Friction laws currently used in dynamic rupture simulations

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1. WHY are you running a dynamic rupture simulation?
   WHAT do you expect to learn from it? (More than just to match data!)
2. Select friction law based on answer to 1.

(vs. adding more physics/process to make simulations "more realistic" – only do that if it helps you achieve your objective and/or reduces uncertainty by allowing validation against additional data)

Why do we run dynamic rupture simulations?

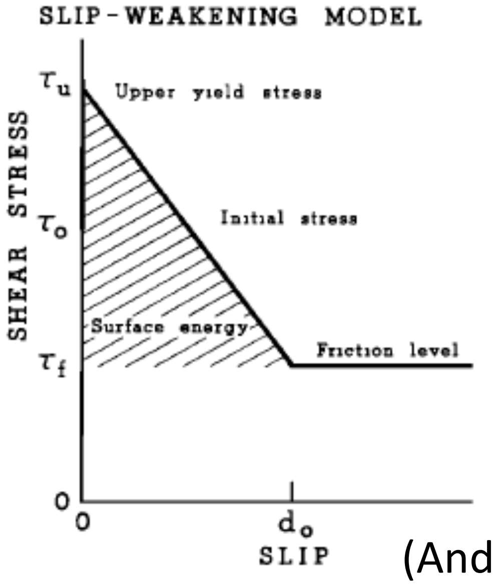
1. **ground motion simulation** (primary motivation for SCEC's dynamic rupture verification/validation efforts due to funding from PG&E, Yucca Mountain project, etc.)
2. **constrain possible rupture behaviors** (which might place constraints on kinematic inversions or kinematic forward models used for ground motion simulation) or **explain observed ruptures**
3. **constrain rupture front weakening and energy dissipation processes** by quantifying fracture energy, etc. (addressing fundamental earthquake physics questions)

Objective: **Simulation(s) that produce ground motions consistent with observations** (validated by matching intensity measures and other observables)

- Often done with *single event simulations* (prescribed initial stress, artificial initiation)
- Variability in ground motion comes from variability in initial stress (or friction parameters)

→ objective met by using **slip-weakening friction**, essentially a regularization of otherwise singular stresses that arise in LEFM=linear elastic fracture mechanics

historically dynamic rupture simulations emerged from LEFM studies in 1960s and 1970s, and slip-weakening was quickly adopted (following Andrews, 1976) as convenient way to get convergent, non-oscillatory solutions to LEFM problems



(Andrews, 1976)

Objective: **Simulation(s) that produce ground motions consistent with observations** (validated by matching intensity measures and other observables)

Necessity for **stochastic models** (ensembles with randomly generated initial stress or other features) were recognized in 1980s (e.g., Andrews, 1980, 1981) and later implemented in dynamic rupture simulations (e.g., Mai et al., 2001; Oglesby and Day, 2002; Ripperger et al., 2007; Shi and Day, 2013).

→ most with *slip-weakening friction*!

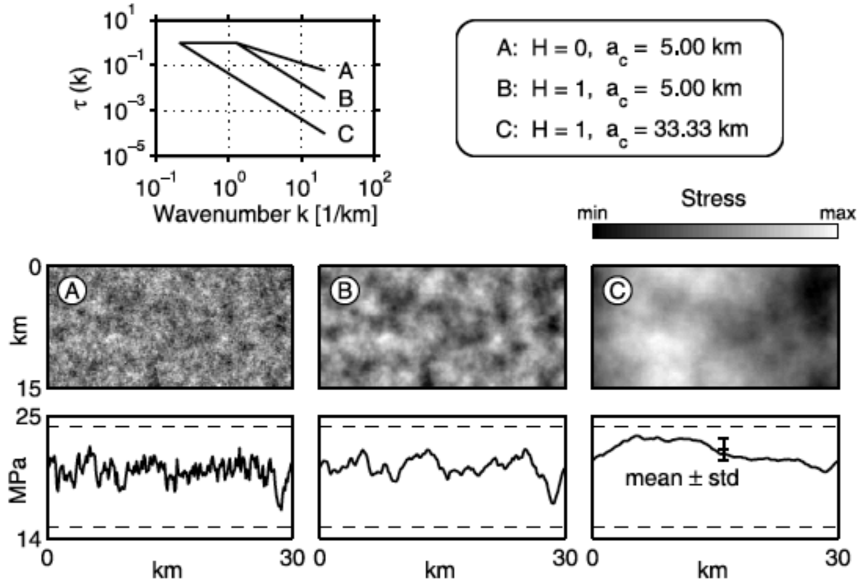


Figure 2. Illustration of random stress field generation. (top) Prescribed Fourier amplitude spectra for three different combinations of Hurst exponent H and correlation length a_c. Shown are one-dimensional

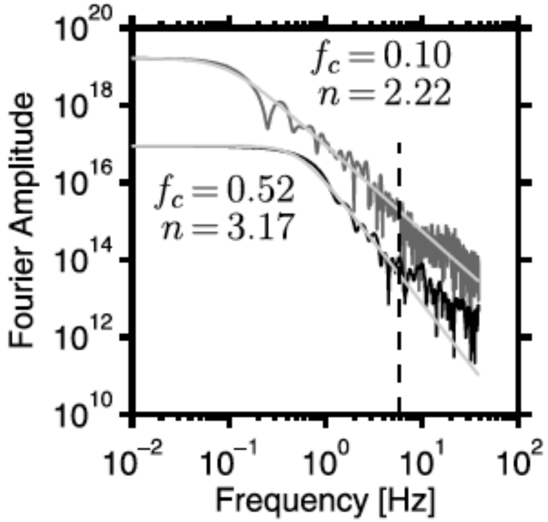


Figure 13. Spectra of moment rate functions for the

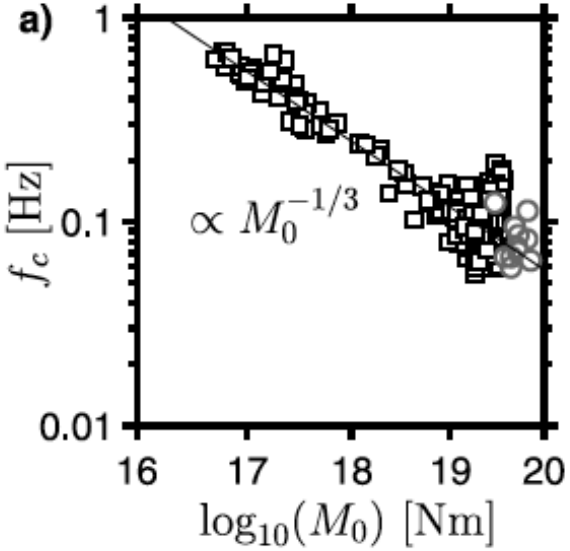
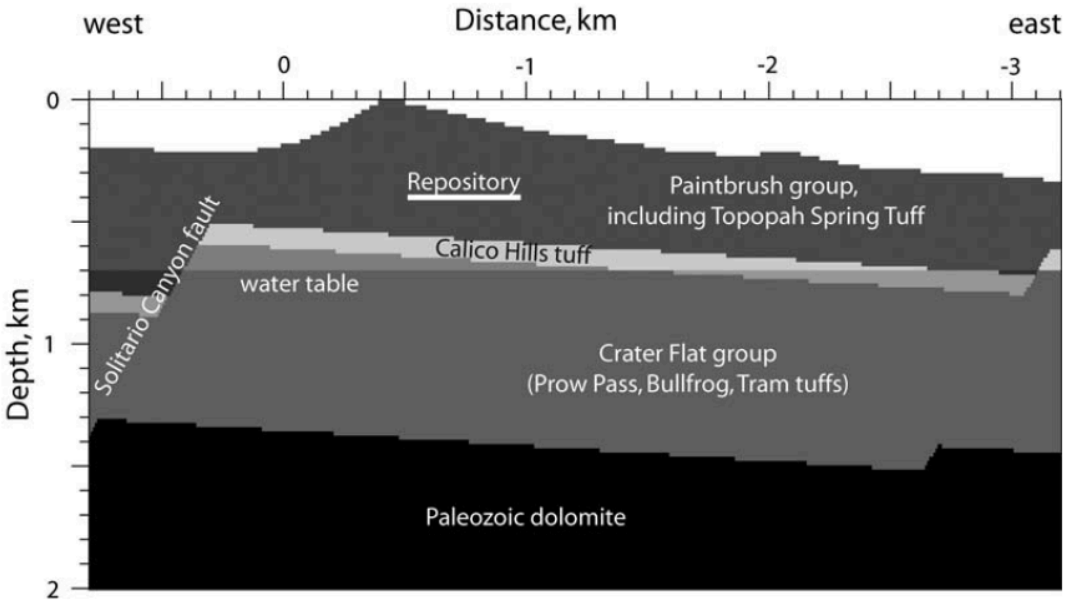


Figure 14. Spectral parameters of moment rate functions for all simulations plotted against seismic moment. (a) Corner frequencies. They show the expected scaling with seismic moment of $f_c \propto M_0^{-1/3}$ indicated by the black

(Ripperger et al., 2007)

Objective: **Simulation(s) that produce ground motions that are useful for engineering applications**

Sometimes **additional processes must be added**, like yielding (off-fault plasticity) when calculating physical limits of ground motion at Yucca Mountain (proposed) nuclear repository. Again, these were single-event dynamic rupture simulations with slip-weakening friction.



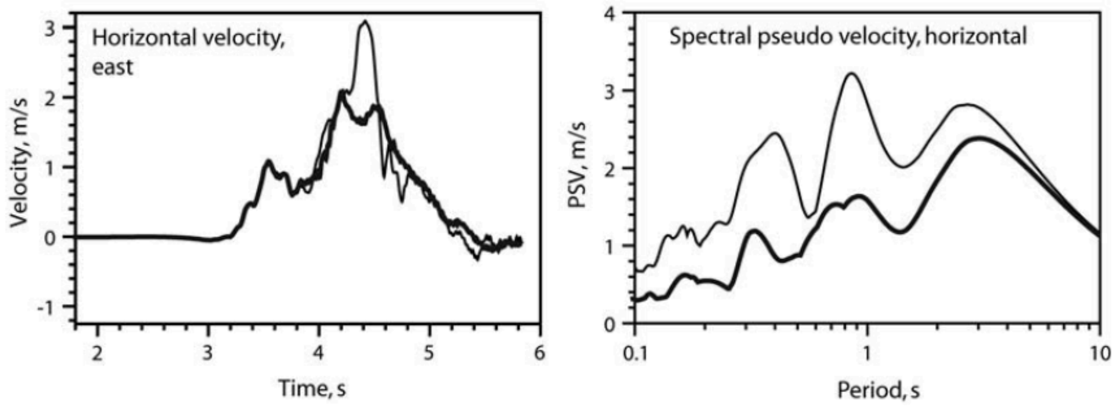


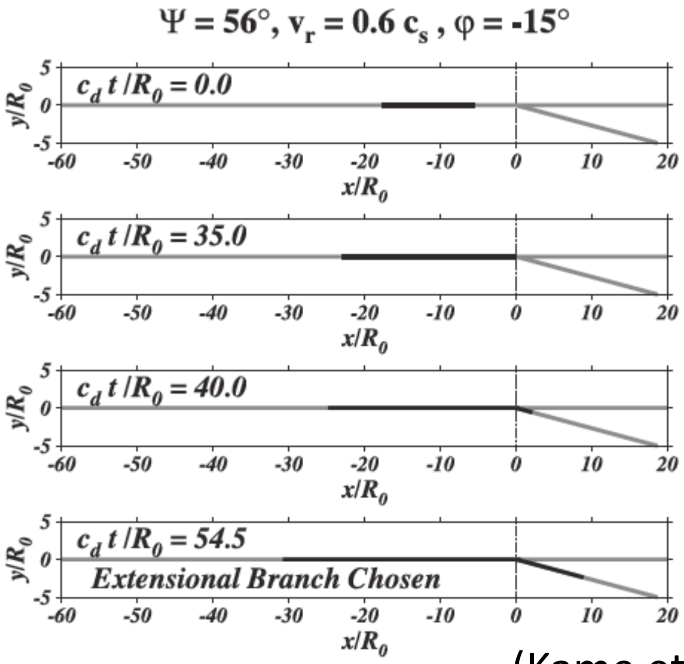
Figure 22. Ground motion at the repository depth at 1 km east of the Solitario Canyon fault with 5-m fault slip and sub-Rayleigh rupture propagation with and without yielding. Elastic calculation, light curves; calculation with Coulomb yielding, heavy curves.

(Andrews et al., 2007)

Objective: **Constrain possible rupture behaviors** (validated by matching data from real events, typically ground motion and deformation)

Sometimes, motivating question is *rupture path through complex fault network* (e.g., branches, step-overs), as at Diablo Canyon nuclear plant.

Dynamic rupture simulations, with *slip-weakening friction*, are primary tool for addressing these questions (e.g., Harris and Day, 1993; Kame et al., 2003; Duan and Oglesby, 2006, 2007; Pelties et al., 2012)



(Kame et al., 2003)

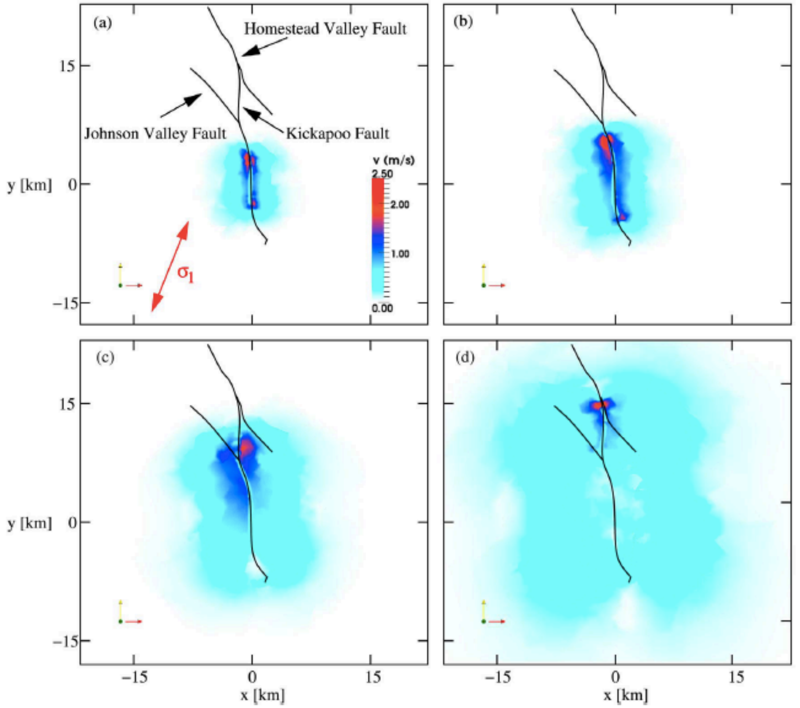


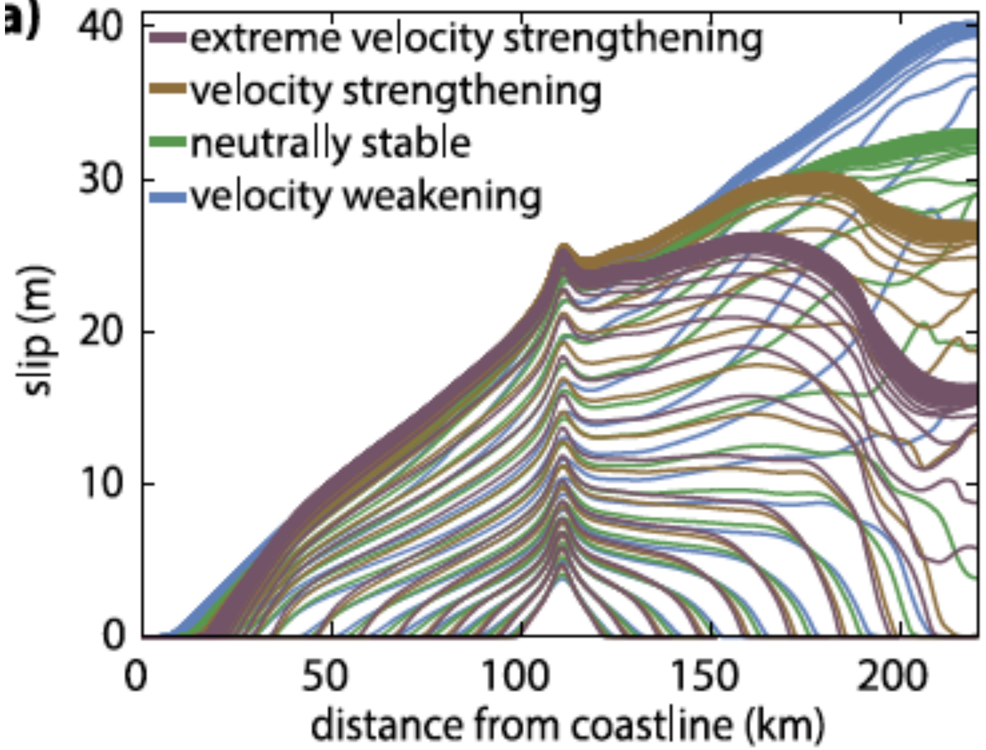
Figure 8. Snapshots of absolute particle velocity at (a) 1, (b) 1.5, (c) 2.5, and (d) 4.5 s after rupture

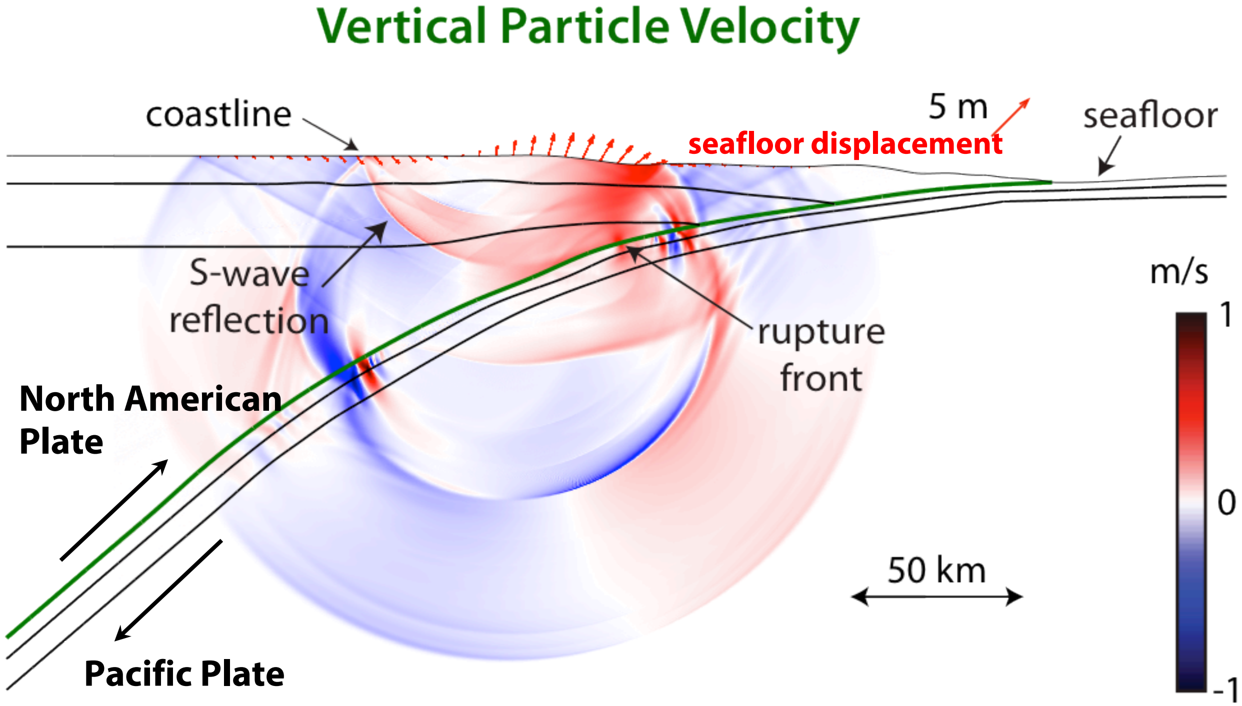
(Pelties et al., 2012)

Objective: **Constrain possible rupture behaviors** (validated by matching data from real events, typically ground motion and deformation)

Other rupture behaviors of interest include **supershear** (e.g., Andrews, 1976; Aagaard and Heaton, 2004; Dunham and Archuleta, 2004**), rupture through velocity-strengthening regions** with or without additional dynamic weakening (e.g., Noda and Lapusta, 2013; Kozdon and Dunham, 2013)

near-trench friction:

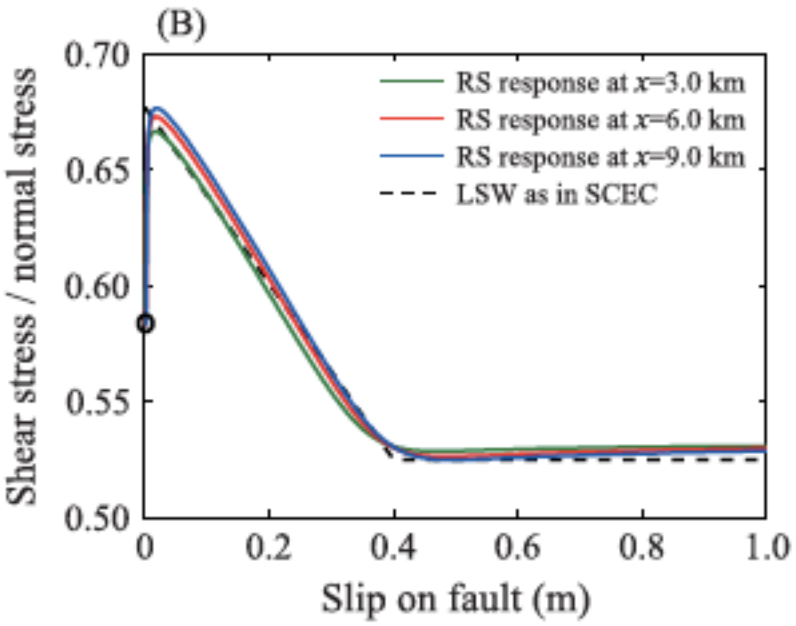


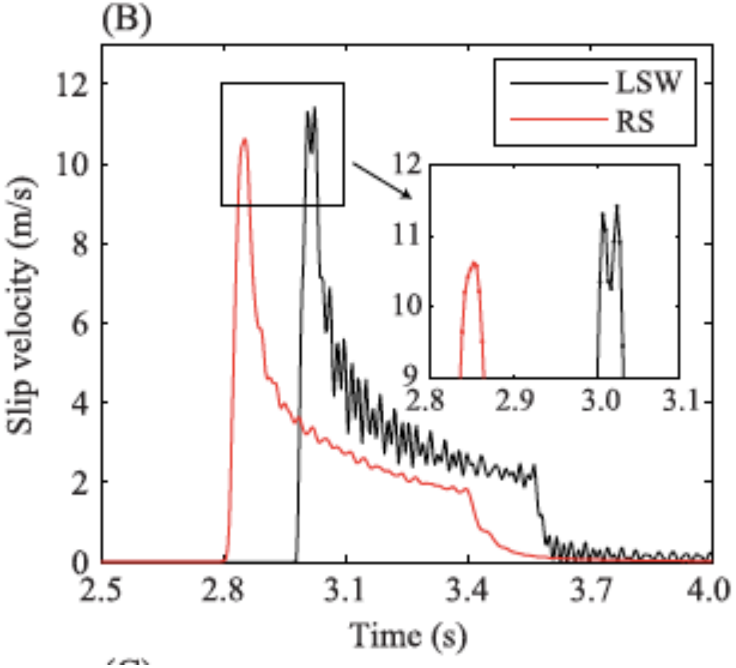


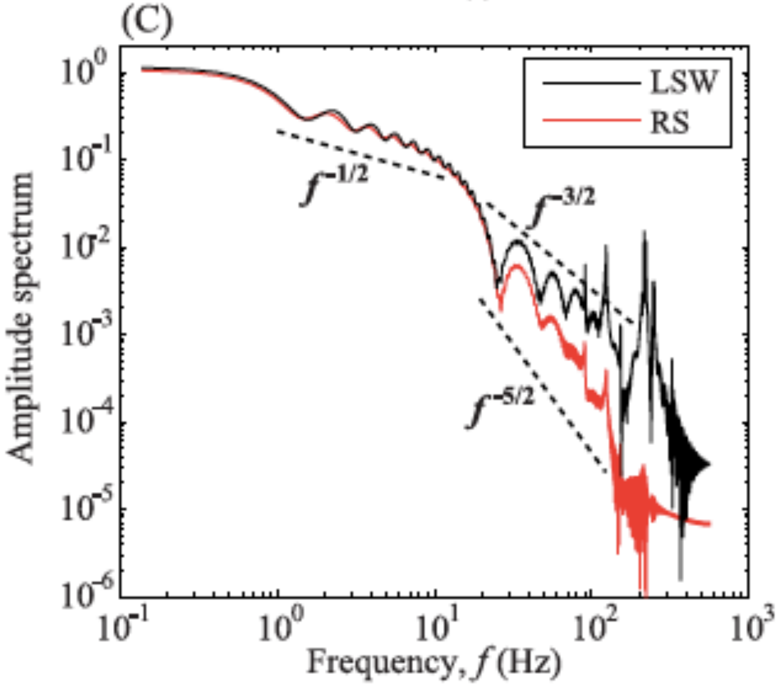
(Kozdon and Dunham, 2013)

Rate-and-state vs. slip-weakening

With standard log(V) dependence, velocity-weakening rate-and-state is almost identical to slip-weakening, but has slightly fewer short wavelength oscillations due to direct effect (e.g., Kaneko et al., 2008)







differences are insufficient to warrant using rate-and-state instead of slip-weakening for classic single-event simulations

(Kaneko et al., 2008)

Why did dynamic rupture modelers start using rate-and-state instead of slip-weakening?

LEFM idealization of rupture propagation (1960s and 1970s)

↓

single event dynamic rupture simulations by Andrews, Das, Day, Harris, Archuleta, Olsen, Madariaga, Oglesby, etc.

↓

lab friction experiments and associated theory by Dieterich, Ruina, Rice, etc.

↓

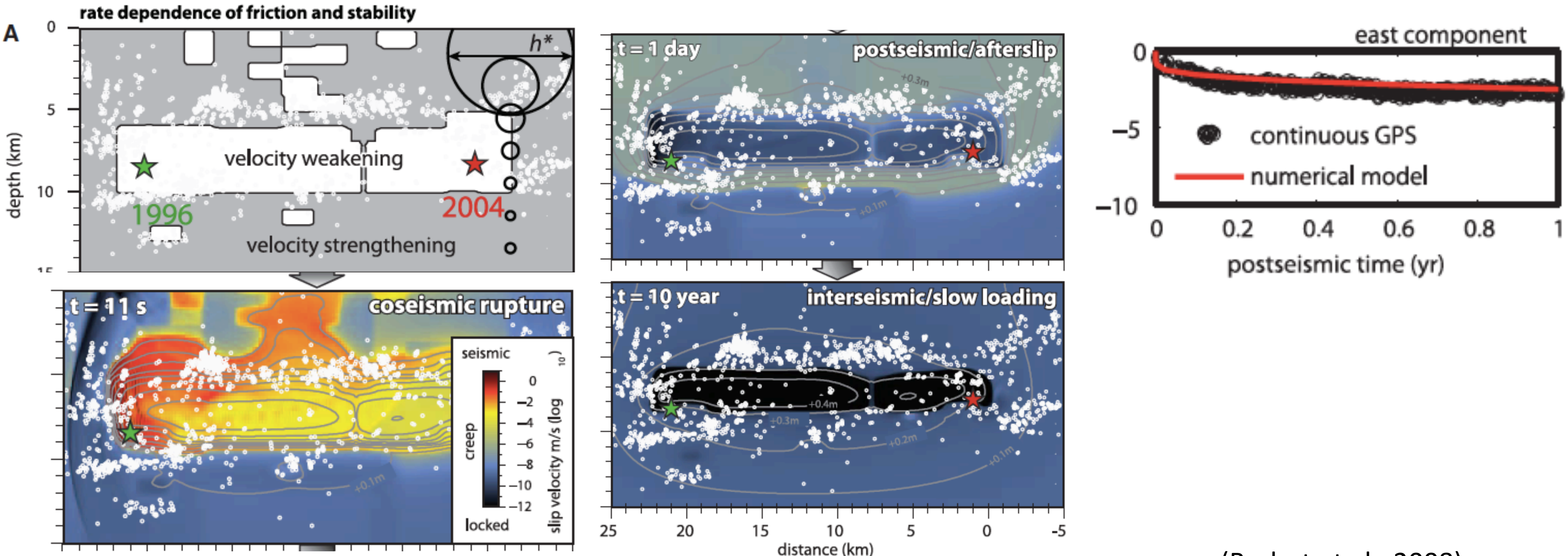
earthquake sequence simulations by Mavko, Rice, Ben-Zion, Lapusta, etc.
(NOT intended for ground motion simulation)

↙

but now distinction between dynamic rupture simulations and sequence simulations is blurring, as we add inertia to sequence simulations (e.g., Lapusta et al., 2000; Kaneko et al., 2011; Barbot et al., 2012; Duru et al., 2019)

Why rate-and-state? It accounts for **interseismic healing and transient aseismic slip (e.g., nucleation, afterslip)**.

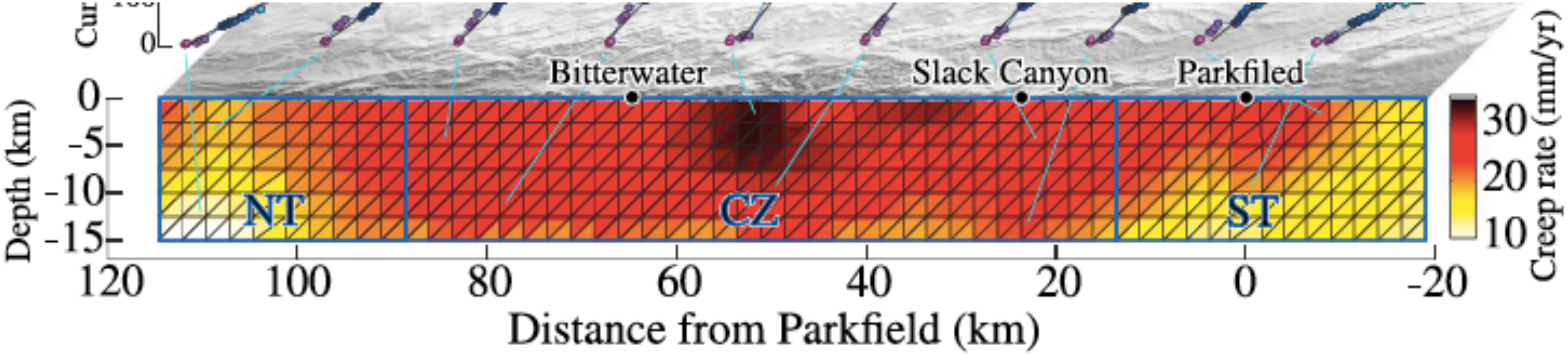
Simulating nucleation and postseismic response, in addition to coseismic rupture, allows connection to geodetic data and mandates **self-consistency of initial stress with loading, prior ruptures, and aseismic slip**



(Barbot et al., 2008)

Simulating nucleation and postseismic response, in addition to coseismic rupture, allows connection to geodetic data and mandates self-consistency of initial stress with loading, prior ruptures, and aseismic slip

accounting for **aseismic slip** will be essential to quantify hazard and rupture behavior of partially **creeping faults**



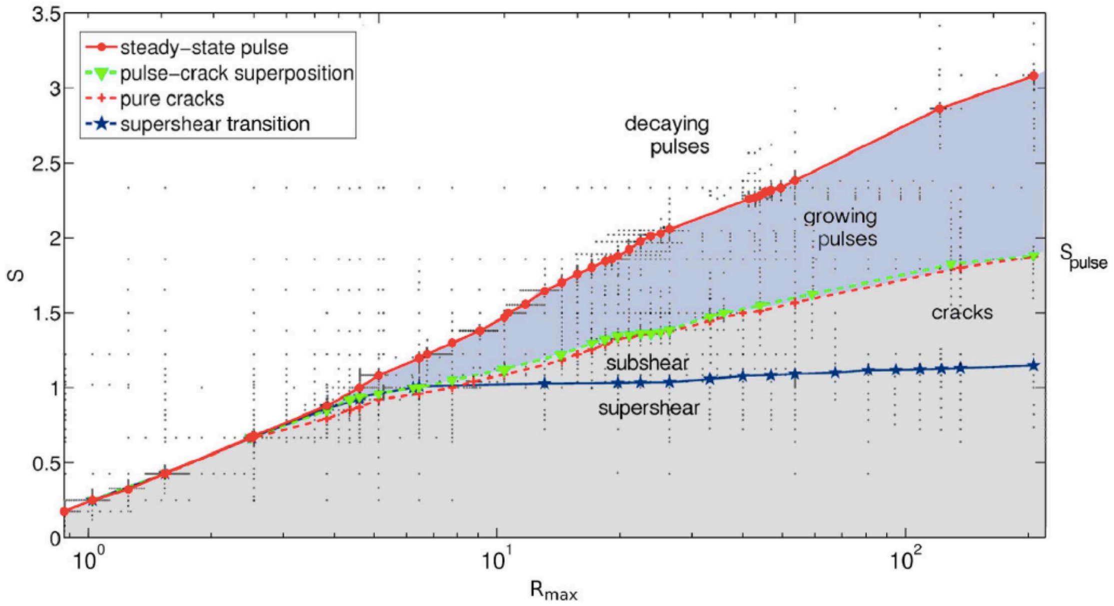
(Khoshmanesh and Shirzaei, 2018)

Slip pulses

Certain features of seismograms indicate **slip pulse ruptures** (Aki, 1968; Heaton, 1990). Various explanations:

- heterogeneity in stress, friction, geometry, etc. (even with slip-weakening friction)
- strongly rate-weakening friction

→ Motivated studies that utilized **strongly rate-weakening friction** (often, but not always, in rate-and-state form): Lapusta and Rice, 2003; Zheng and Rice, 1998; Nielsen and Carlson, 2000; Ampuero and Ben-Zion, 2008; Gabriel et al., 2012

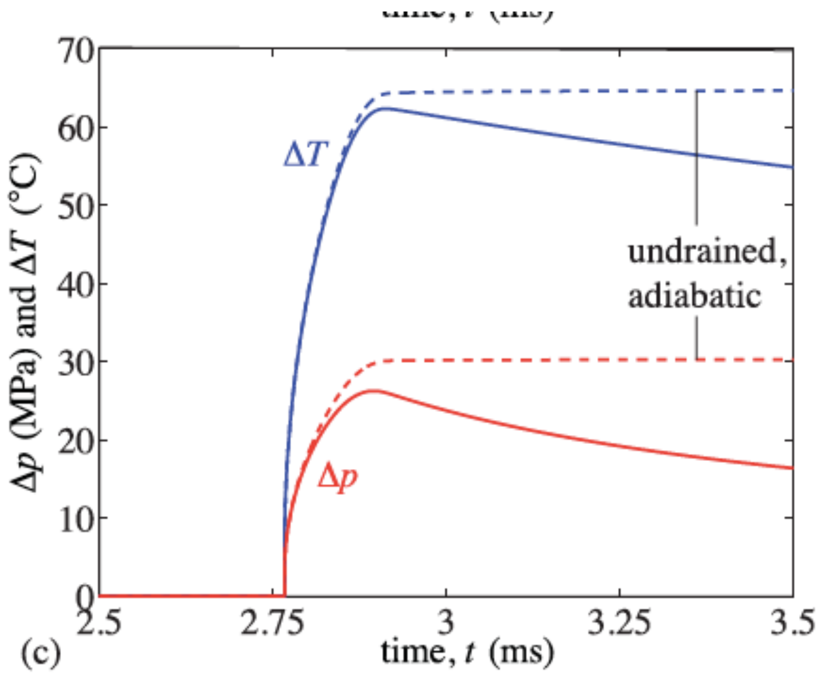


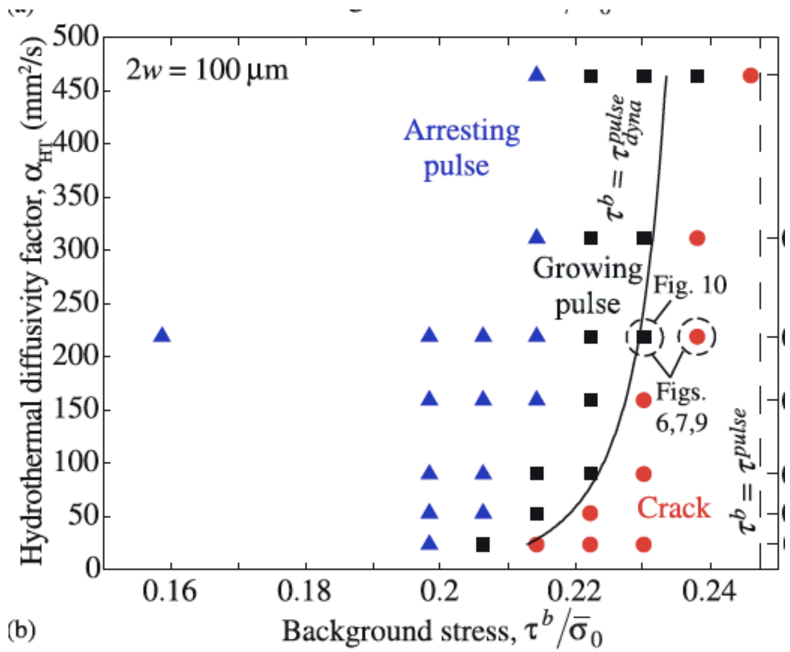
map out parameter space for different rupture behaviors, so that observations of one style can be linked to specific conditions

(Gabriel et al., 2012)

Objective: **Constrain possible rupture behaviors** (with *consistency with lab experiments* or other constraints)

- started with Mavko, 1980s, unpublished; Tse and Rice, 1986 attempting to connect lab measurements of temperature dependence of rate-and-state a-b to observed earthquake depths
- continued in 2000s with explosion of experimental work on dynamic weakening (fueled in part by SCEC's FARM effort)
- led to dynamic rupture and sequence simulations incorporating flash heating, thermal pressurization, and other weakening mechanisms (e.g., Noda et al., 2009)
- simulations possibly consistent with heat flow (and temperature from drilling) constraints

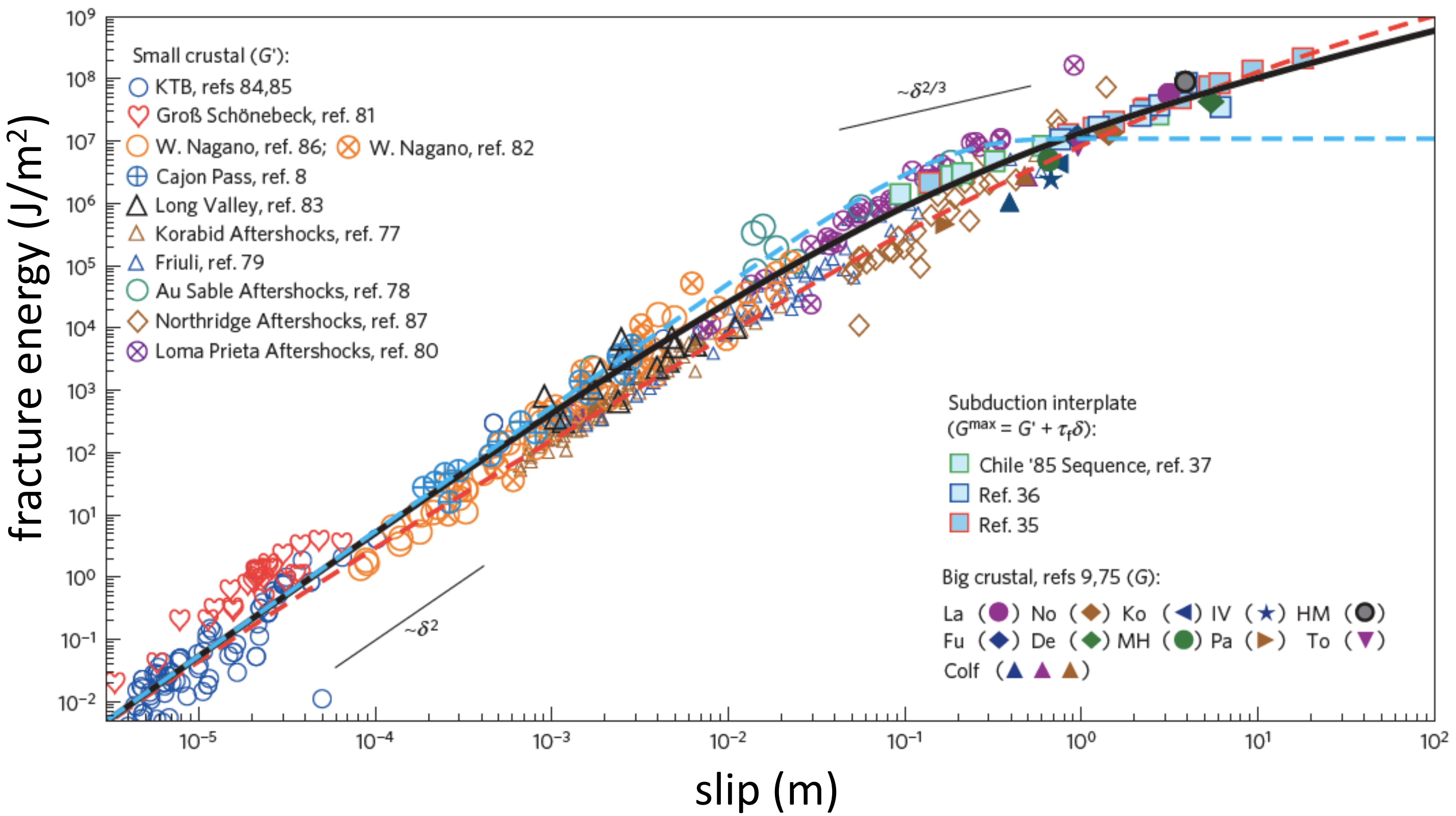




(Noda et al., 2009)

Constraints from scaling

Rather underutilized constraint on weakening and energy dissipation comes from scaling of (indirectly constrained) fracture energy with event size.



Is this scaling evidence for thermal pressurization? or off-fault plasticity? We need **multiscale dynamic rupture simulations** to investigate!

(Viesca and Garagash, 2015)

Thoughts on friction in dynamic rupture simulations

- For many traditional objectives involving single-event dynamic rupture simulations, slip-weakening is fine
- Primary reason to switch to rate-and-state is for earthquake sequence modeling (and to validate/calibrate with interseismic and postseismic observations)
- Dynamic weakening is ubiquitous in experiments, but are experimental set-ups sufficiently like real faults (specifically in terms of shear localization)? And why do many faults operate at standard Byerlee friction stress levels?
- How much attention do we want to place on friction and weakening mechanisms when other processes (e.g., plasticity, fluids, stress) are so poorly understood but obviously important?