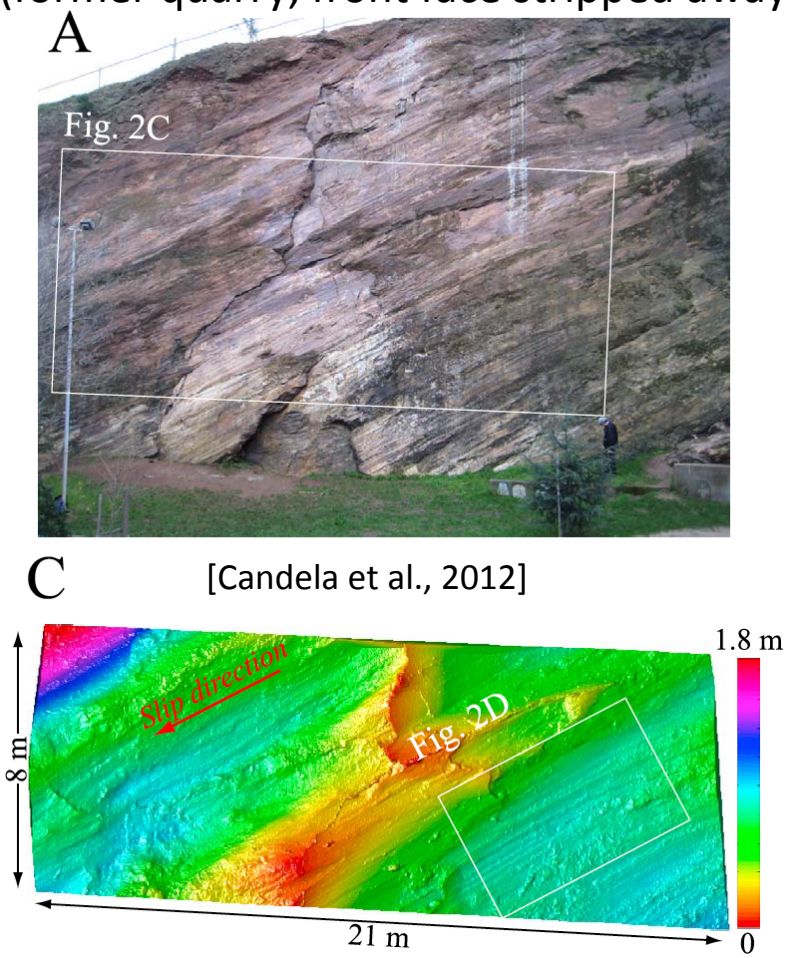
Second explanation appealing because dynamic weakening is ubiquitous in experiments and localization develops rapidly in sheared gouge.

Faults are Geometrically Complex

…in many ways: surface roughness, segmentation, branching, etc.

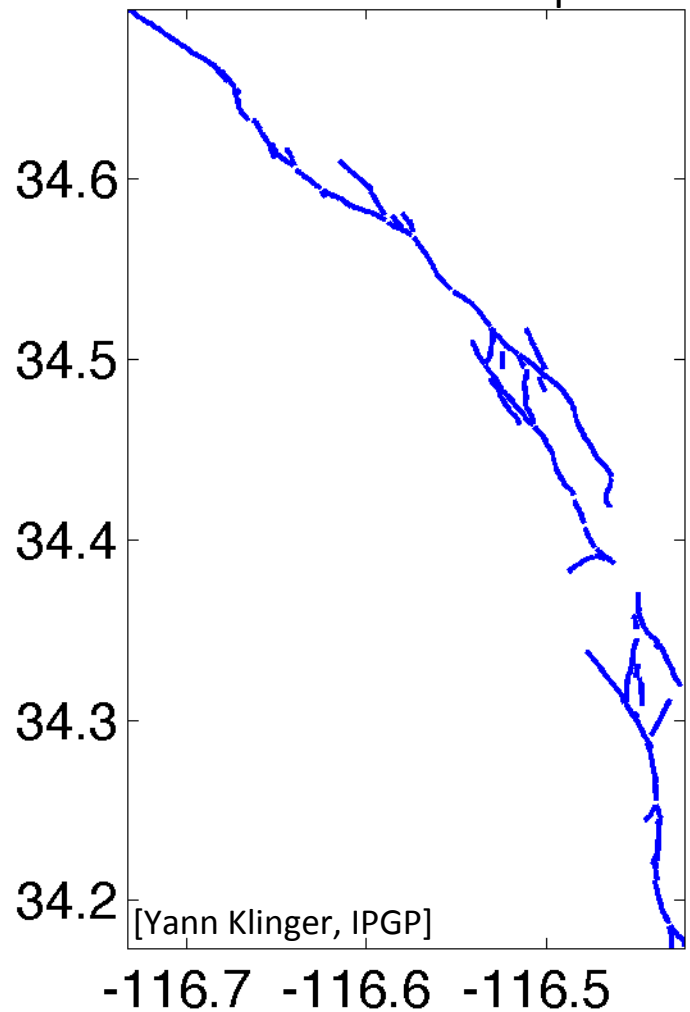
This geometric complexity introduces resistance to slip, even when faults are frictionless.

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



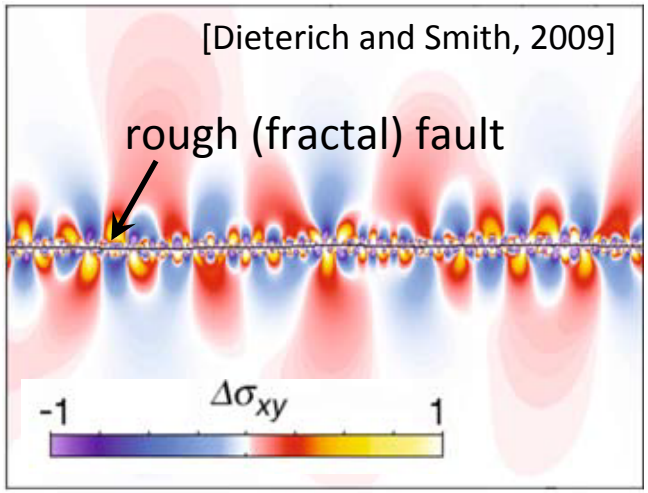
[Candela et al., 2012]

1992 Landers earthquake



[Yann Klinger, IPGP]

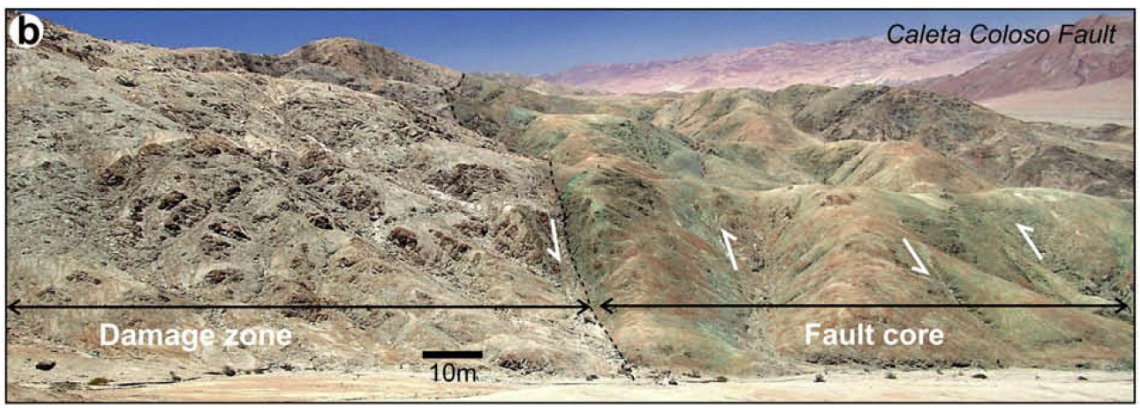
Shear Resistance from Fault Geometric Complexity

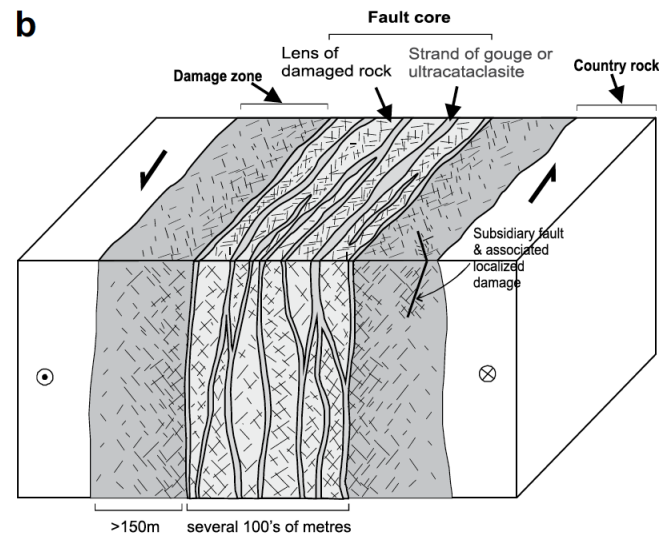


slip on rough fault causes massive near-fault strains, and (elastic) restoring stresses push back on fault in direction opposing average slip

that "backstress" or "roughness drag" τ^{drag} increases with structural complexity, but is ultimately bounded by finite strength of off-fault material

(in damage zones 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*

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

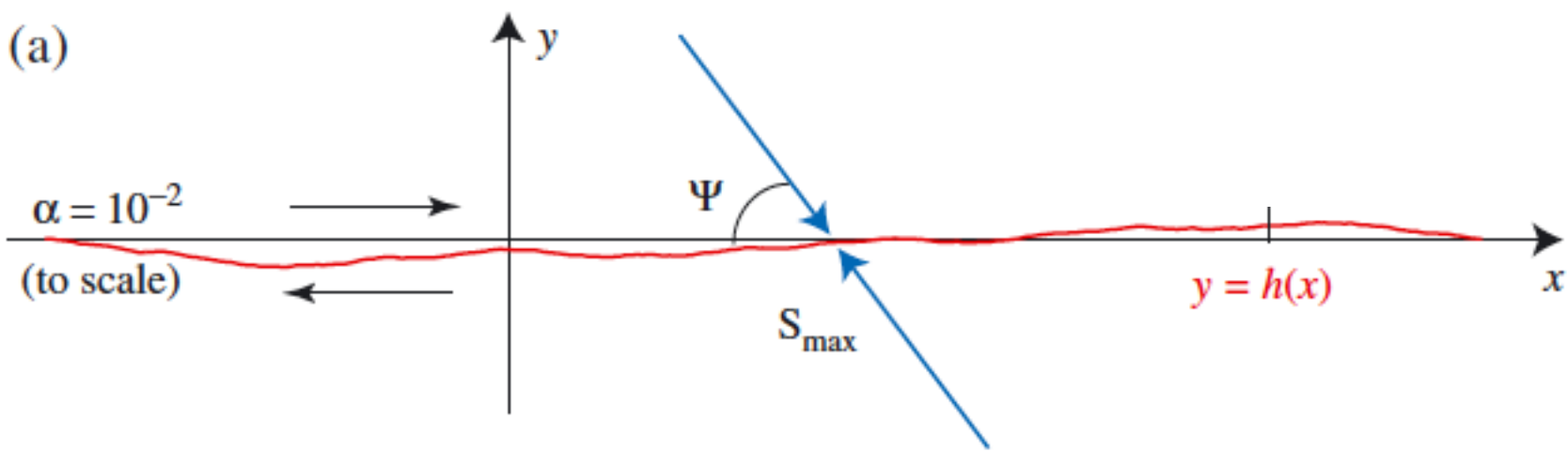
Dynamics Ruptures on Geometrically Complex Faults with Extreme Dynamic Weakening

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

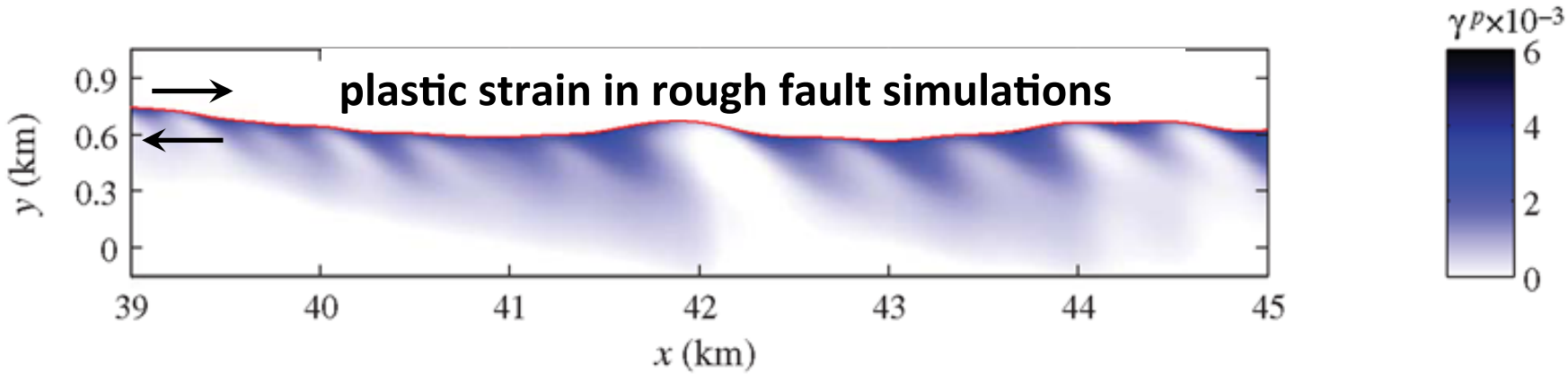
[Power and Tullis, 1991; Brodsky et al., 2011; Candela et al., 2013]

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

[Dunham et al., 2011]

Vary roughness, measure threshold stress for self-sustaining rupture

…but no unique threshold stress for rupture on rough faults

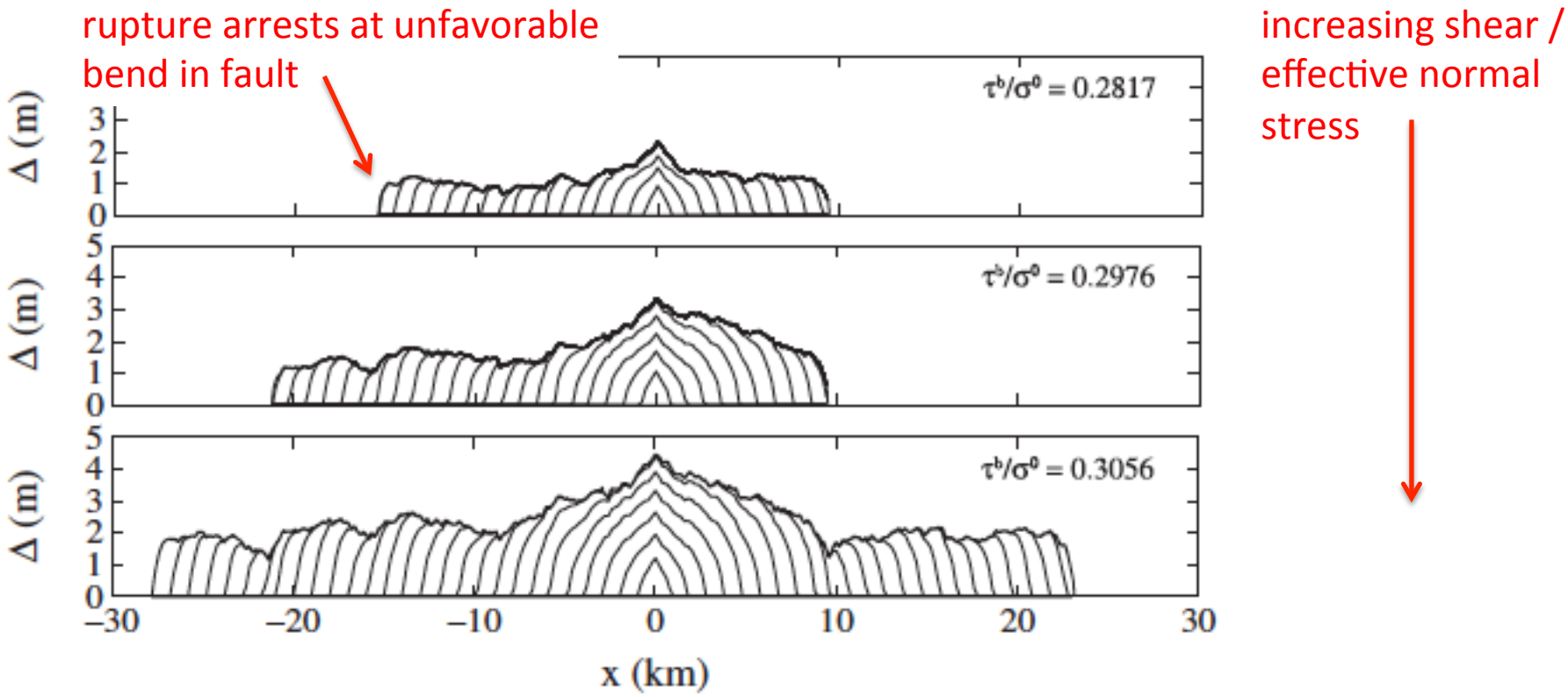
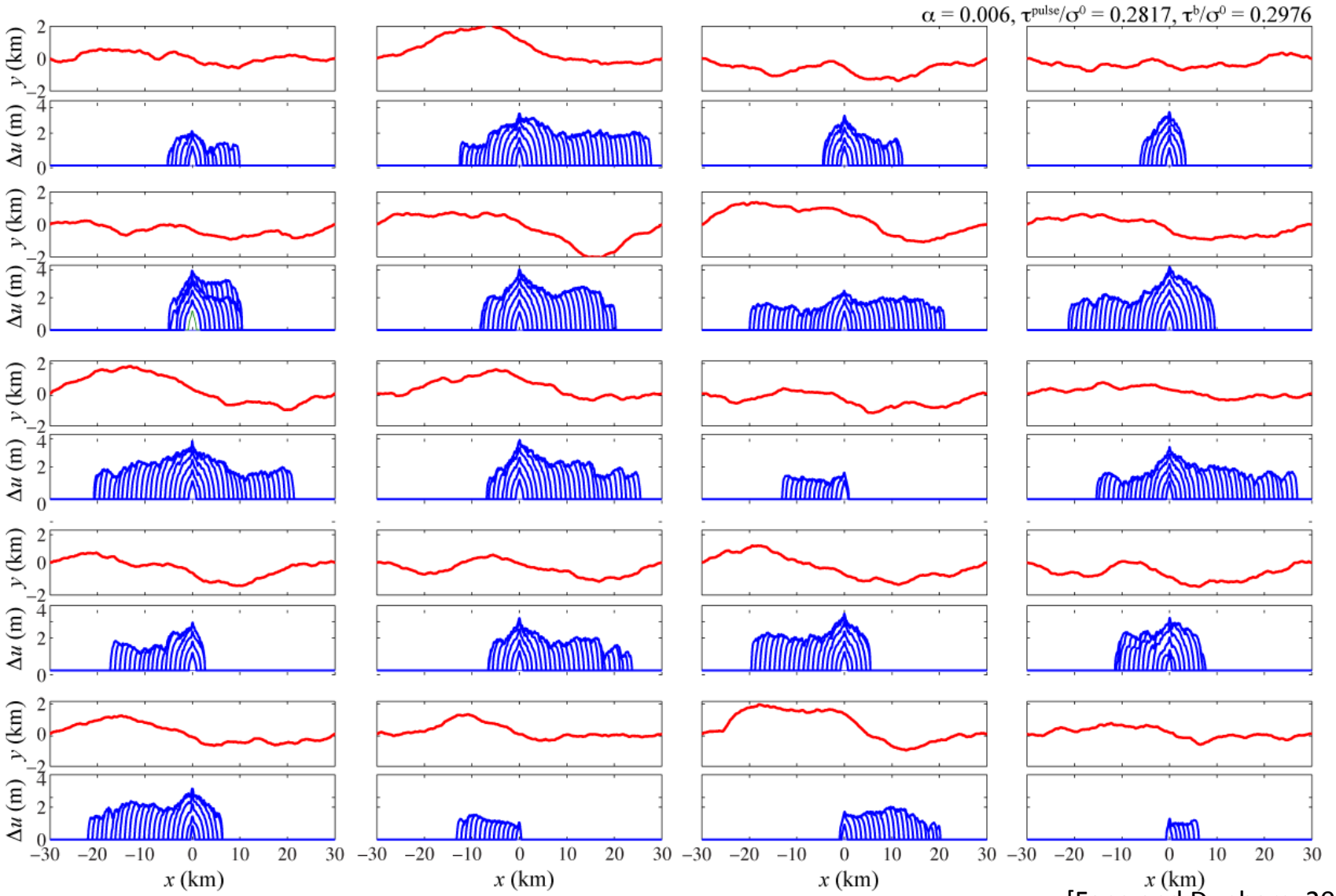


Figure 4. Sequences of cumulative slip Δ every 0.28 s for ruptures occurring on the same fault but at three different τ^b levels. The extent of rupture and the amount of fault slip increase with background stress.

[Fang and Dunham, 2013]

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

red=fault profile, blue=slip snapshots

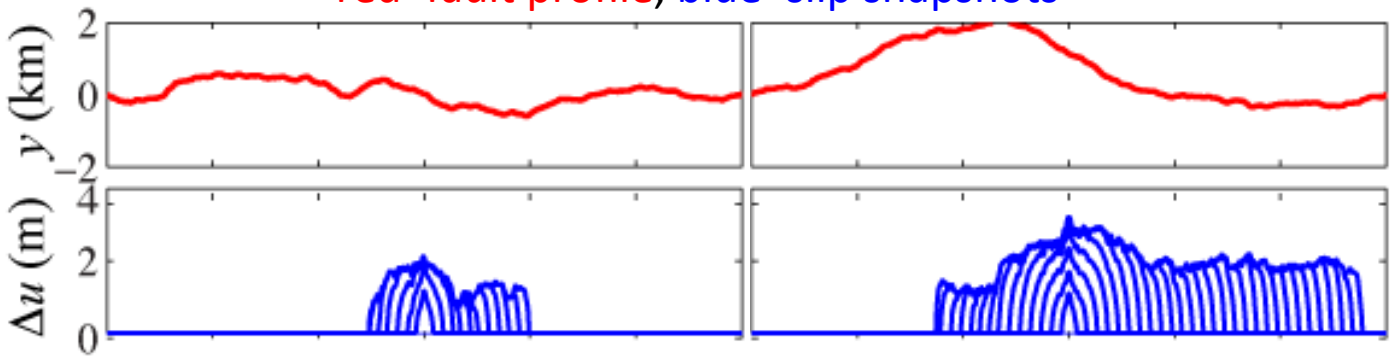


[Fang and Dunham, 2013]

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

one interpretation of these ensemble simulations is ***different hypocenters along single fault***

red=fault profile, blue=slip snapshots



extreme sensitivity to local conditions helps explain why M_w 7.3 foreshock two days prior to M_w 9.0 Tohoku earthquake remained "small" despite its proximity to mainshock hypocenter

(similar behavior observed at Parkfield and elsewhere)

[Fang and Dunham, 2013]

Ensemble Dynamic Rupture Simulations

instead of just running a few simulations on
one realization of a random fractal fault,
we ran ***>1000 simulations***
(100 realizations for each τ_b, α combination)

while limited to 2D, we can begin to ask
(and address) new types of questions

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 $\tau_b/(\sigma-p) \approx 0.6$

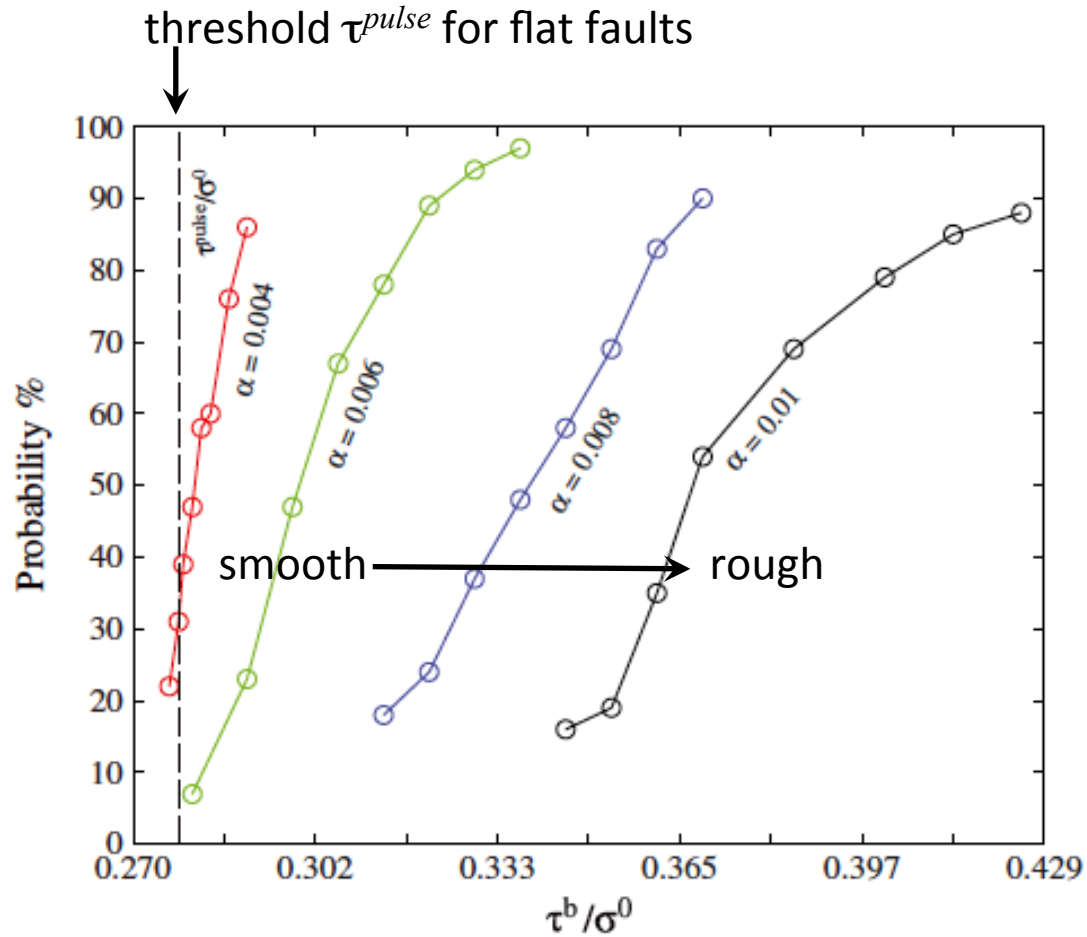


Figure 6. Probabilities of rupture to reach an extent of 20 km (in either direction) from the hypocenter as a function of background stress level τ^b. Rougher faults require larger τ^b to reach the same extent.

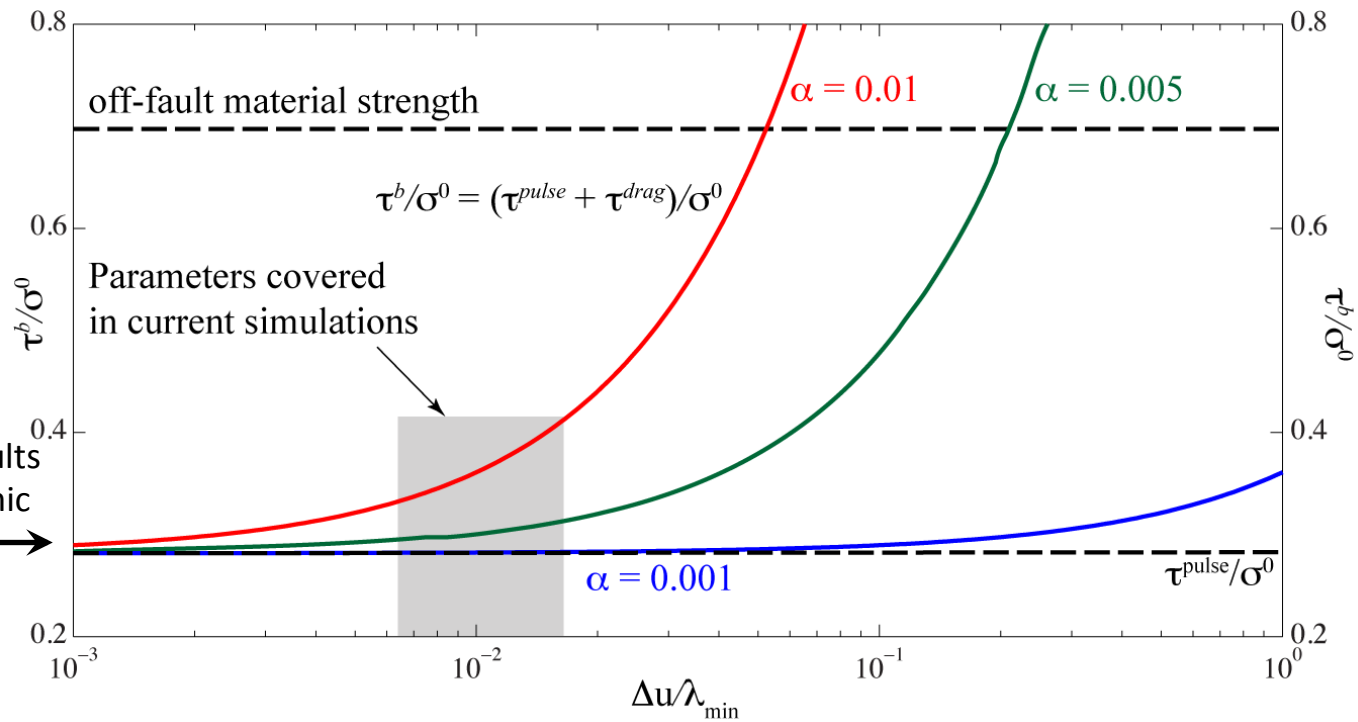
[Fang and Dunham, 2013]

Roughness-induced stress perturbations and geometric resistance largest at short wavelengths, but computational expense limits us to $\lambda > \lambda_{min} \sim 100$ m

Bringing Simulations Closer to Reality
(with additional computational resources)

predicted threshold stresses τ^b based on analytical estimate of τ^{drag} and hypothesis that $\boldsymbol{\tau^b \approx \tau^{pulse} + \tau^{drag}}$

threshold for flat faults with extreme dynamic weakening



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Bringing Simulations Closer to Reality
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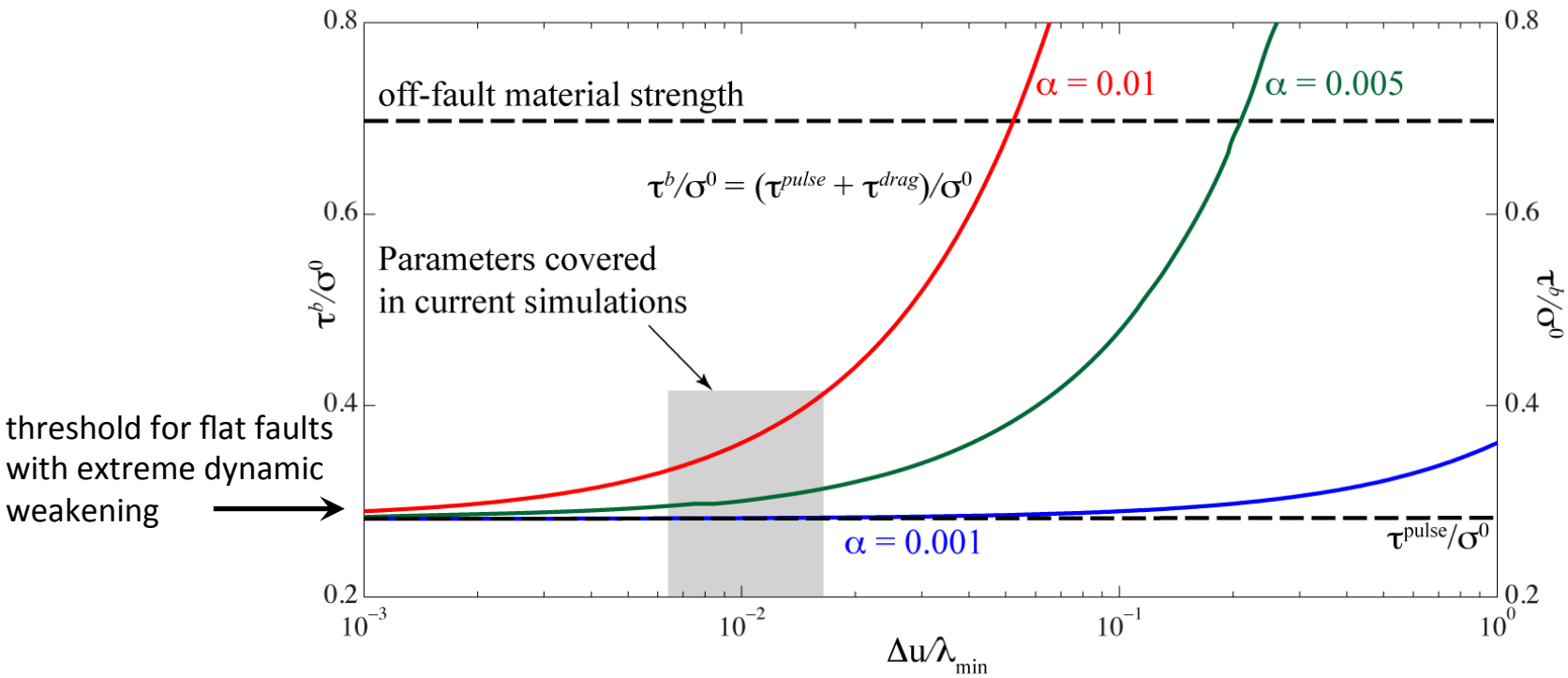


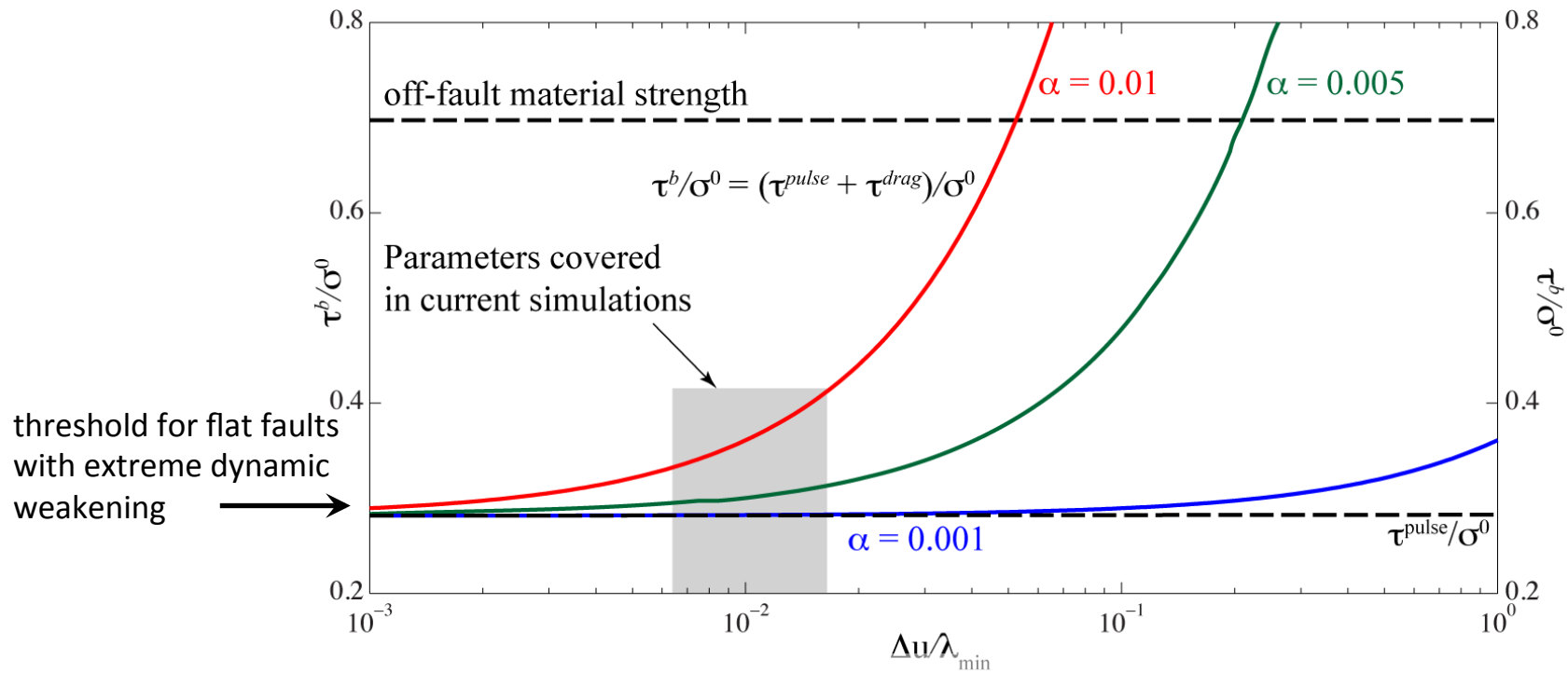
smooth faults: τ^{drag} negligible, so $\tau^b \approx \tau^{pulse} \approx 0.25(\sigma - p)$ (like SAF)

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

[Fang and Dunham, 2013]

Bringing Simulations Closer to Reality
(with additional computational resources)

predicted threshold stresses τ^b based on analytical estimate of τ^{drag} and hypothesis that $\boldsymbol{\tau^b \approx \tau^{pulse} + \tau^{drag}}$

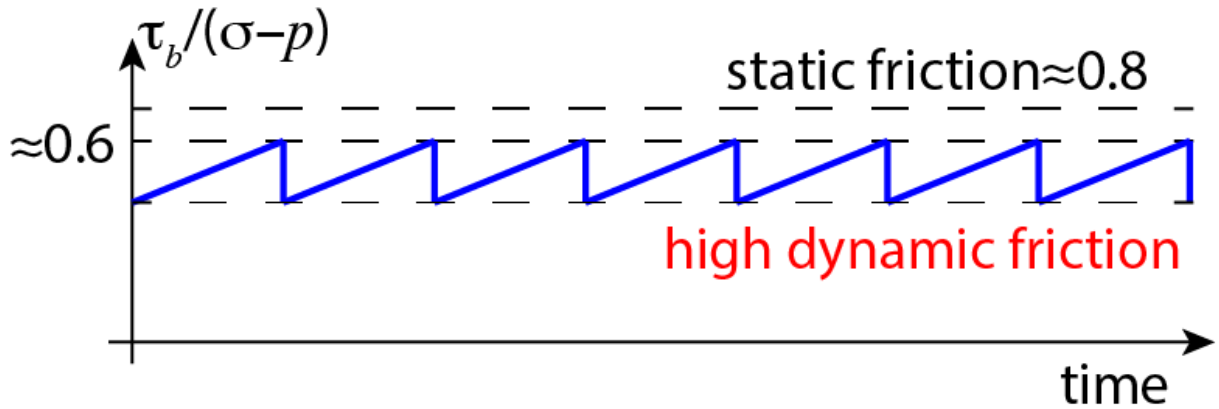


another possibility is development of additional subparallel fault strands, oriented so as to provide "cooperative strain accommodation" [Shaw, Richards-Dinger, Dieterich] and less overall resistance

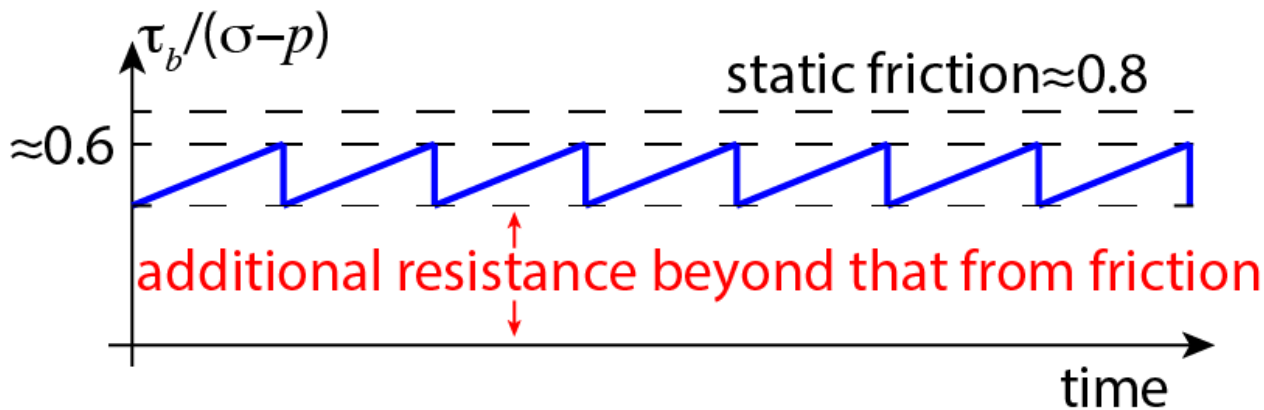
[Fang and Dunham, 2013]

Can we distinguish between these two possibilities?

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

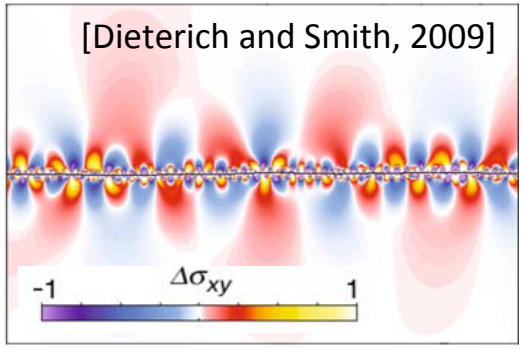


2. dynamic weakening eliminates frictional resistance, but ***some other mechanism provides resistance to slip in addition to friction***



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

Possible Discriminants



geometric resistance model predicts:

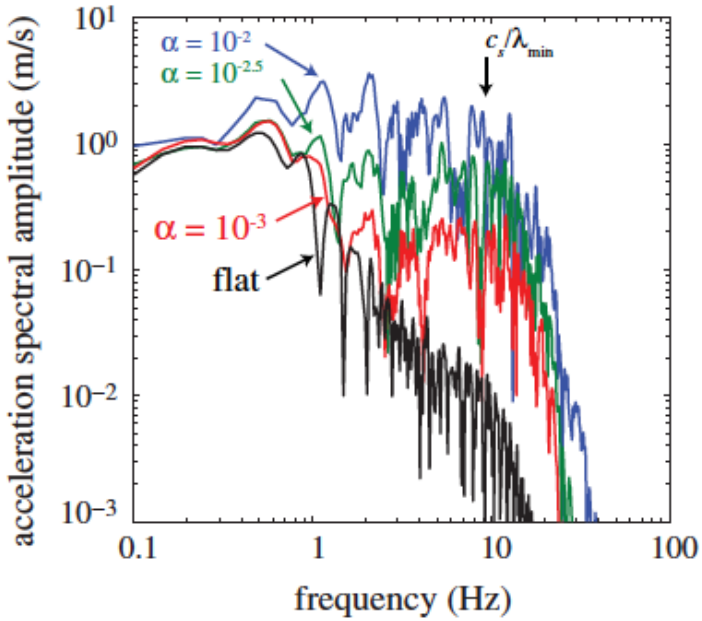
local near-fault stress changes ~ absolute stress (~100 MPa)

➔ *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 << 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]



Possible Discriminants

geometric resistance model predicts:

net heat generation far less than during sliding at high τ

- along fault, τ reduced by dynamic weakening during slip, so minimal ΔT and no melting
- away from fault surface, throughout 100 m wide damage zone, heating with ΔT~0.01 K accompanies plastic deformation

total energy converted to heat in two models:

geometric resistance: $$W_{off} = \int_{volume} \int \sigma_{ij} \dot{\varepsilon}_{ij}^{p} \, dt d^3x \sim \tau_{high} \int_{volume} \varepsilon^p d^3x \sim \tau_{high} P_{volume}$$

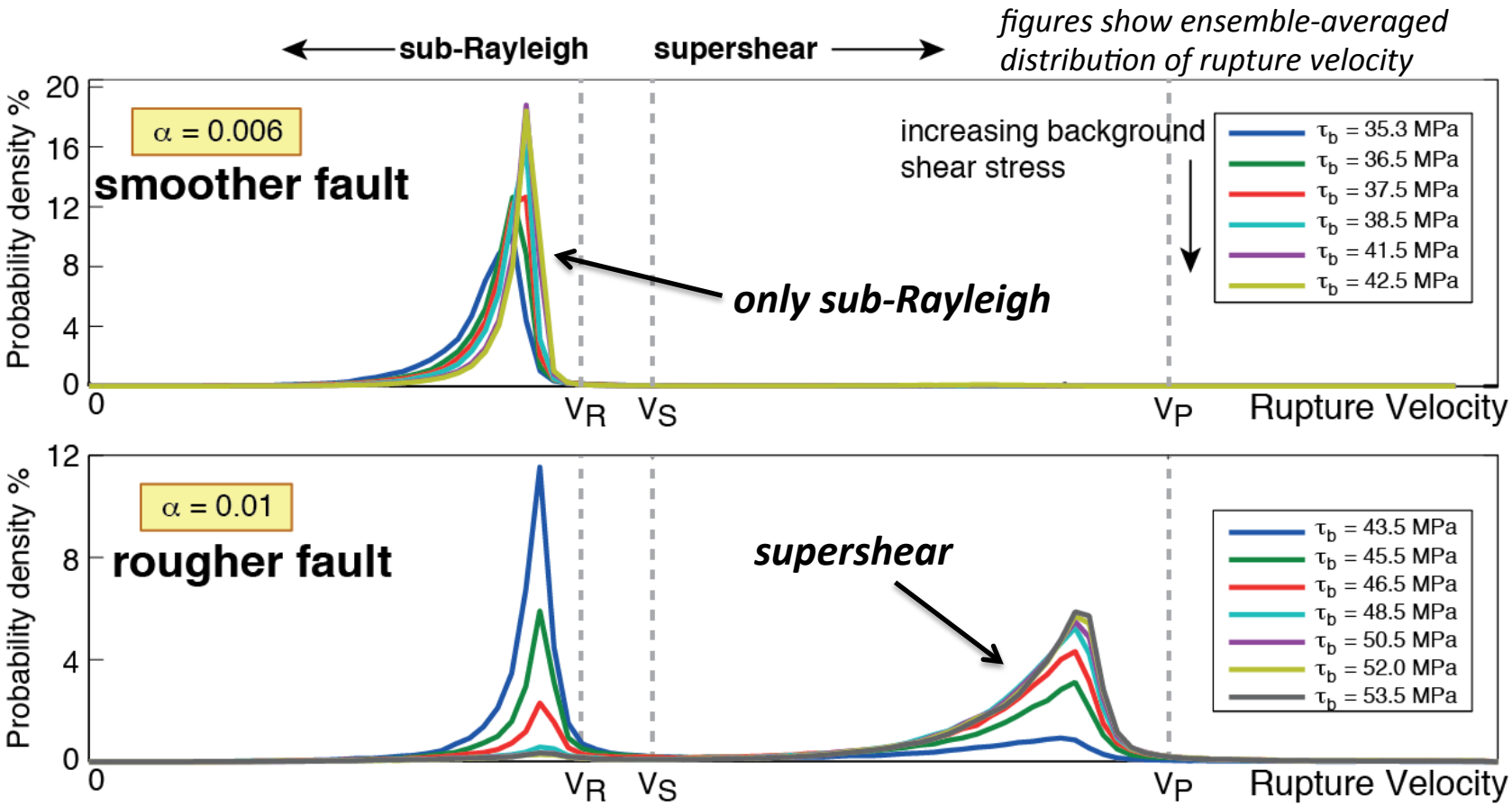
high dynamic friction: $$W_{on} = \int_{fault} \int \tau V \, dt d^2x \sim \tau_{high} \int_{fault} \Delta u d^2x \sim \tau_{high} P_{fault}$$

ratio of dissipated energy ~ ratio of potency release off and on fault = P_{volume}/P_{fault} << 1

Moving Toward Probabilistic Quantification of Rupture Style (and Ground Motion) using Ensemble Dynamic Rupture Simulations

Supershear ruptures occur only on rougher faults, exactly opposite of common statement [Bouchon et al., 2010] that supershear requires smooth fault segments!

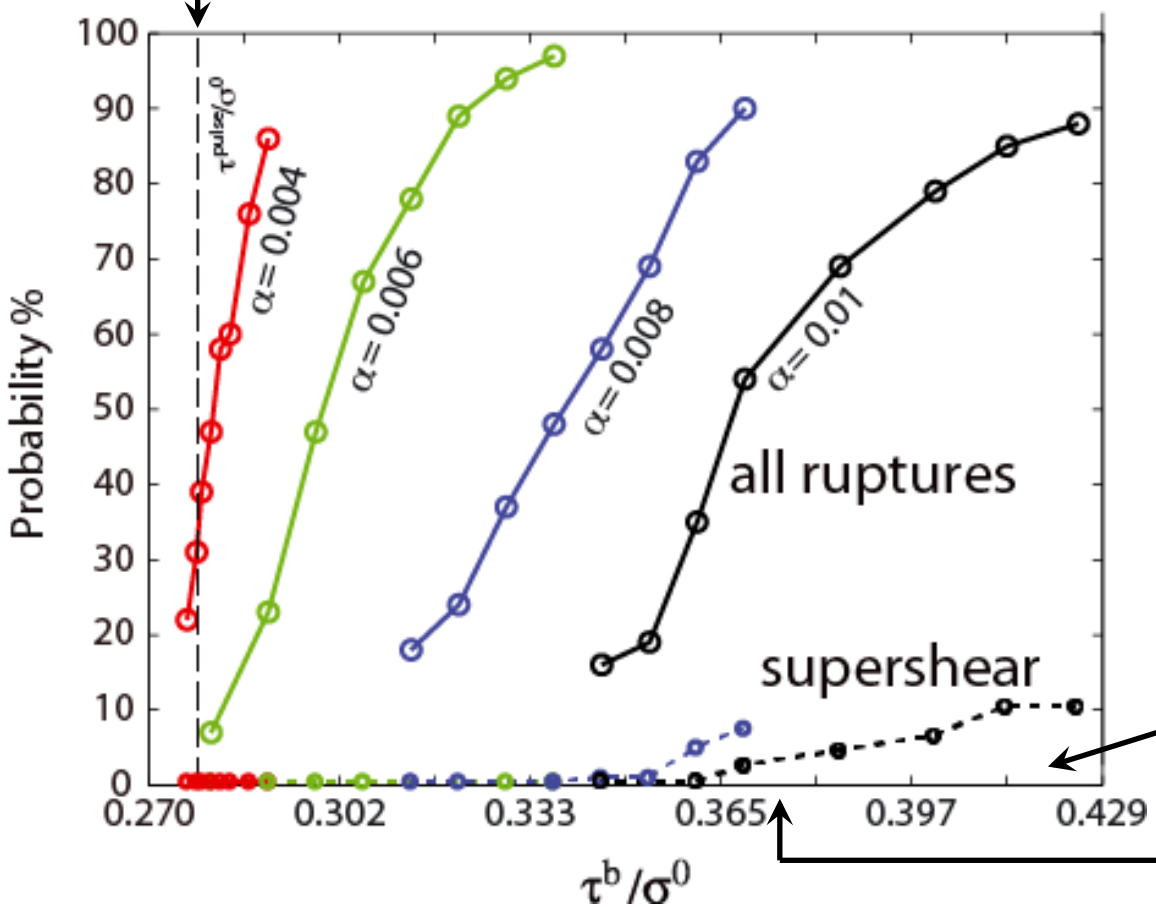
figures show ensemble-averaged distribution of rupture velocity



[Bruhat, Fang, Dunham, work in progress, 2014]

Moving Toward Probabilistic Quantification of Rupture Style (and Ground Motion) using Ensemble Dynamic Rupture Simulations

threshold τ^{pulse} for flat faults



could also quantify likelihood of ruptures

- taking branches
- jumping step-overs
- linking segments in multifault event

...but this is still incomplete, as we also need to know probability that nucleation will occur some τ^b

unlikely fault will reach these high τ^b because, as tectonic loading increases τ^b, earthquakes likely occur earlier and relax τ^b

[Bruhat, Fang, Dunham, work in progress, 2014]

Vision for SCEC5

simulation of earthquake sequences on geometrically complex faults (with plasticity, inertial rupture dynamics, and in 3D, of course!)

single-event dynamic rupture codes

earthquake simulators (boundary elements)

we've taken some initial steps toward this goal, and in the process stumbled on something quite interesting

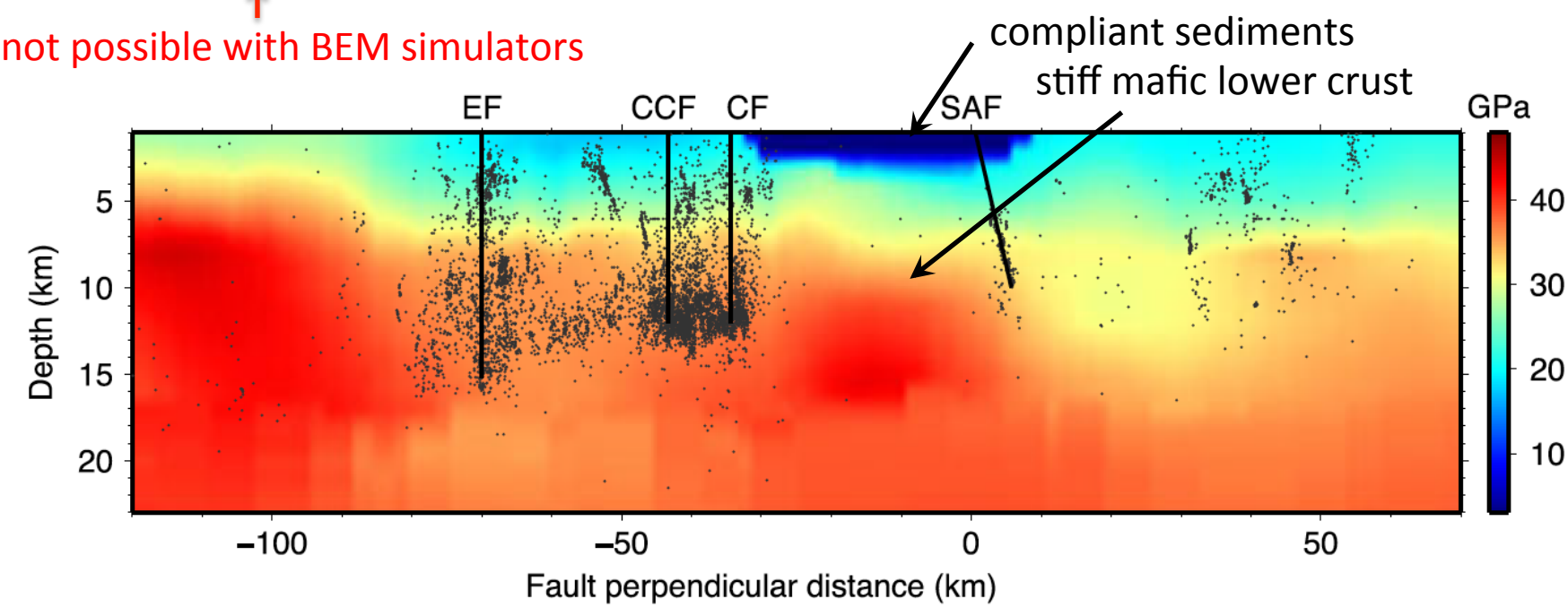
Earthquake Sequences in Sedimentary Basins

Current modeling capabilities:

- 2D quasi-dynamic simulation
- rate-and-state friction
- using finite difference method to accommodate ***elastic heterogeneity*** (no plasticity)

not possible with BEM simulators

sedimentary basins like Salton Trough in southern CA



[Lindsey and Fialko, 2013] shear modulus cross-section from SCEC CVM-H 6.3

Earthquake Sequences in Sedimentary Basins

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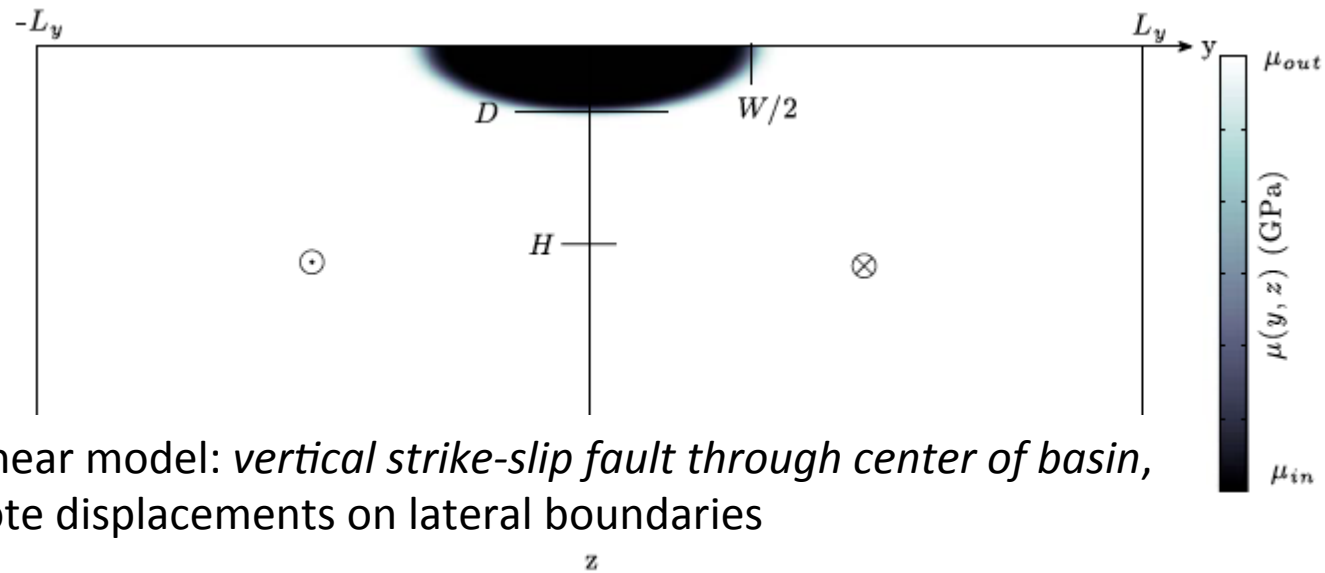
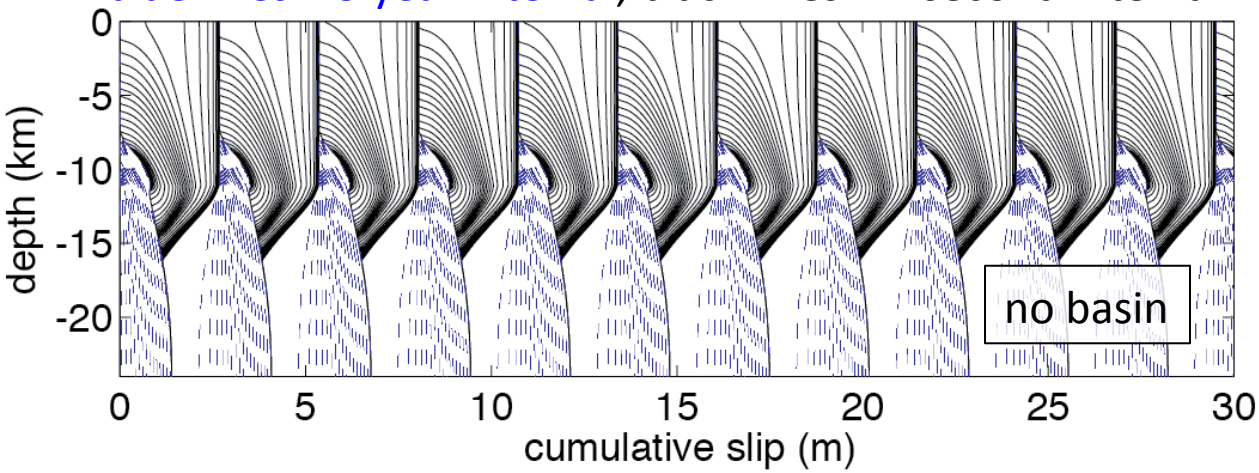


2D antiplane shear model: *vertical strike-slip fault through center of basin*, driven by remote displacements on lateral boundaries

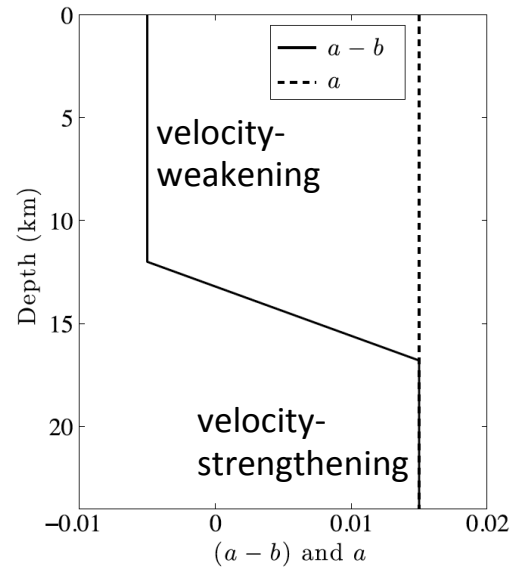
[Erickson and Dunham, 2014; Allison, Erickson, Dunham, work in progress]

Earthquake Cycles in Sedimentary Basins

blue lines = 5 year interval, black lines = 1 second interval



rate-and-state friction:

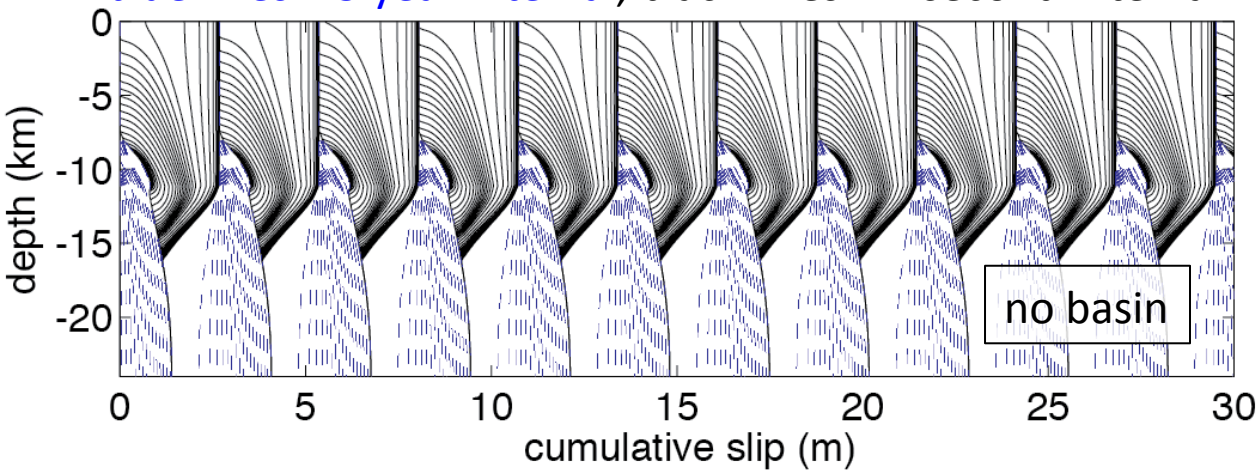


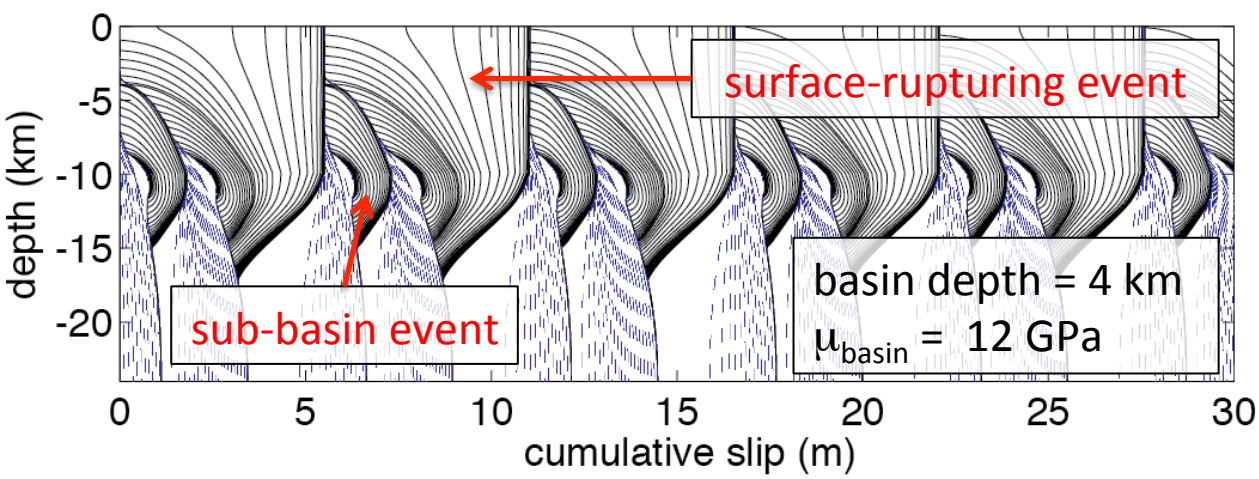
[Erickson and Dunham, 2014; Allison, Erickson, Dunham, work in progress]

Earthquake Cycles in Sedimentary Basins

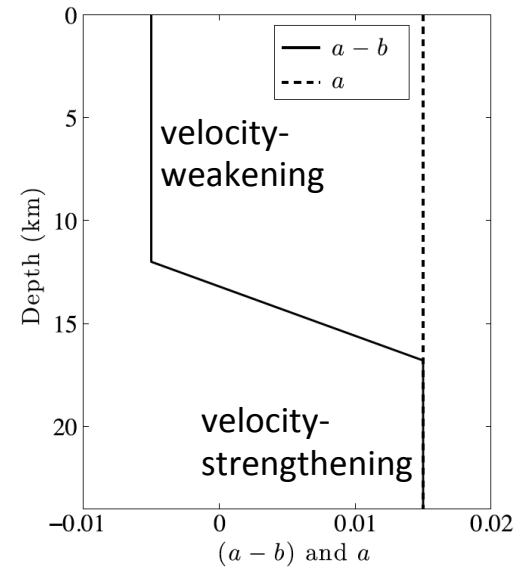
compliant basins give rise to alternating sequences of ***sub-basin*** and ***surface-rupturing events***

blue lines = 5 year interval, black lines = 1 second interval





rate-and-state friction:

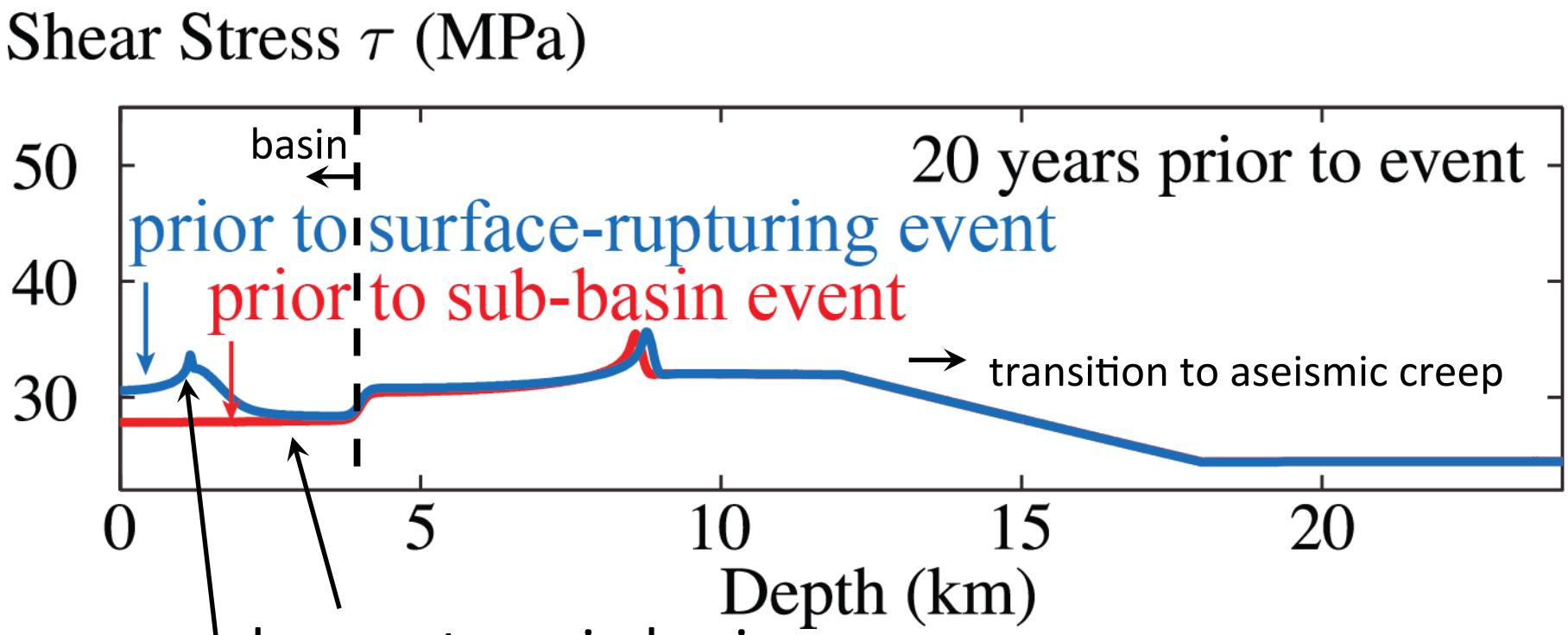


surface-rupturing events are much larger, and feature extensive shallow coseismic slip

[Erickson and Dunham, 2014; Allison, Erickson, Dunham, work in progress]

Why do Compliant Basins Inhibit Rupture?

+ other causes, not modeled here, including velocity-strengthening in sedimentary rocks and lower $\sigma - p$ near surface (future work)

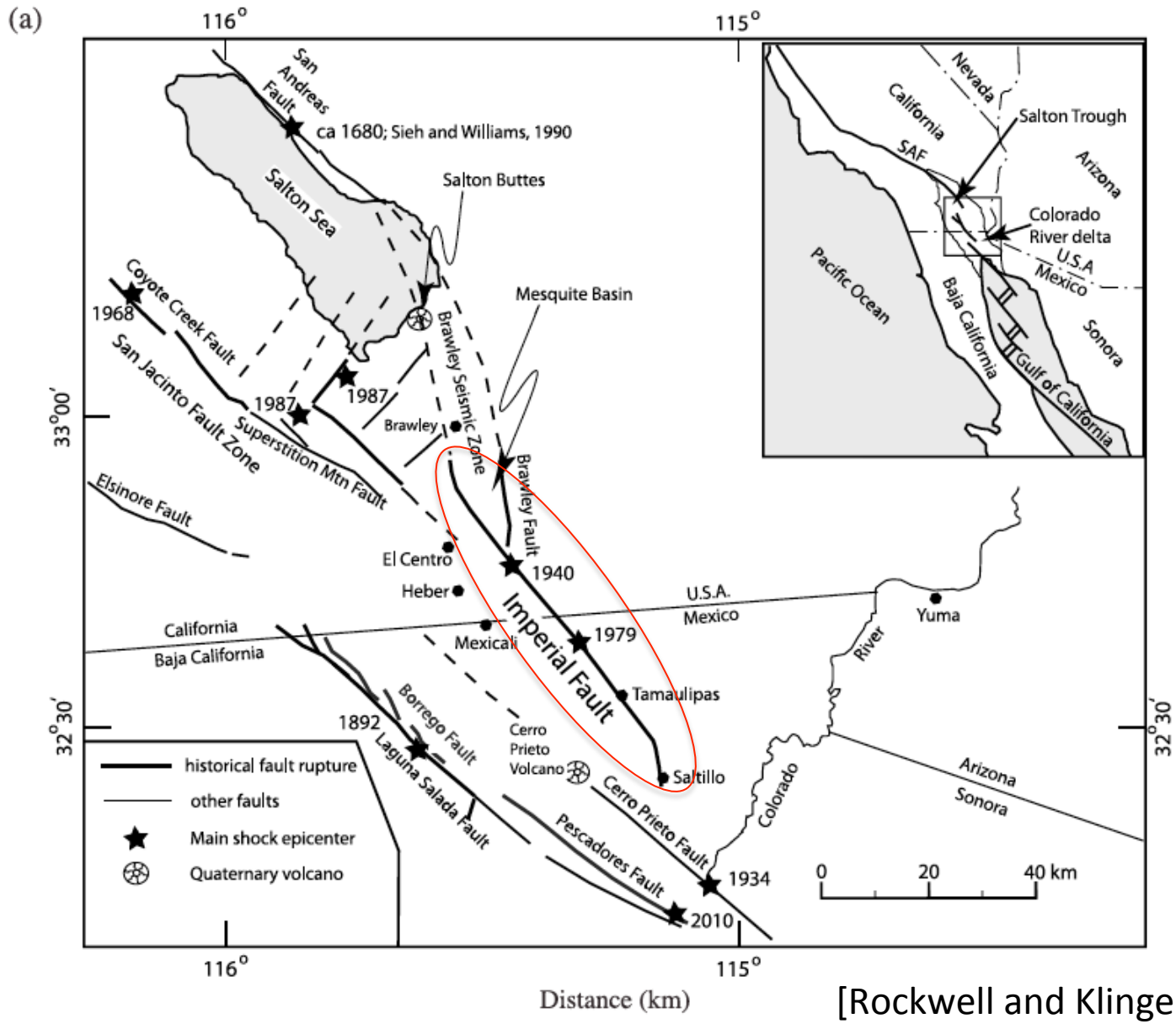


lower stress in basin

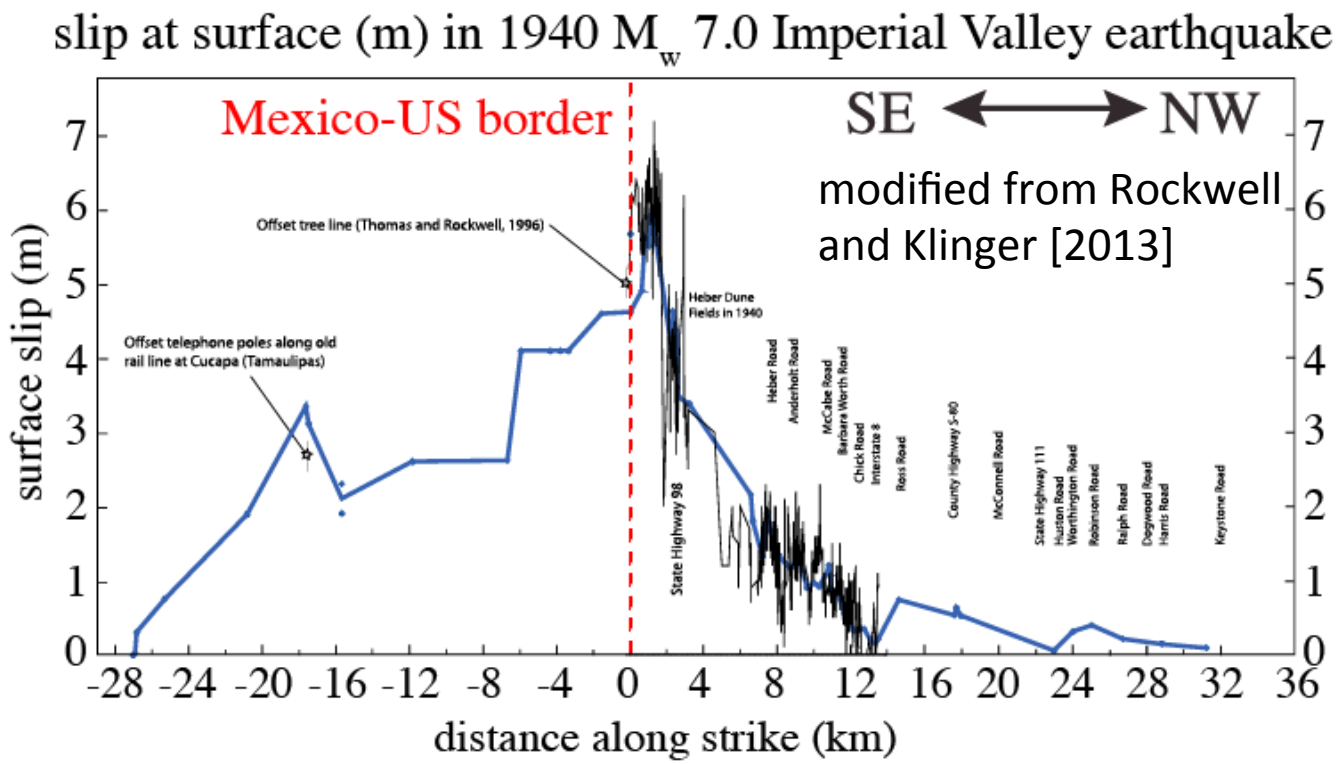
stress concentration left behind by sub-basin event (facilitates subsequent ruptures)

[Erickson and Dunham, 2014; Allison, Erickson, Dunham, work in progress]

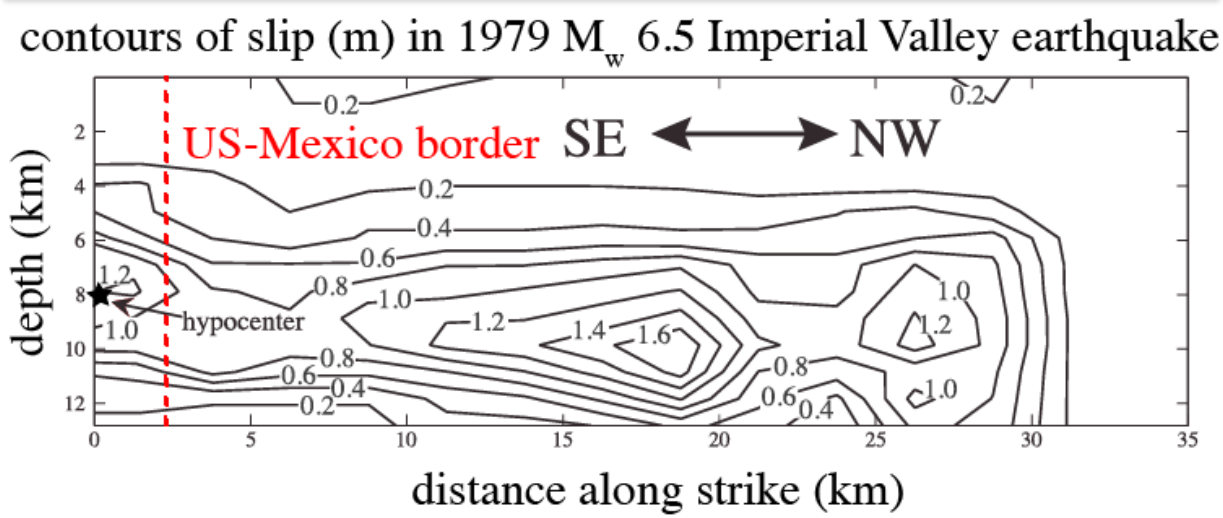
Does This Happen in Nature?

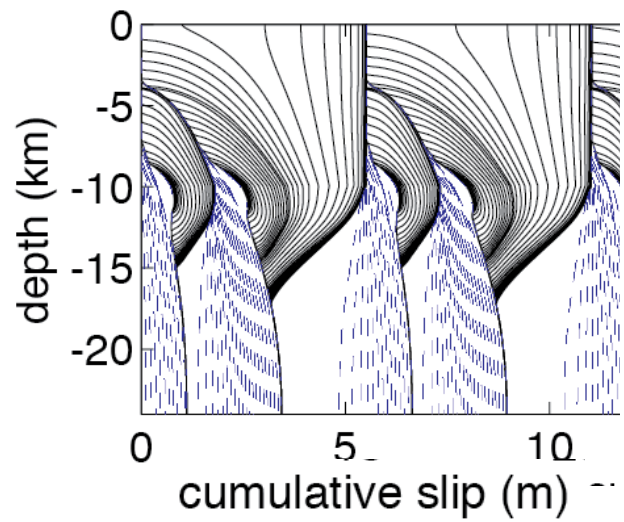


[Rockwell and Klinger, 2013]



rather similar to our models, with implications for seismic hazard, paleoseismology, shallow-slip deficit





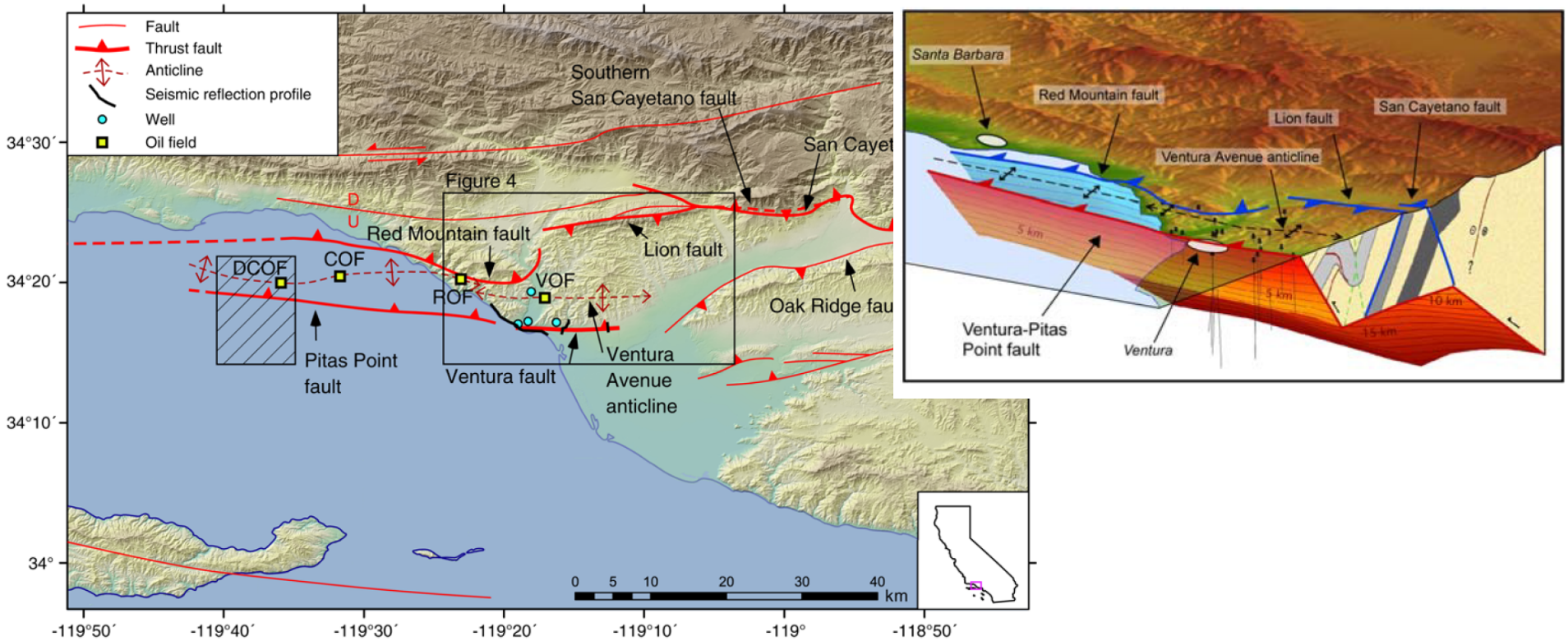
modified from Archuleta [1984]

Uncovering these fascinating behaviors is only the start, as we begin to incorporate elastic heterogeneity and ultimately inelastic deformation in earthquake simulators.

We can also take simulations in other new directions, such as adding gravity…

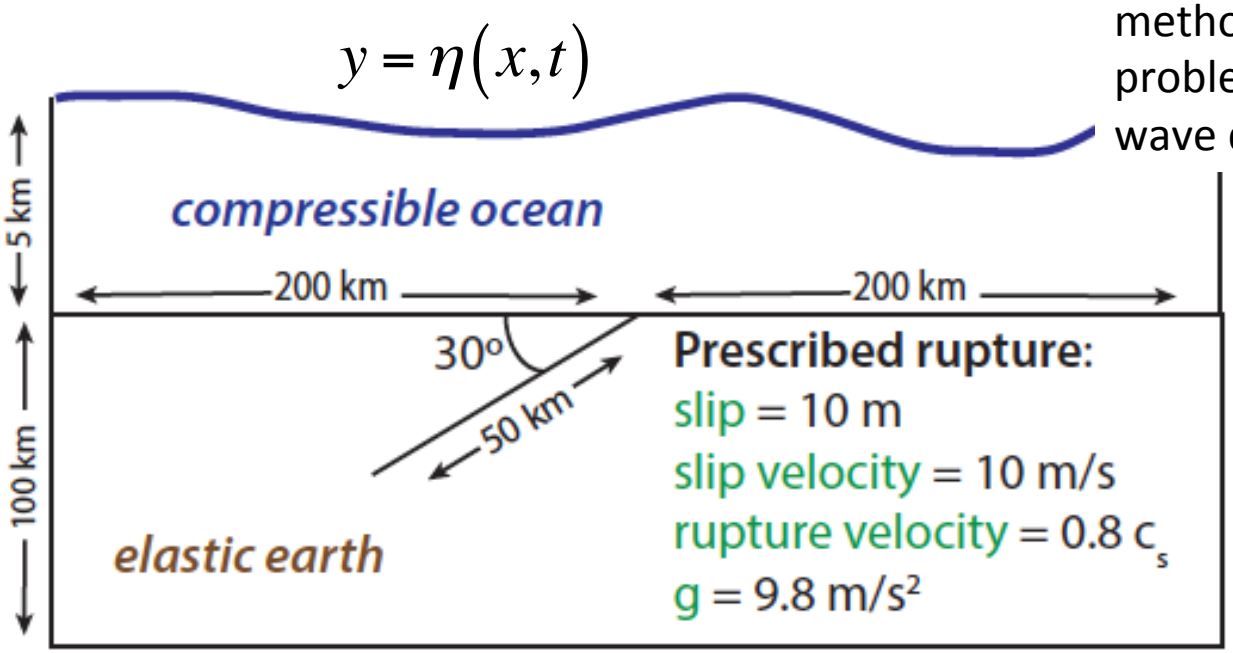
Tsunamis from Dynamic Ruptures

With SCEC's new focus on the Ventura-Pitas Points fault system, the need to understand *tsunami generation* has risen to a new prominence



[Hubbard et al., 2014]

It's easy to extend wave propagation codes to simulate tsunamis!



method rigorously solves linearized problem, including surface gravity wave dispersion at short wavelengths

free surface BC on moving surface (Eulerian description): $p = 0 \quad \text{on} \quad y = \eta(x,t)$

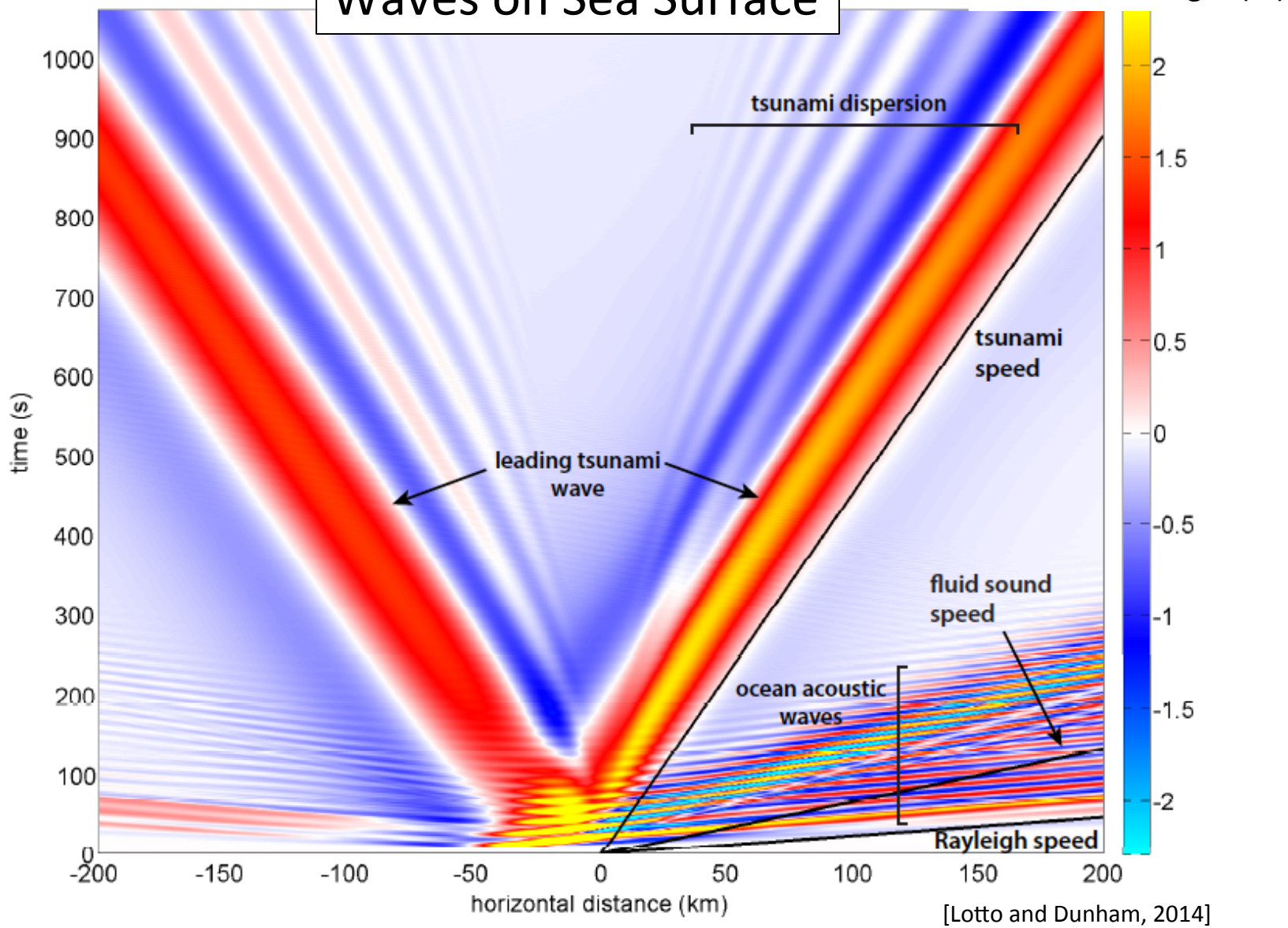
apply *approximate* free surface BC on unperturbed surface (linearization): $p(\eta) \approx p(0) + \left.\frac{\partial p}{\partial y}\right|_{y=0} \eta \approx p(0) - \rho g \eta$

$$\boxed{\Rightarrow p = \rho g \eta, \quad \partial \eta / \partial t = v_y \quad \text{on} \quad y = 0}$$

with no other changes to governing equations!

[Lotto and Dunham, 2014]

Waves on Sea Surface

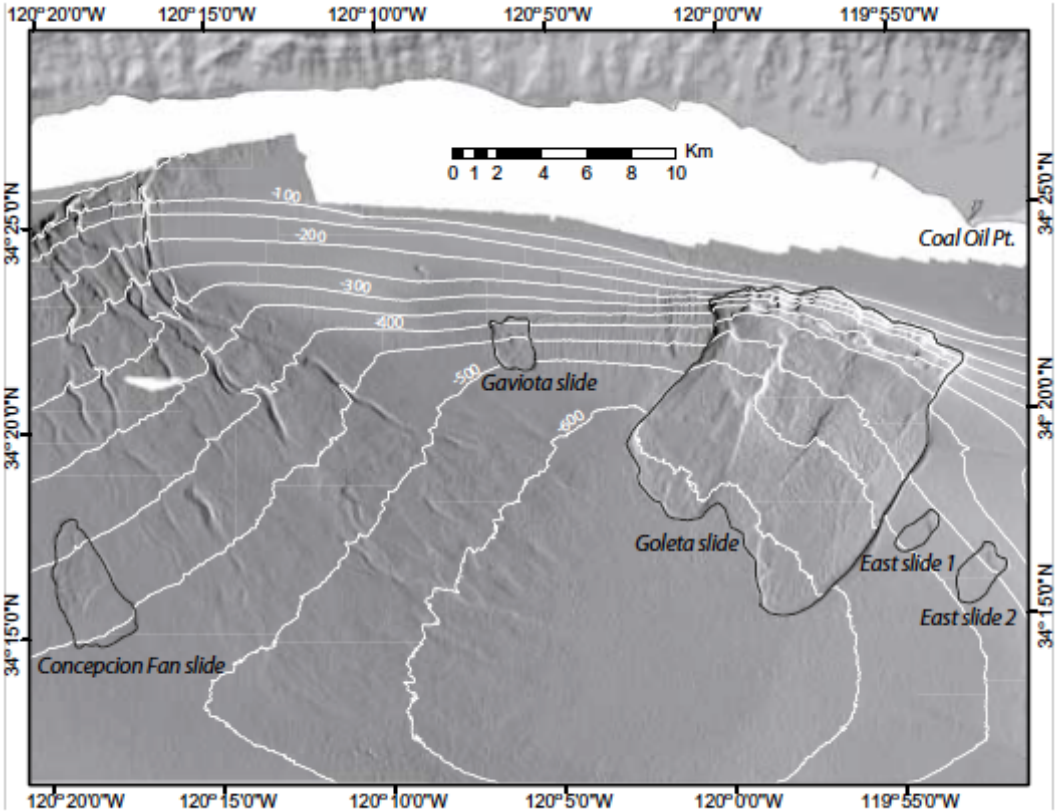


[Lotto and Dunham, 2014]

Fig. 5 Space-time plot of sea surface η, illustrating the variety of waves generated by an earthquake on a thrust fault beneath the ocean. The black lines are drawn at the tsunami speed in the shallow water limit, $\sqrt{gH}$; the fluid sound speed, $c = \sqrt{K/\rho}$; and the Rayleigh wave speed, $0.919\, c_s$. After about 300 s, the bulk of the seismic and ocean acoustic waves have propagated out of the domain and only slower-traveling surface gravity waves remain. Note the dispersive tail to the tsunami.

While our method is not useful for estimating run-up and inundation, it can provide self-consistent initial conditions for nonlinear tsunami simulations (unresolved issues with complex bathymetry)

...perhaps even more exciting would be modeling initiation of submarine landslides (gravity+inelastic failure)



[Greene et al., 2006]

landslide near Santa Barbara, possible 10 m local tsunami – could such events be triggered by seismic shaking?

Conclusions and Vision for SCEC5

simulation of earthquake sequences on geometrically complex faults (with plasticity, inertial rupture dynamics, and in 3D, of course!)

single-event dynamic rupture codes

earthquake simulators (boundary elements)

- consideration of fault geometric complexity resolves many outstanding issues in earthquake science (stress/heat flow, high-frequency ground motion), but we must move ***beyond elasticity***
- ensemble dynamic rupture simulations allow us to quantify variability of earthquake behavior
- earthquakes cause tsunamis and landslides – we can potentially model these hazards, too, in a unified framework