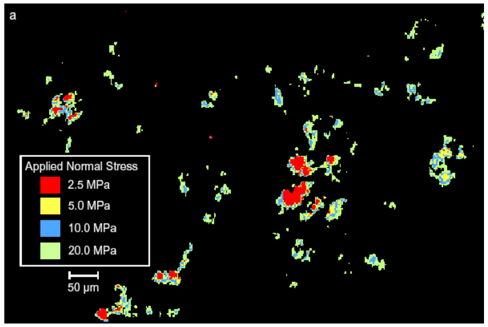
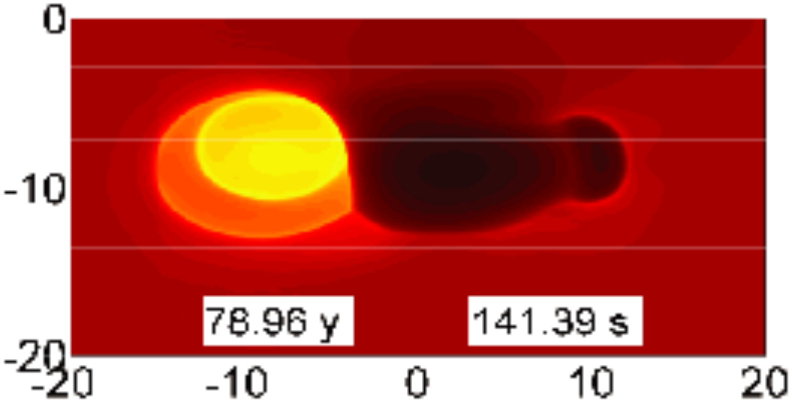
Modeling Approaches That Reproduce a Range of Fault Slip Behaviors: What We Have and What We Need

Nadia Lapusta

California Institute of Technology





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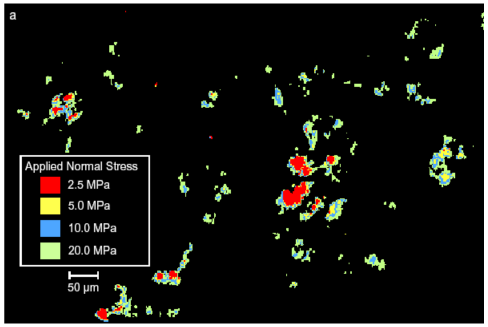

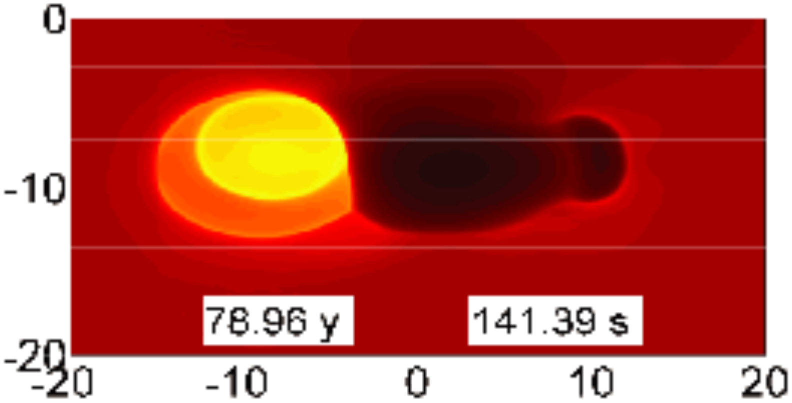

> **“Essentially, all models are wrong, but some are useful.”**
>
> **George E. P. Box**

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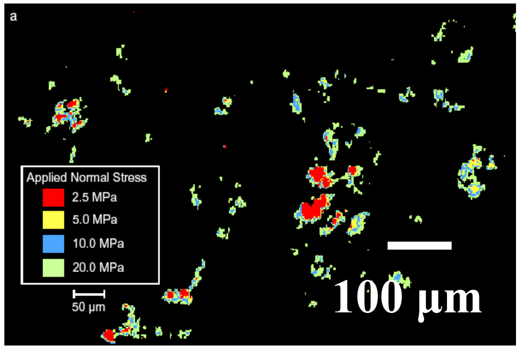
Fault deformation modeling is multiscale on several levels

Multiscale Aspect I

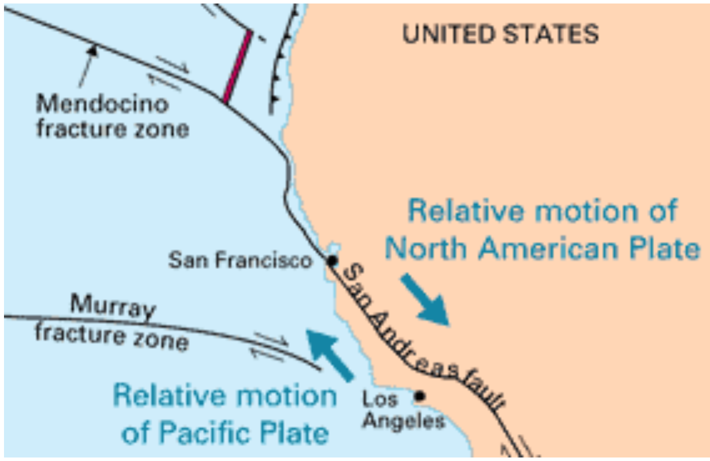
Constitutive response of a finite-width shear zone or asperity populations on a frictional interface



Multiscale Aspect II

Spontaneous slip accumulation on a planar interface under slow loading assuming simple (elastic) bulk

10^9-10^{10} s slow loading / aseismic slip / slow deformation
10^5-10^6 s accelerating nucleation process
10 -100 s duration of a large inertially-controlled event
10^{-3}-10^{-1} s variation of stress and slip rate at rupture front



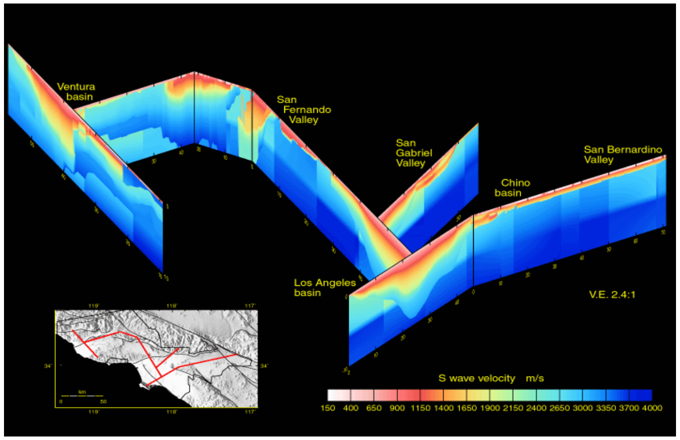
Multiscale Aspect III

Heterogeneous damaged temperature- and pressure-dependent visco- poro- elasto- plastic bulk material;

Locally non-planar shear zone with varying thickness.

Multiscale Aspect IV

Hierarchy of shear zones, interaction between them; large-scale fault system structure



⇒ **Need appropriately formulated laws, multiple physical inputs, and advanced numerical methods**

Fault constitutive law

Multiscale Aspect I

Constitutive response of a finite-width shear zone or asperity populations on a frictional interface

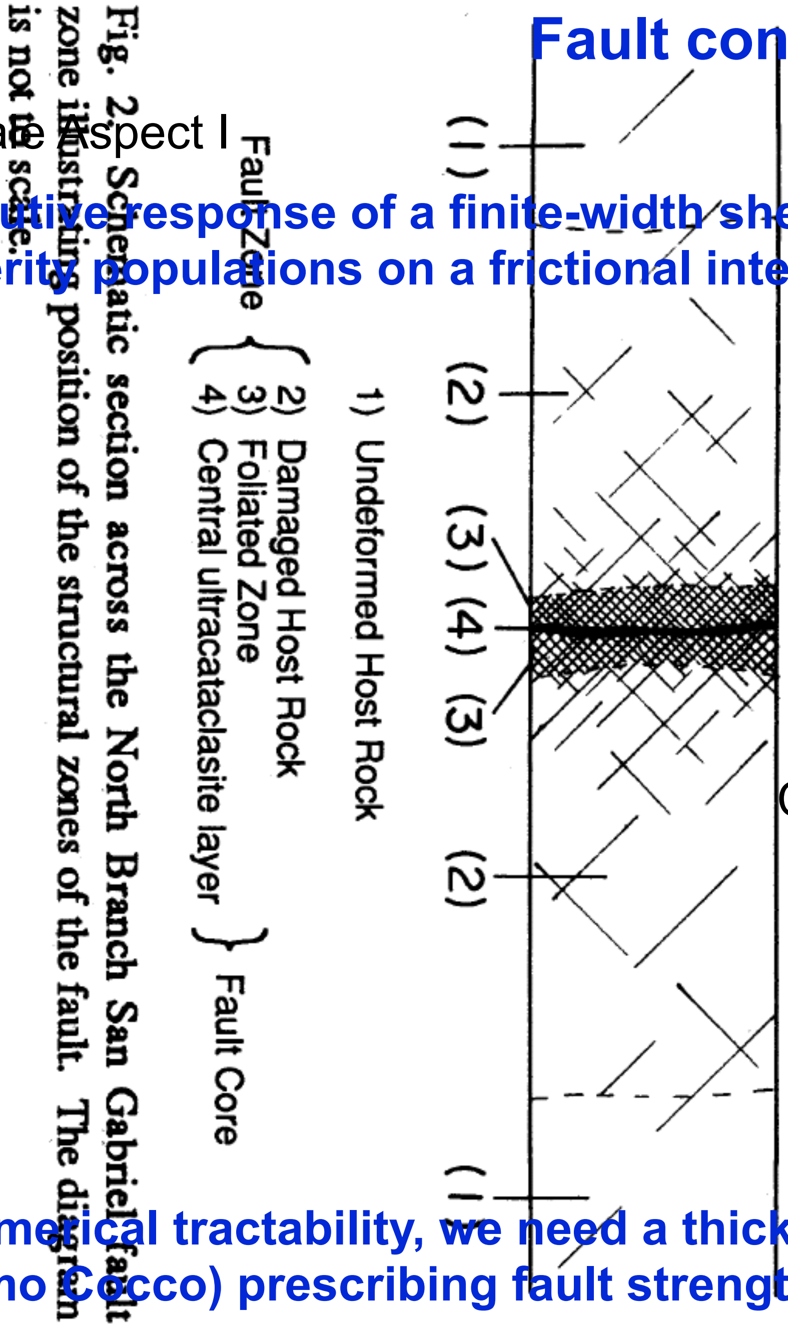
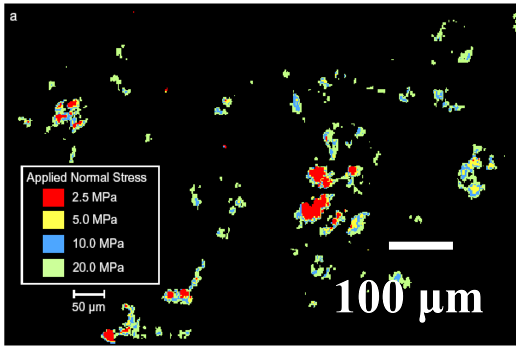


Fig. 2. Schematic section across the North Branch San Gabriel fault zone illustrating position of the structural zones of the fault. The diagram is not to scale.

Chester et al., 1993



Dieterich and Kilgore, 1994

For numerical tractability, we need a thickness-averaged law (recall presentation by Massimo Cocco) prescribing fault strength:

$$\tau = f\,(\delta, V, \theta_i, T, \ldots, \sigma, p)$$

Major advance: standard rate and state friction laws

Laboratory-derived (Dieterich, Ruina, Blanpied, Marone, Tullis and others, based on earlier work of Scholz and others)

for slip velocities small (~ 10^{-9} – 10^{-2} m/s) compared to the seismic range.

Unique tool for simulating earthquake cycles in their entirety,

from accelerating slip in slowly expanding nucleation zones

to dynamic rupture propagation (***turn into linear slip weakening***)

to post-seismic slip and interseismic creep

to fault restrengthening between seismic events.

$$\tau = \bar{\sigma} f = (\sigma - p)[f_o + a \ln \frac{V}{V_o} + b \ln \frac{V_o \theta}{L}]; \quad \frac{d\theta}{dt} = 1 - \frac{V\theta}{L}$$

A number of additional important effects

Dilatancy (another state variable) and associated pore-pressure effects

Rapid shear heating and associated changes, mostly weakening

Quasi-static shear heating and associated changes, similar to rate dependence

Dependence on the shear layer structure and composition

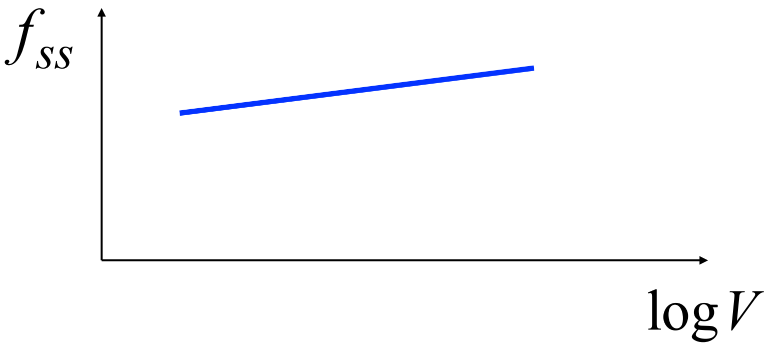
Issues with the proper state-evolution law; multiple state variables

Evolution of shear resistance in response to normal stress changes

$$\tau / \bar{\sigma} = f = f_o + a \ln \frac{V}{V_o} + b \ln \frac{V_o \theta}{L}; \quad \frac{d\theta}{dt} = 1 - \frac{V\theta}{L}$$

$$V \text{ constant}, \ \theta_{ss} = L / V, \ \tau_{ss} / \bar{\sigma} = f_{ss} = f_o + (a-b) \ln(V / V_o)$$

$a - b > 0$, velocity strengthening



Aseismic slip under slow loading

Factors that favor VS in experiments:

High temperatures (▯ 300▯ C)

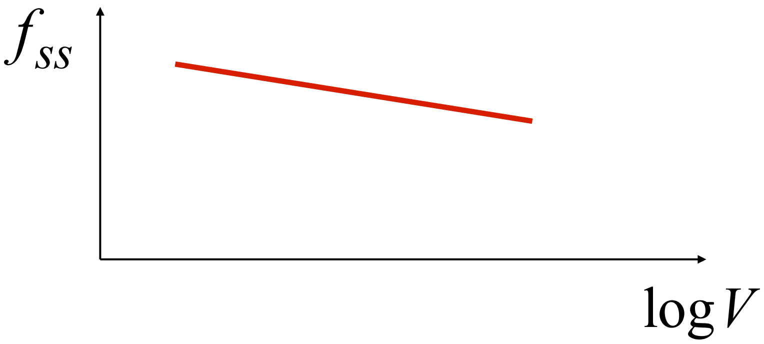
Aseismic faults below certain depth

Low effective normal stress

Shallow VS layers

Certain types of rocks and fault gouge

$a - b < 0$, velocity weakening



Seismic slip in *large enough* regions

Aseismic slip in smaller regions

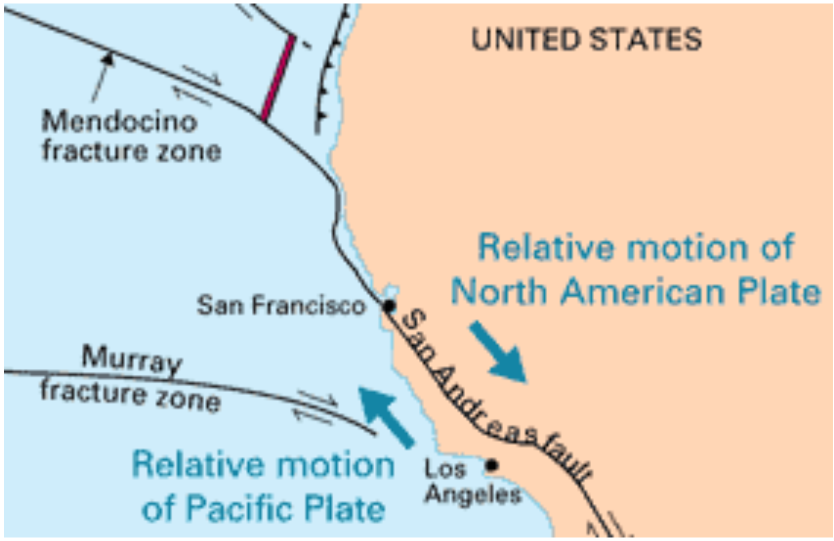
Estimates of the critical size

(Rice and Ruina, 1983; Rice, Lapusta, Ranjith, 2001; Rubin and Ampuero, 2005):

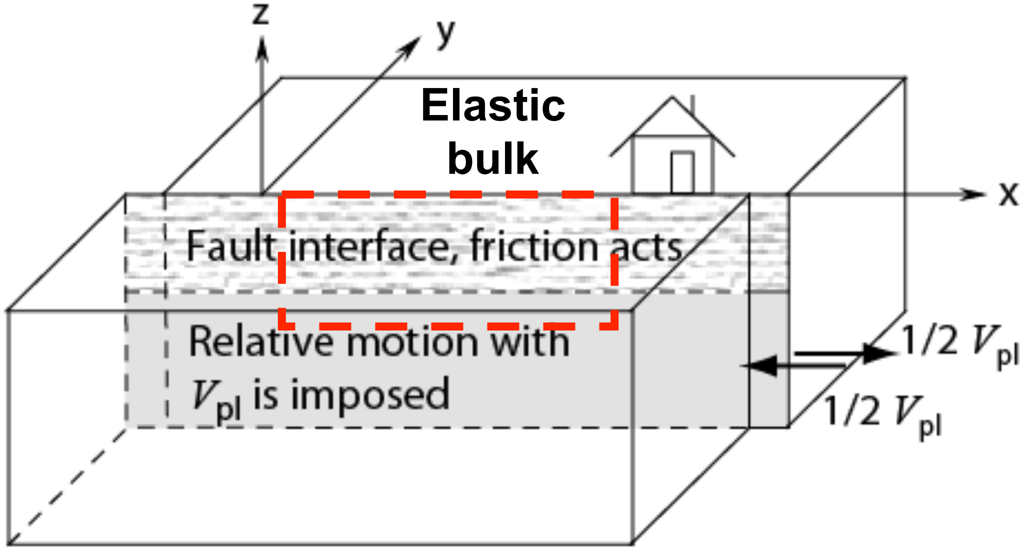
$$h^* \propto \frac{\text{shear modulus} \times \text{char. slip}}{\text{normal stress} \times F(a, b)}$$

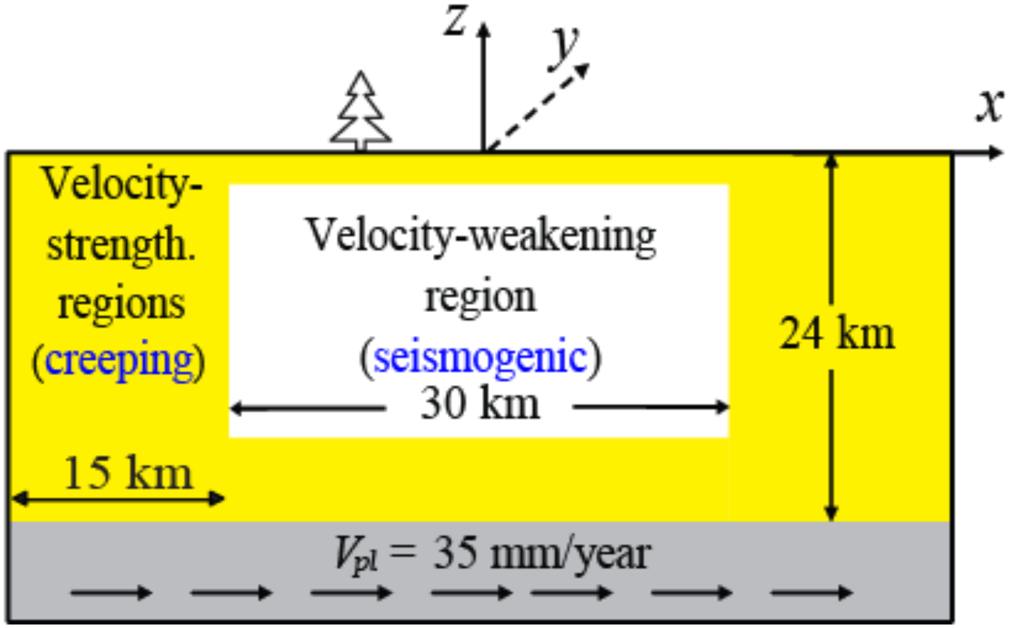
$$h^*_{RR} \propto \frac{\mu L}{\bar{\sigma}(b-a)}; \quad h^*_{RA} \propto \frac{\mu L}{\bar{\sigma}(b-a)^2 / b}$$

Model of a single seismogenic segment



http://pubs.usgs.gov/publications/text/dynamic.html





We use **boundary integral method** to simulate ***spontaneous*** slip accumulation on the interface by solving the system

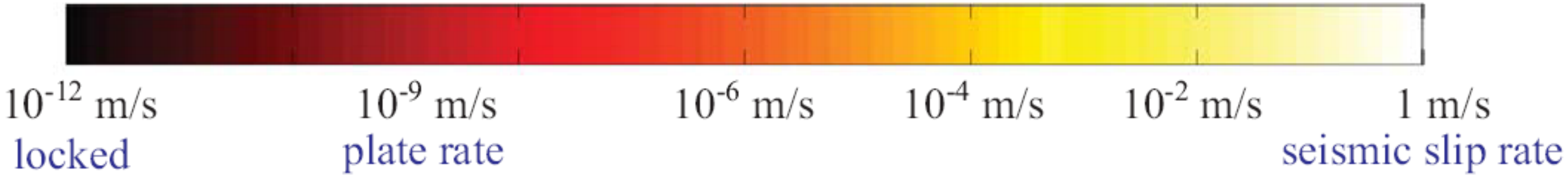
Shear traction on the fault =

Friction strength of the fault

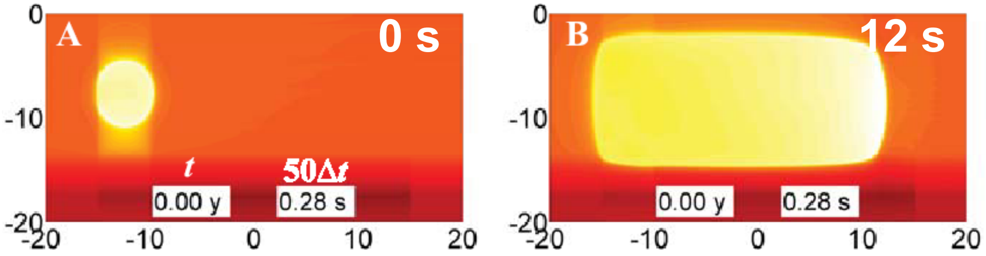
Example: 3D simulation that resolves all stages of earthquake cycles

Snapshots of relative sliding velocity on the interface

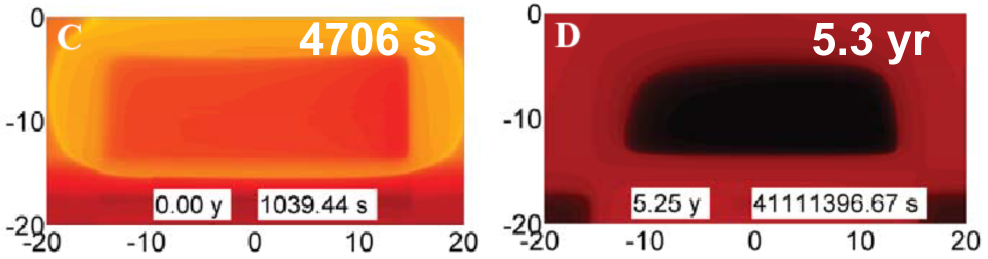
(Lapusta and Liu, JGR, 2009)



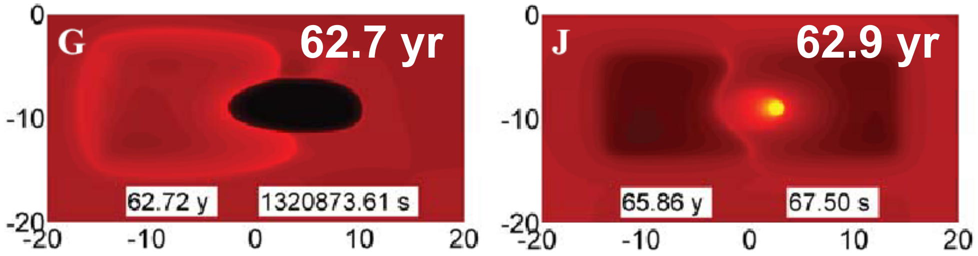
Large earthquake, lasts seconds.
Time steps < 0.01 s.



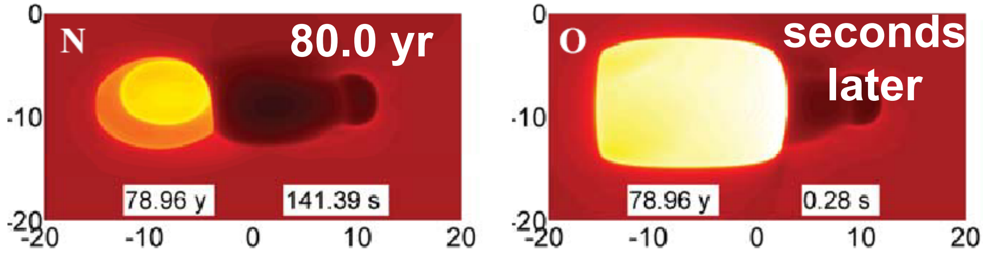
Postseismic slip, interface locks.
Large time steps.



60 years later: Aseismic transients,
small “earthquake”.

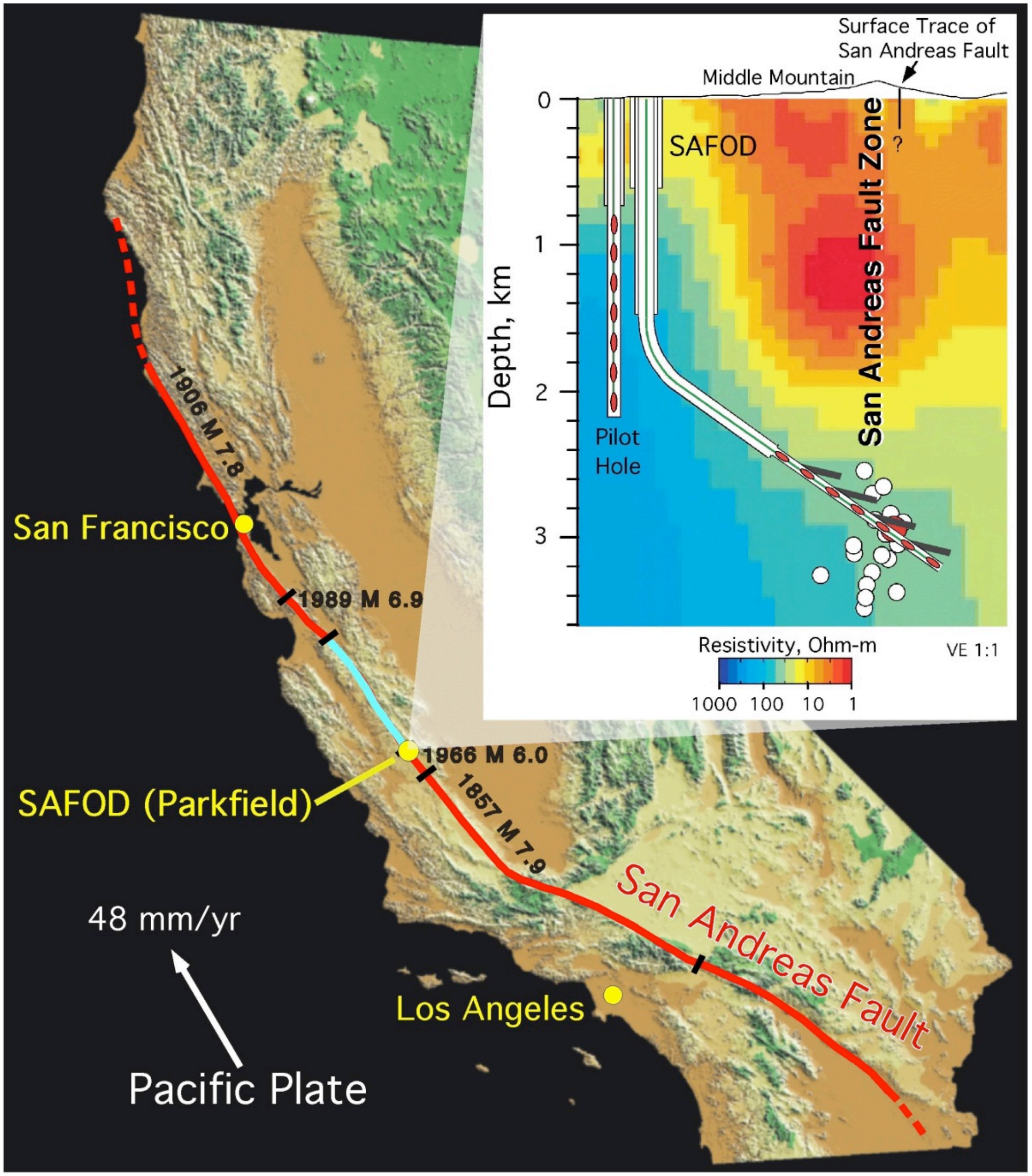


80 years later: Slow nucleation,
fast next large earthquake.



Fully spontaneous solution; all inertial effects are included during seismic events;
variable time stepping, boundary integral formulation.

Application example: Scaling of small repeating earthquakes



Hickman, Zoback, Ellsworth, 2004

Occur on a number of faults;

Have short recurrence times and known locations;

Present a rare predictable opportunity for detailed field observations;

Are targeted by SAFOD (San Andreas Fault Observatory at Depth);

Are used to study:

- fault creeping rates,
- postseismic slip,
- earthquake nucleation,
- earthquake interactions,
- stress drops.

Scaling between recurrence time *T* and seismic moment *M_0*

Nadeau and Johnson, 1998

Observed $T \propto M_0^{1/6}$

Expected $T \propto M_0^{1/3}$

For a circular rupture with constant stress drop $\Delta\tau$ and no aseismic slip:

$$T = \frac{\ddot{A}^{2/3} \quad {}_0^{1/3}}{1.81ì \quad {}_L} \propto M_0^{1/3}$$

μ shear modulus

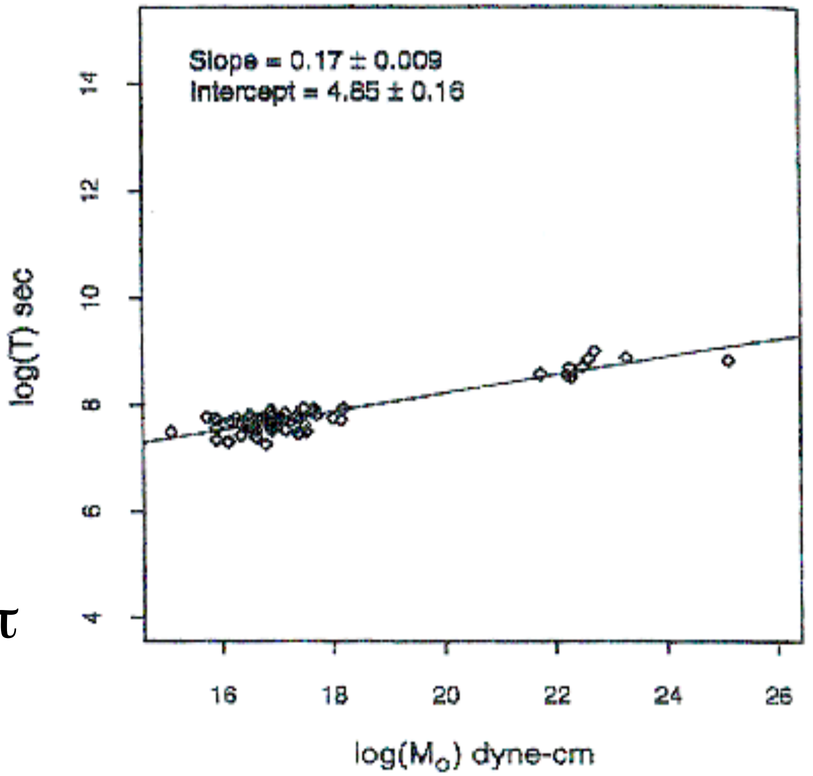
V_L loading velocity

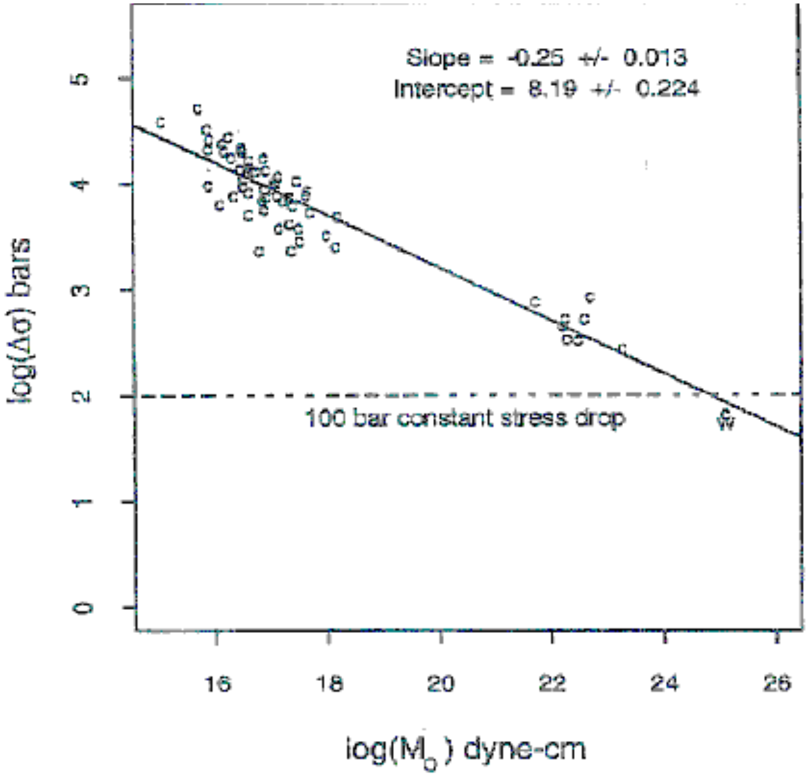
Nadeau and Johnson (1998):

Stress drops may be larger for smaller events (**as large as 2000 MPa = 2 GPa, which is not supported by observations**).

Beeler et al. (2001):

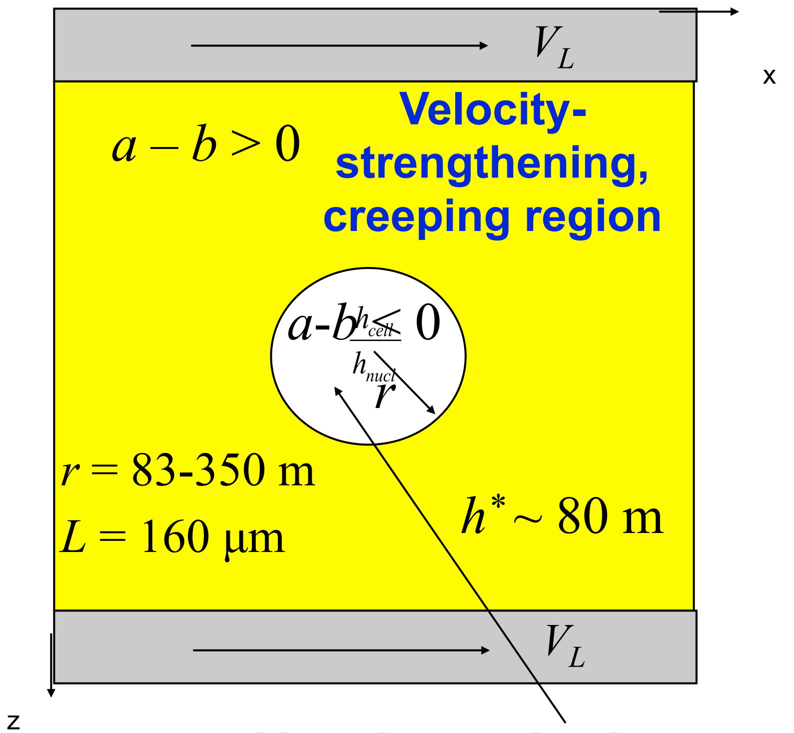
Aseismic slip in a spring-slider model due to complex friction law





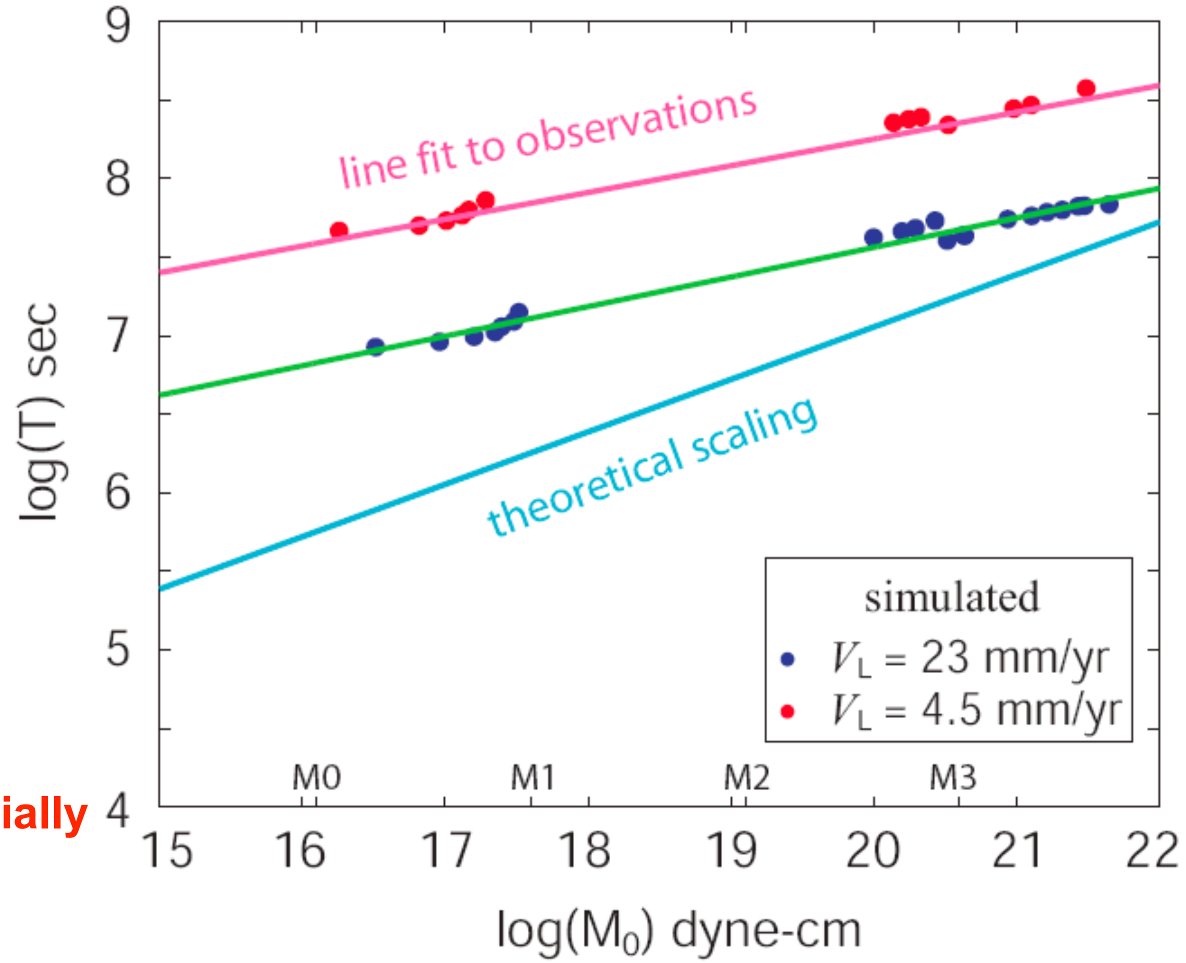
Model that explains the scaling:
Velocity-strengthening region with velocity-weakening patch

(Chen and Lapusta, JGR, 2009)



Velocity-strengthening, creeping region

Velocity-weakening, potentially seismogenic patch



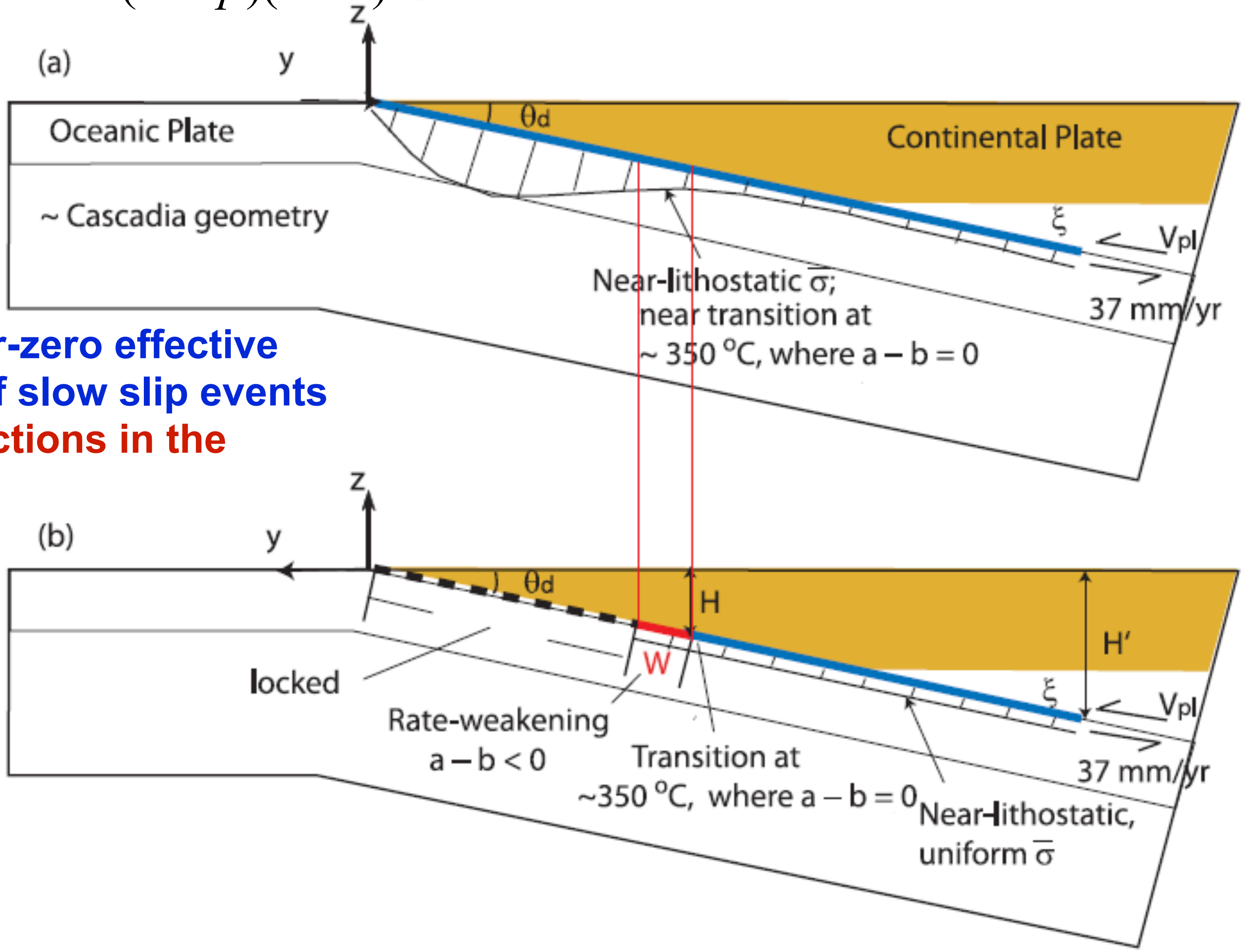
Significant aseismic slip occurs at the locations of repeating earthquakes.

Earthquakes have typical stress drops of the order of 1-10 MPa.

Used this model to reproduce the response of repeaters to 2004 Parkfield earthquake (**Kate Chen, Bürgmann, Nadeau, Ting Chen, Lapusta, EPSL, 2010**)

Standard rate and state friction, models of slow slip due to large pore pressure and hence large nucleation sizes (Liu and Rice, 2005-2009)

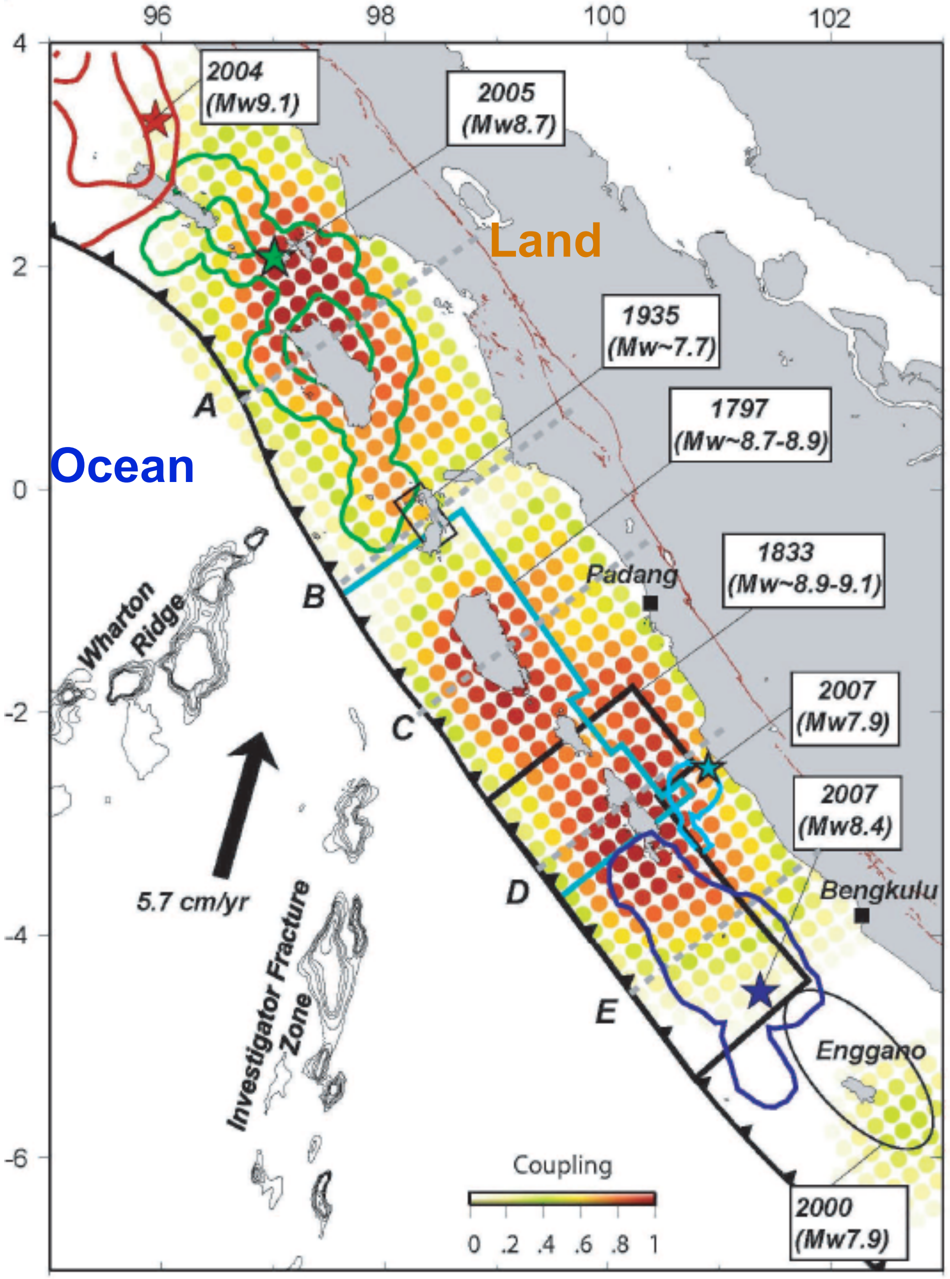
$$h^*_{RR} \propto \frac{\mu L}{(\sigma - p)(b-a)}; \quad h^*_{RA} \propto \frac{\mu L}{(\sigma - p)(b-a)^2/b}$$



Critical ingredient: near-zero effective stress at the location of slow slip events due to dehydration reactions in the subducting slab.

Standard rate and state friction + heterogeneity in friction properties
Example: Relation between earthquakes and interseismic coupling

(Kaneko, Avouac, Lapusta, Nature Geoscience, 2010)



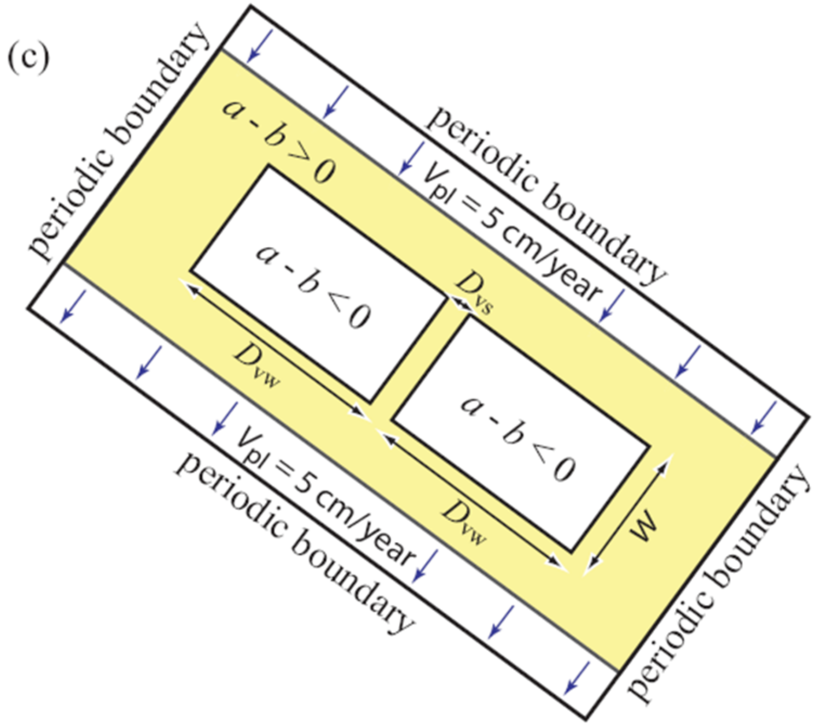
Chlieh, Avouac, Sieh, Natawidjaja, and Galetzka, 2008

Sunda megathrust in Sumatra

Spatially variable coupling

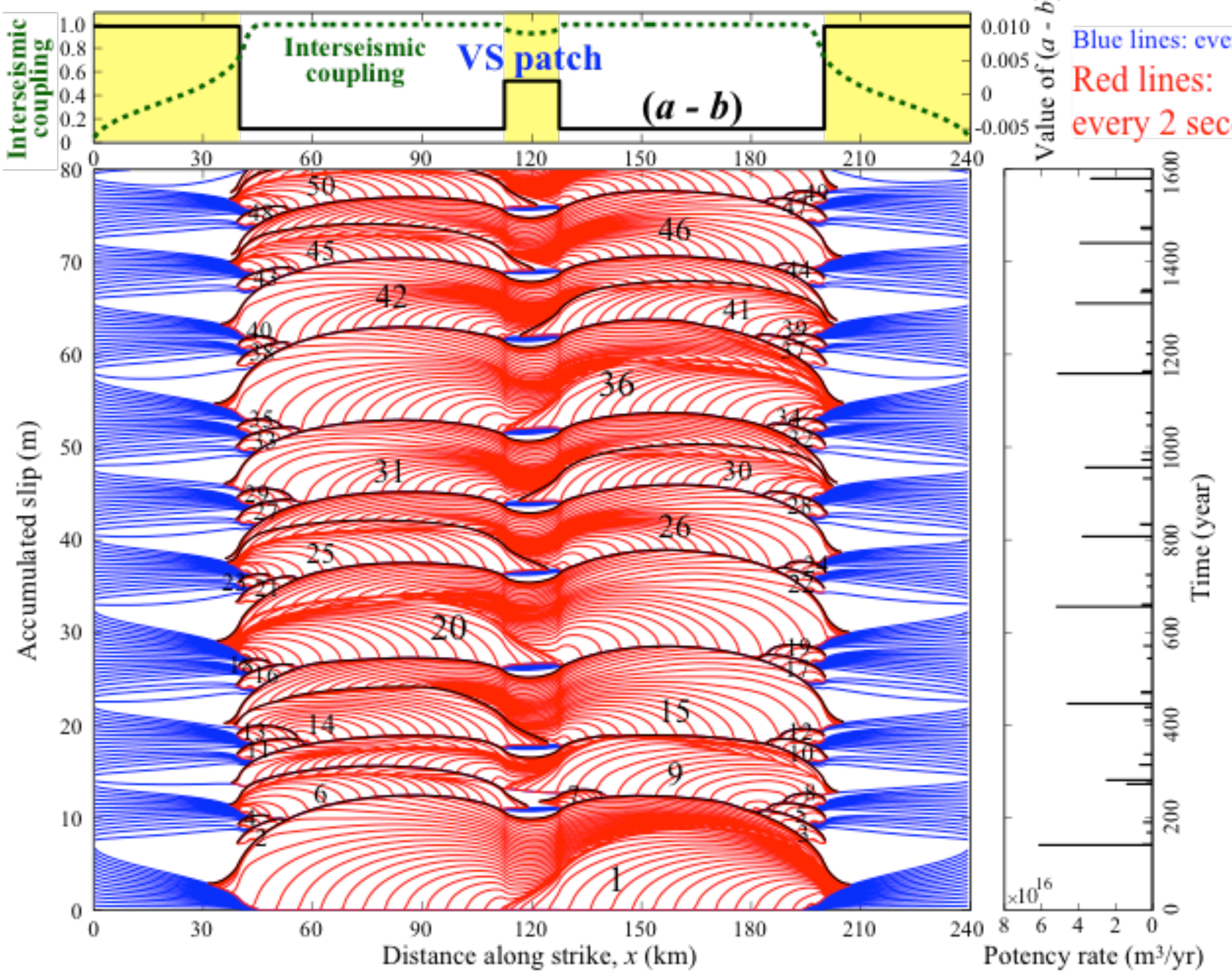
Earthquakes are stopped at what appears to be permanent barriers

Earthquake overlap and cluster in time



Simulated long-term fault behavior

(Kaneko, Avouac, Lapusta, Nature Geoscience, 2010)



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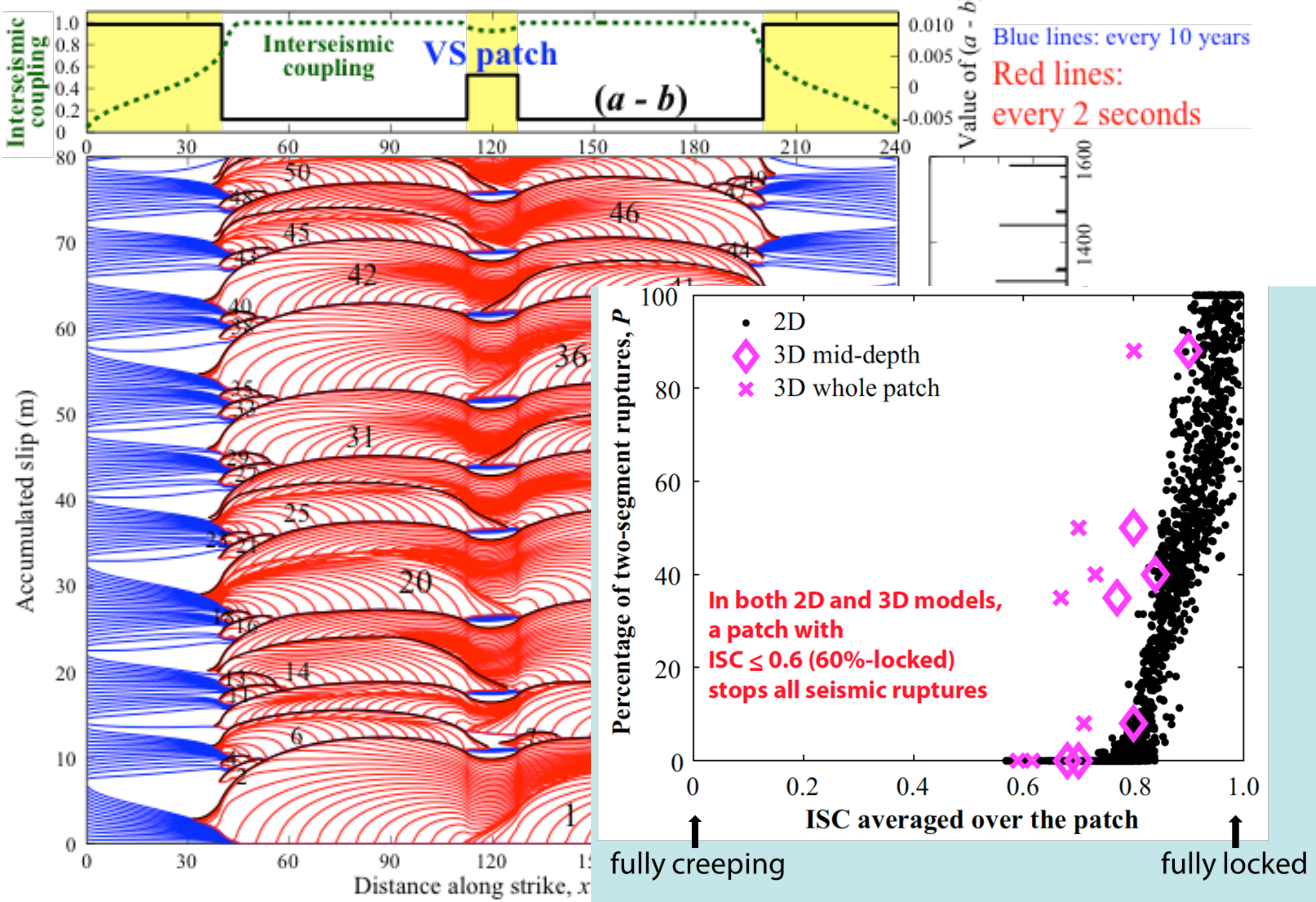


Blue lines: every 10 years

Red lines: every 2 seconds

In both 2D and 3D models, a patch with ISC ≲ 0.6 (60%-locked) stops all seismic ruptures

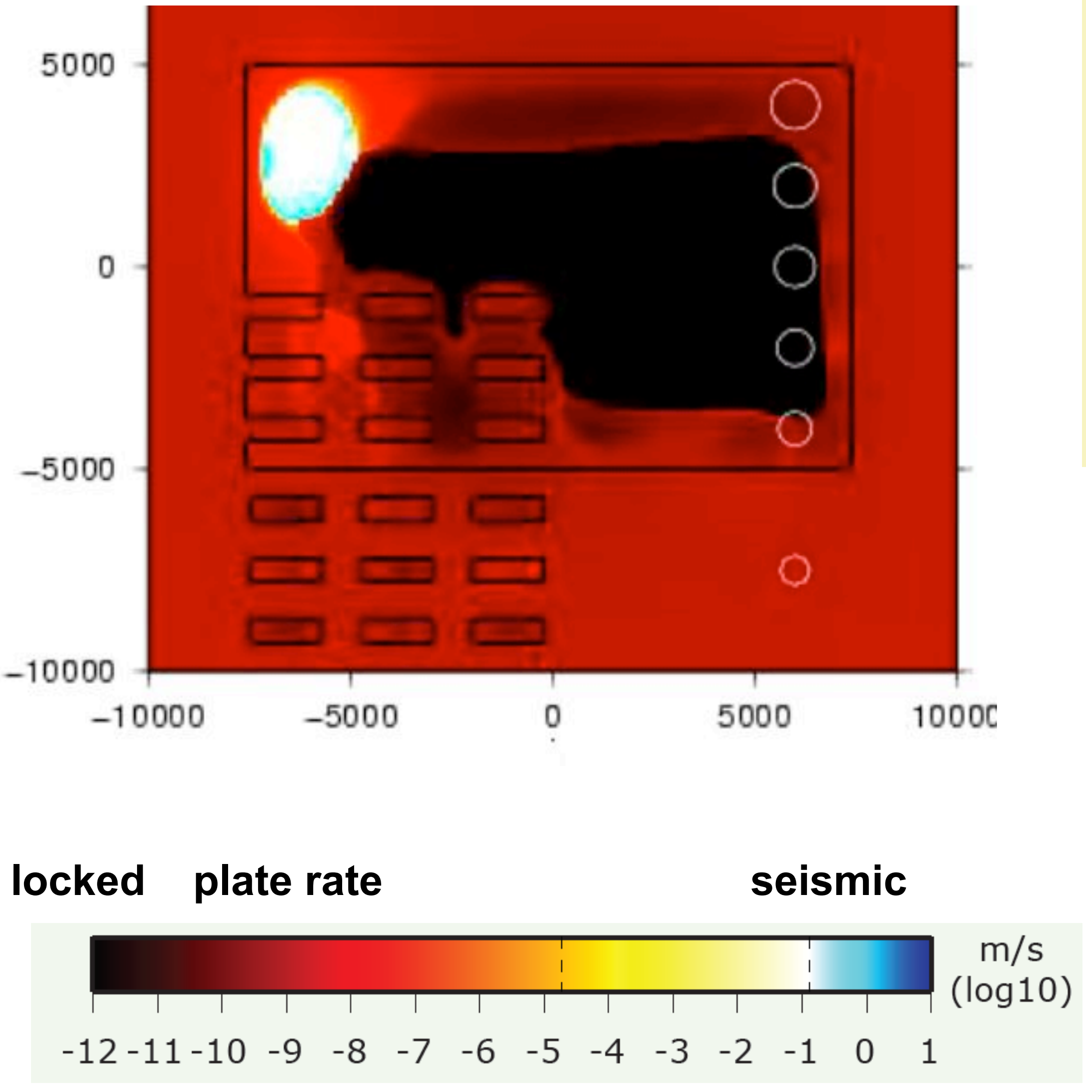
fully creeping

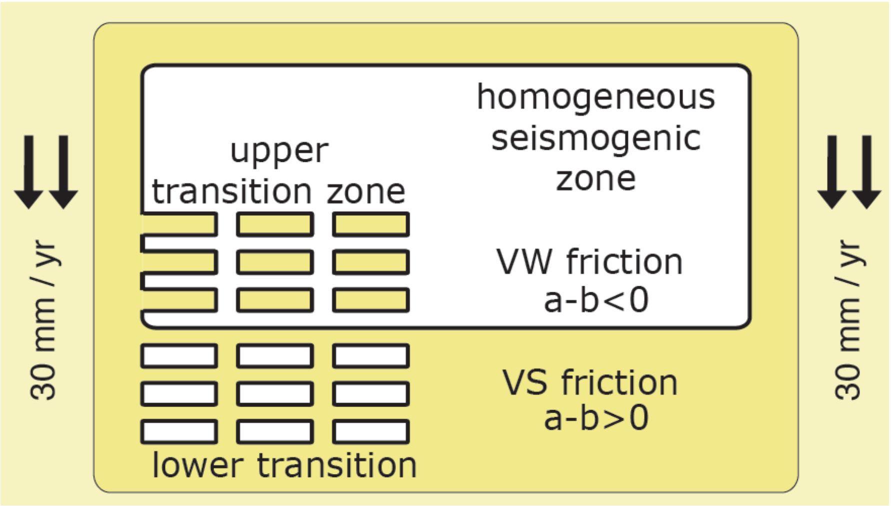
fully locked

Standard rate and state friction + heterogeneity in friction properties
How about heterogeneous properties near transition?

(Barbot, Lapusta, and Avouac, work in progress)

Movie of slip rate on the fault





All inertial effects (wave propagation) included during simulated earthquakes.

Some heterogeneity would likely be needed to produce tremor.

Properly chosen patterns may lead to coherently propagating slow slip.

Rate and state friction,
behavior of a velocity-strengthening region with asperities

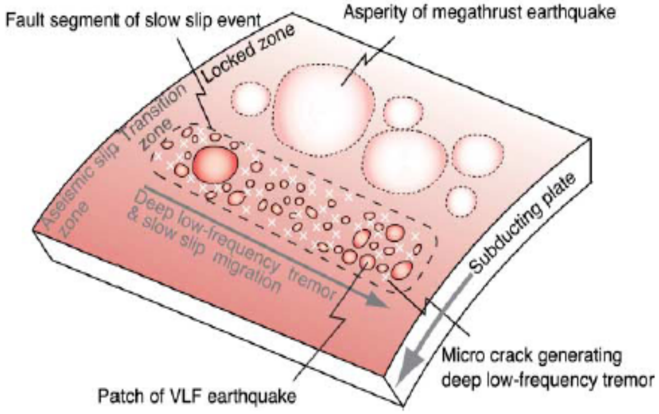
Perfettini and Ampuero, 2009; presentation by Pablo Ampuero

Slow slip occurs as unsteady behavior of a perturbed velocity-strengthening layer.

Tremor is modeled as asperities (velocity-weakening?) inside that region that interact through postseismic slip.

Important difference: Models with dilatancy or non-monotonic steady-state friction produce slow slip by stabilizing instability of velocity-weakening regions.

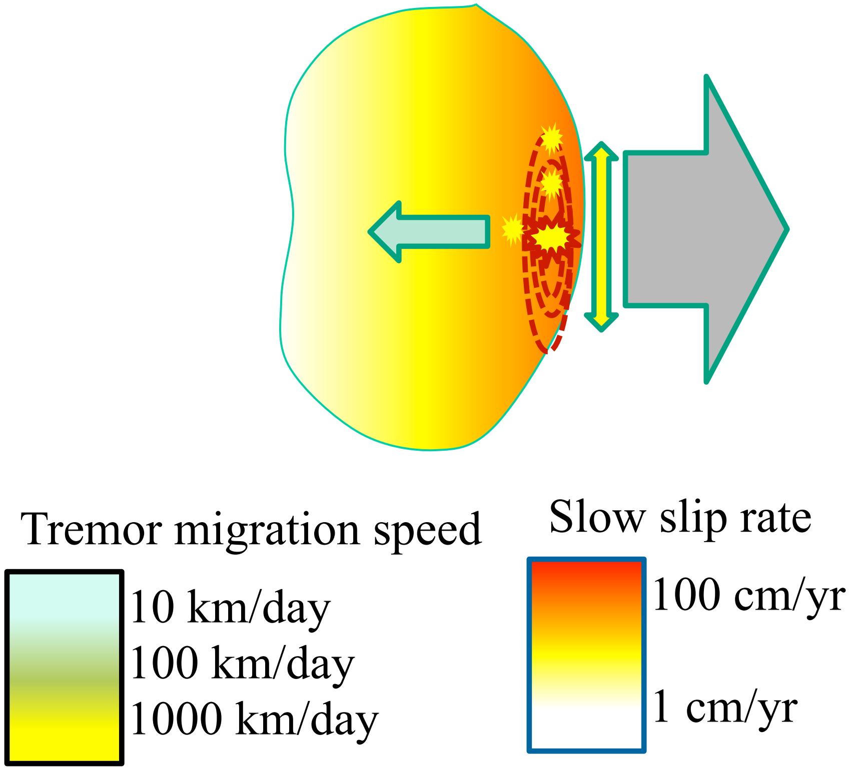
Here slow slip is produced by perturbing velocity-strengthening regions.



Ito et al (2007)

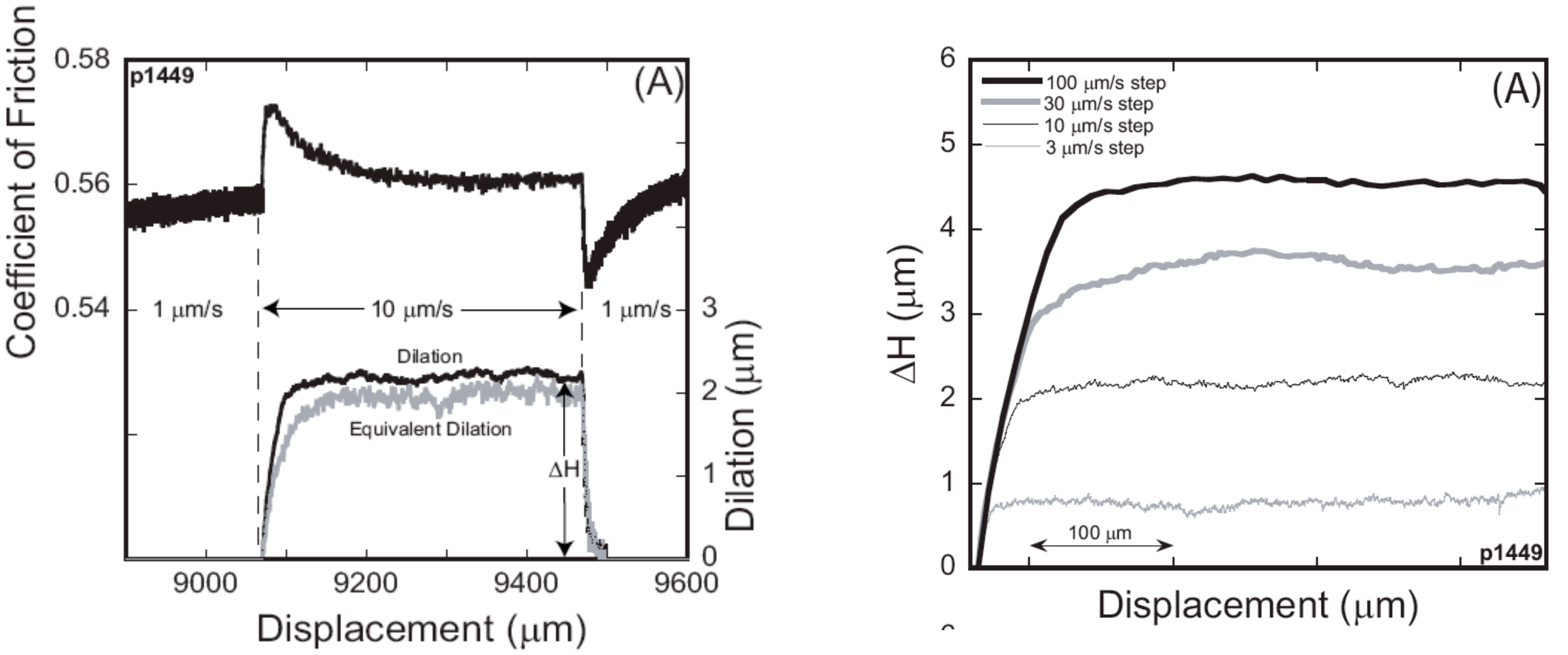
Migration speeds of tremor are related to local slow slip rates.

Possible modification: Asperities within velocity-weakening region.



Standard rate and state friction + dilatancy/compaction

(Rice, 1975; Rice and Simons, 1976, Rudnicki, 1979; Segall and Rice, 1995; Segall and Rubin, 2007-09 AGU; Segall et al, 2010 in press; Liu and Rubin, in press; Suzuki and Yamashita, 2008, AGU; JGR, 2009)



Samuelson, Elsworth, Marone (2009)

Faster shear of compacted gouge → increase in pore space → decrease in pore pressure → increase in effective normal stress → stabilizing effect.

Allows to match propagation speeds of slow events (talk by Paul Segall).

Well-known phenomenon, need more experiments for relevant conditions (talk by Nick Beeler).

Theories, experimental evidence:
Fault resistance at fast slip rates may be significantly smaller

Shear heating mechanisms

Flash heating of contact asperities at small slips (Bowden and Thomas, 1954, Lim and Ashby, 1987, Molinari et al., 1999, Rice, 1999; Beeler and Tullis, 200

Thermal pressurization of pore fluids in the fault zone (Sibson, 1973; Lachenbruch, 1980; Mase & Smith, 1985, 1987; Se Andrews, 2002; Bizzarri and Cocco, 2006; Rice, 2006; and others)

Partial or full melting of the shearing layer (Jeffreys, 1942; McKenzie and Brune, 1972; Tsutsumi and Shimamoto, 1997; Hirose and Shimamoto, 2005; and others)

Other possibilities

Lubrication by silica gel layer (Goldsby and Tullis, 2003; Di Toro et al., 2004)

Normal stress reduction from elastic mismatch (Weertman, 1963, 1980 and others)

Normal interface vibrations (Brune et al., 1993)

Acoustic fluidization (Melosh, 1979, 1996)

Elastohydrodynamic lubrication (Brodsky and Kanamori, 2001)

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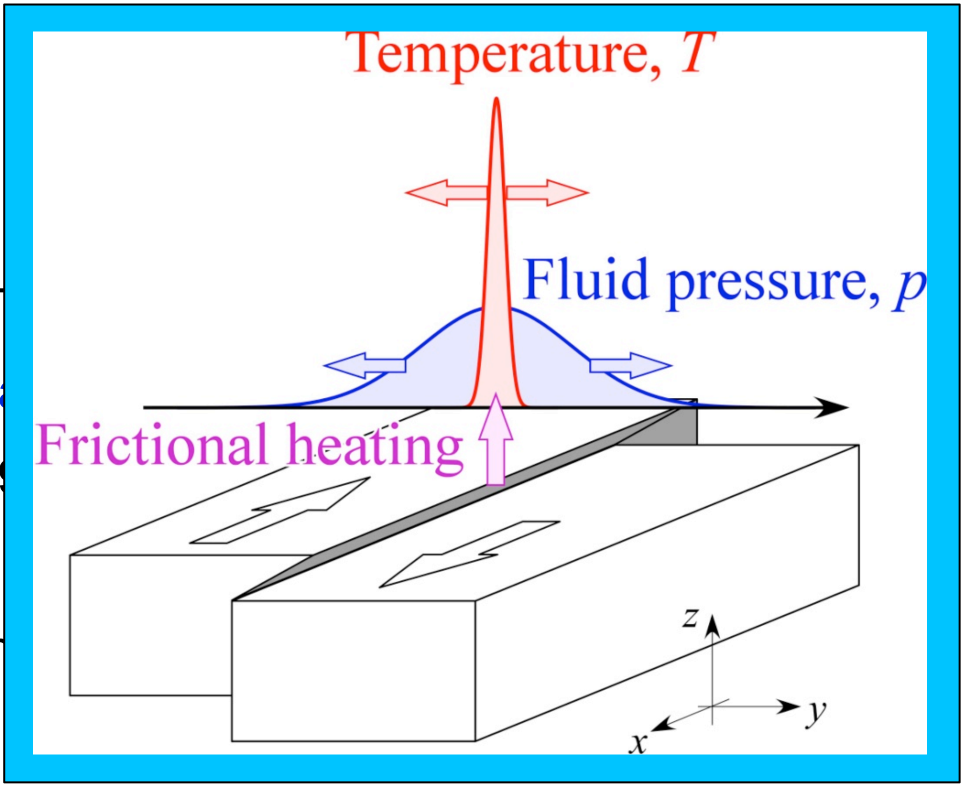

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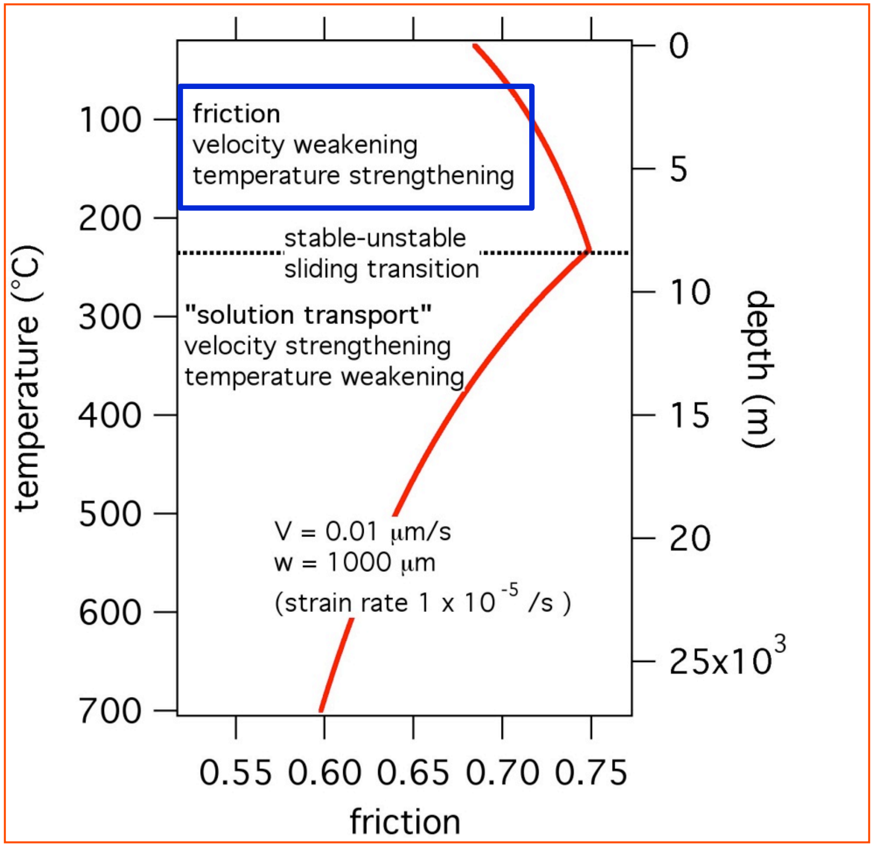
Elastohydrodynamic lubrication (Brodsky ar

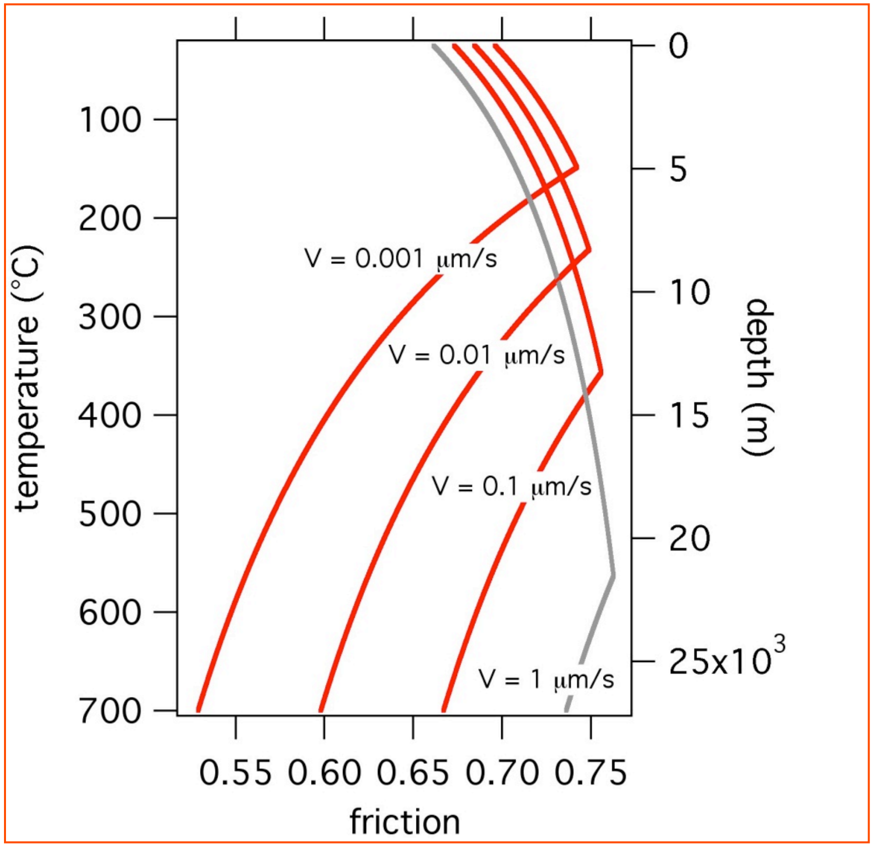
Standard rate and state friction + shear heating effects

Rapid shear heating → flash heating, thermal pressurization, melting → rapid weakening.

Earthquake cycles with temperature and pore pressure evolution due to shear heating (**Noda and Lapusta, JGR, 2010**).

Quasi-static shear heating → temperature–dependent effects similar to rate-dependent effects





(from the presentation by Nick Beeler, after Chester, 1995)

Standard rate and state friction + rate-like temperature effects

(Noda and Lapusta, work in progress)

$$\tau = \bar{\sigma} f = \bar{\sigma}\left[f_o + a\ln\frac{V}{V_o} + b\ln\frac{V_o\theta}{L}\right]; \quad \frac{d\theta}{dt} = 1 - \frac{V\theta}{L}$$

Replace V with

$$Z = V\exp(Q/RT)$$

Absolute temperature

Slip rate

Gas constant

Activation energy

Standard rate and state friction + rate-like temperature effects

(Noda and Lapusta, work in progress)

$$\tau = \bar{\sigma} f = \bar{\sigma}\left[f_o + a \ln\frac{V}{V_o} + b \ln\frac{V_o\theta}{L}\right]; \quad \frac{d\theta}{dt} = 1 - \frac{V\theta}{L}$$

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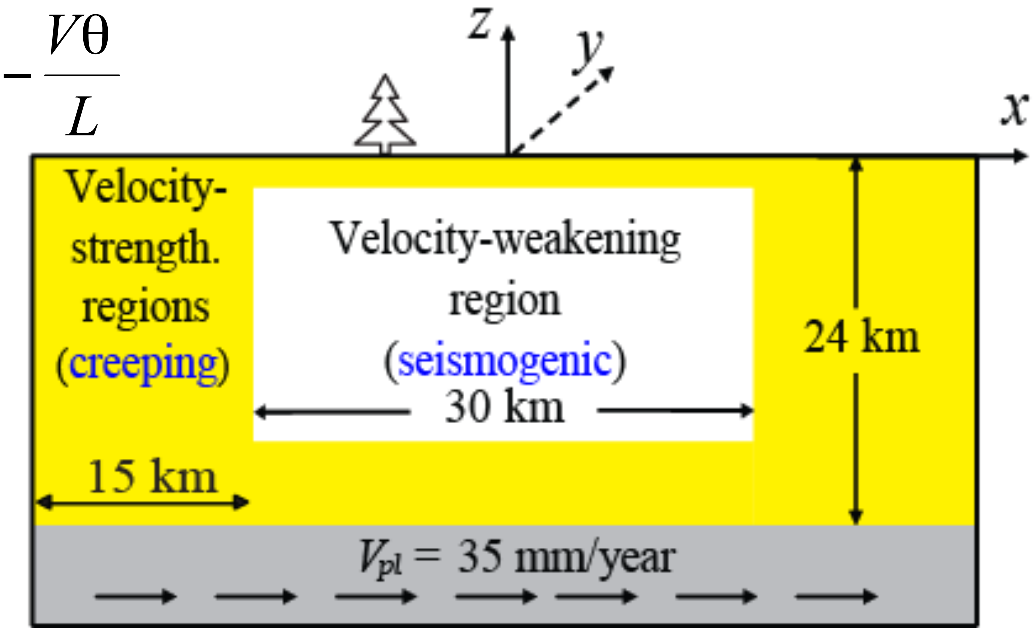

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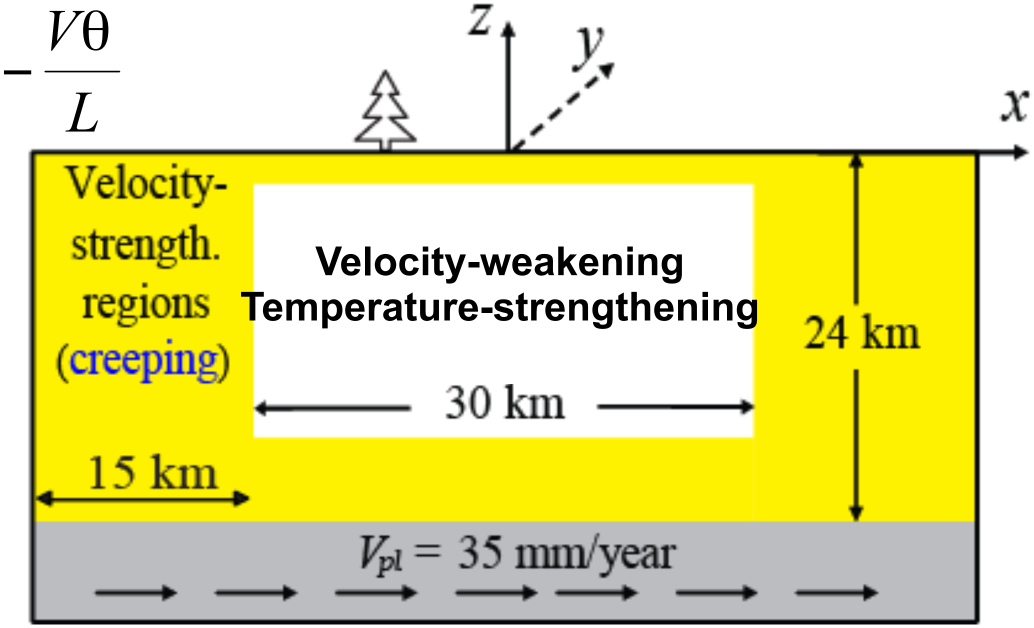

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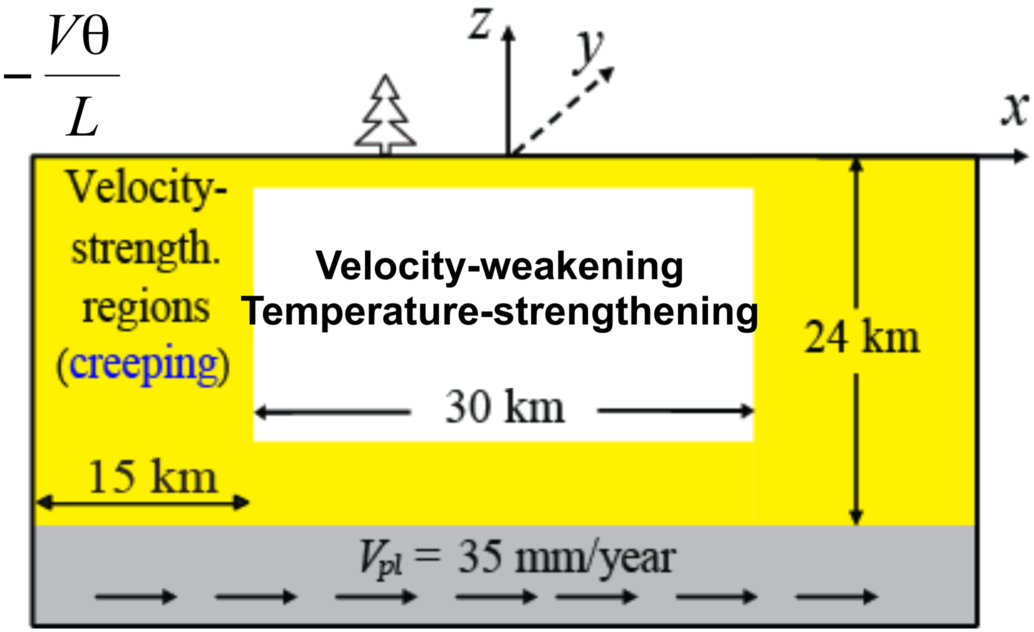
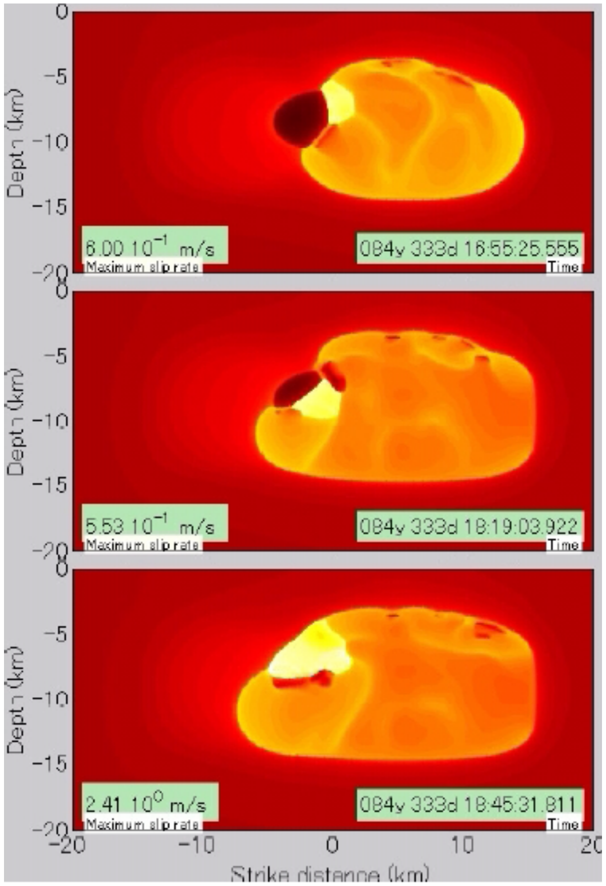
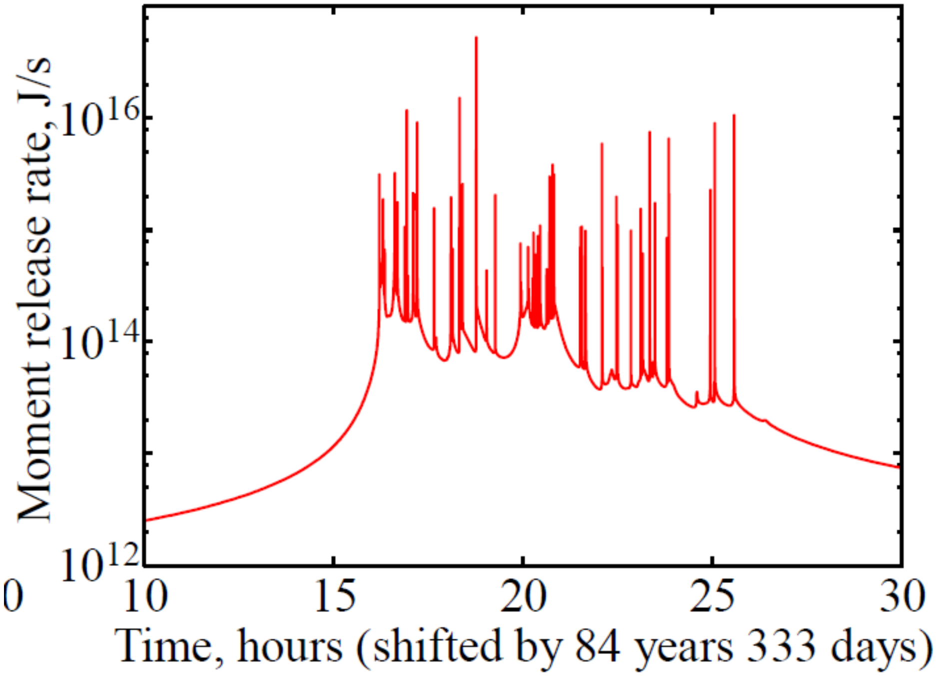
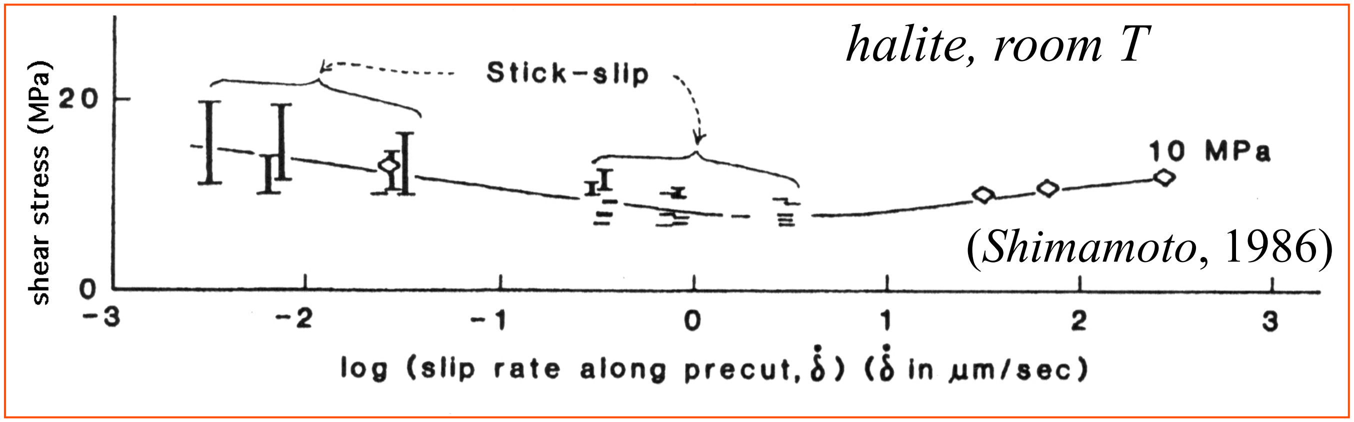




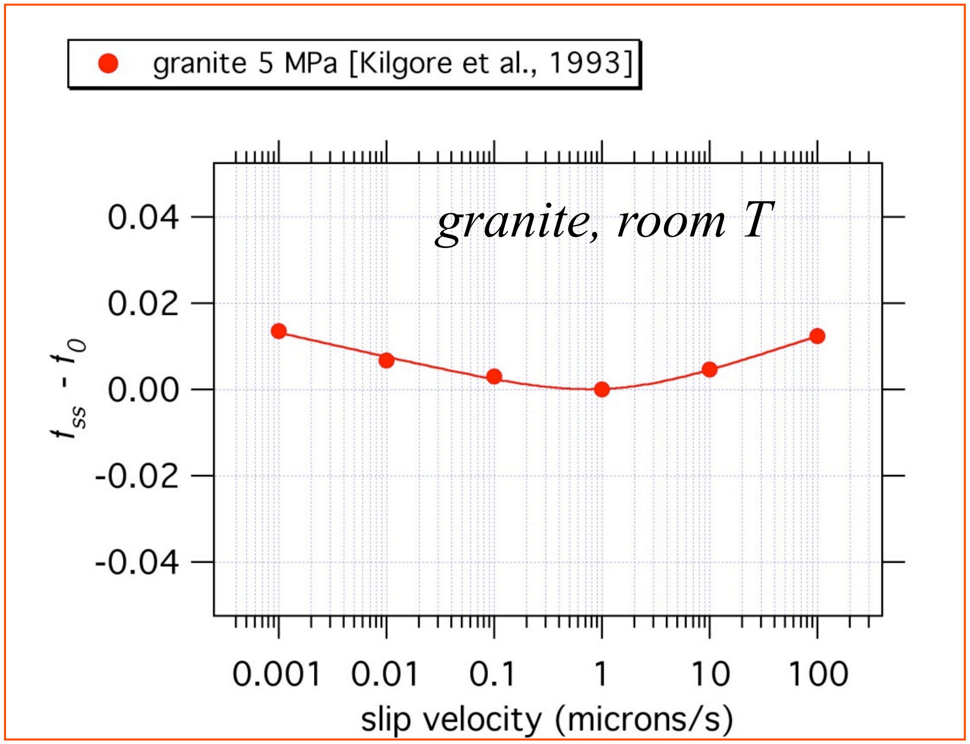


Rate and state friction with non-monotonic steady-state dependence on slip rate



(*Shimamoto*, 1986)

From presentation by
Nick Beeler

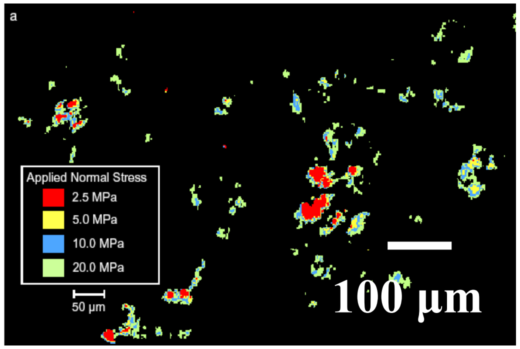


Laws with this ingredient produce slow slip with slip velocity around the transition value (e.g., Shibazaki and Iio, 2003; Shibazaki and Shimamoto, 2007)

Fault deformation modeling is multiscale on several levels

Multiscale Aspect I

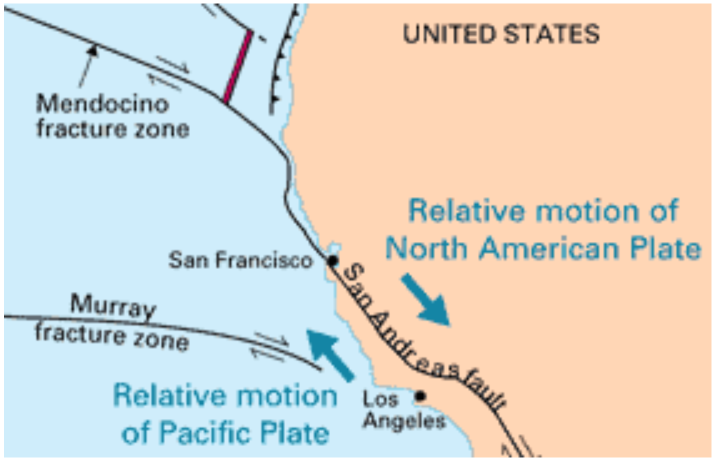
Constitutive response of a finite-width shear zone or asperity populations on a frictional interface



Multiscale Aspect II

Spontaneous slip accumulation on a planar interface under slow loading assuming simple (elastic) bulk

10^9-10^{10} s slow loading / aseismic slip / slow deformation
10^5-10^6 s accelerating nucleation process
10 -100 s duration of a large inertially-controlled event
10^{-3}-10^{-1} s variation of stress and slip rate at rupture front



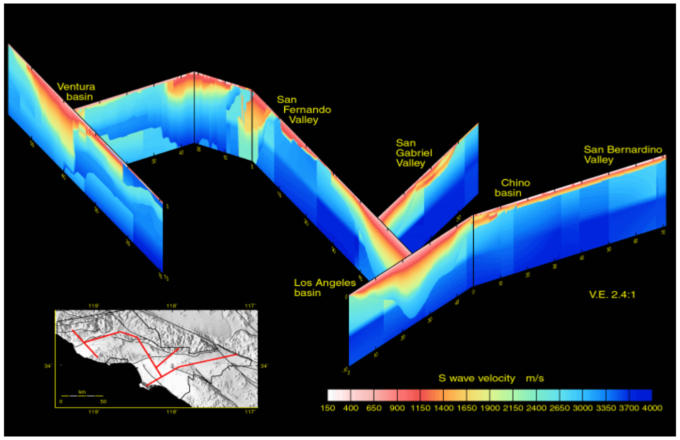
Multiscale Aspect III

Heterogeneous damaged temperature- and pressure-dependent visco- poro- elasto- plastic bulk material;

Locally non-planar shear zone with varying thickness.

Multiscale Aspect IV

Hierarchy of shear zones, interaction between them; large-scale fault system structure



⇒ **Need appropriately formulated laws, multiple physical inputs, and advanced numerical methods**

Simulation methodologies

What we have (an incomplete list)

Quasi-static approaches that reproduce aseismic behavior.

Quasi-dynamic approach that does not incorporate seismic waves (Liu and Rice, studies by Segall, Rubin, and co-authors) but can afford more realistic parameter choices (esp. in 2D).

Fully elastodynamic codes for single dynamic rupture on planar faults (many of them).

Fully elastodynamic codes for single dynamic rupture on rough faults (Duhnam).

Fully elastodynamic models that reproduce the entire earthquake cycle (as presented here) but applicable only to planar faults in homogeneous elastic bulk.

Semi-kinematic approach based on standard rate-and-state (presented by Jim Dieterich).

A good mix of models that work for different purposes and complement each other.

What we need

On the way: Finite-element-based models that would be able to simulate earthquake cycles while incorporating bulk and geometric complexity (e.g., depth dependence, inelasticity) but these approaches would be much more computationally intensive (e.g., Kaneko, Lapusta, Ampuero, 2010; Aaggard, Surendra, Ampuero, Lapusta, work in progress; other groups).

Multiscale/hybrid approaches that allow to simulate large-scale fault structures while resolving small-scale physics in the needed places.

Model ingredients

What we have

Models based on rate and state framework are capable of reproducing the entire spectrum of fault slip behavior and its interaction, from stable creep to regular earthquakes, to aftershocks and afterslip, to slow slip events and perhaps tremor.

Models that incorporate fluid effects (fluid overpressure and dilatancy) and their interplay with thermal pressurization seem to be the most robust and well-supported, incorporating both slow slip and large earthquakes.

Tremor is not yet as well-modeled. It can be envisioned as a by-product of slow slip, presumably due to some compositional or structural heterogeneity, with migration patterns consistent with underlying patterns of slow slip.

Ideas about the importance of bulk deformation mechanisms at the location of slow slip events and tremor.

What we need (an incomplete list)

More laboratory experiments that systematically explore identified mechanisms and properties – dilatancy, compaction, permeability, rate dependence, temperature dependence – for relevant temperatures, stress conditions, and material compositions.

Proof-of-concept modeling: Can we fully explain a spectrum of slip behavior in a simple and more accessible system, e.g., in the experiments of Jay Fineberg and co-authors?

Understanding how to combine the frictional concepts for faults in damaged elastic media with ideas about bulk deformation mechanisms and geological structure below the seismogenic transition.

More constraints on fault zone composition, structure, and geometry.