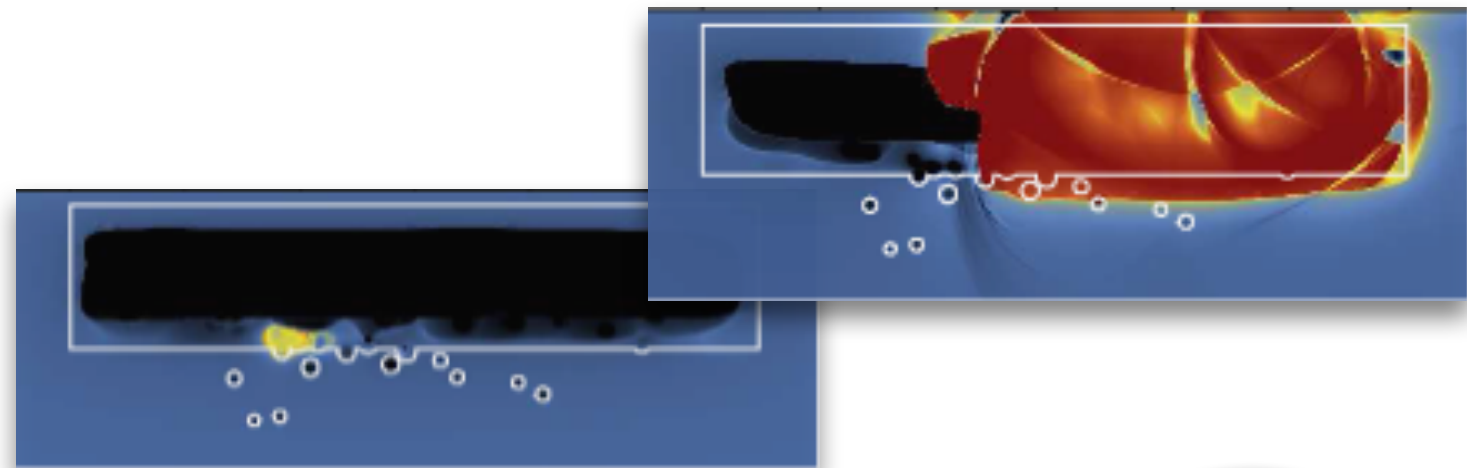
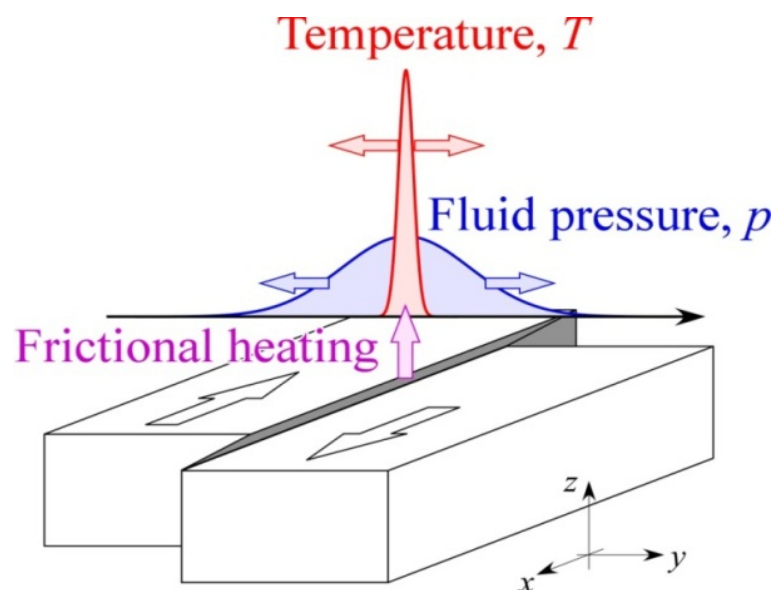


# Coseismic weakening and depth penetration of large earthquakes

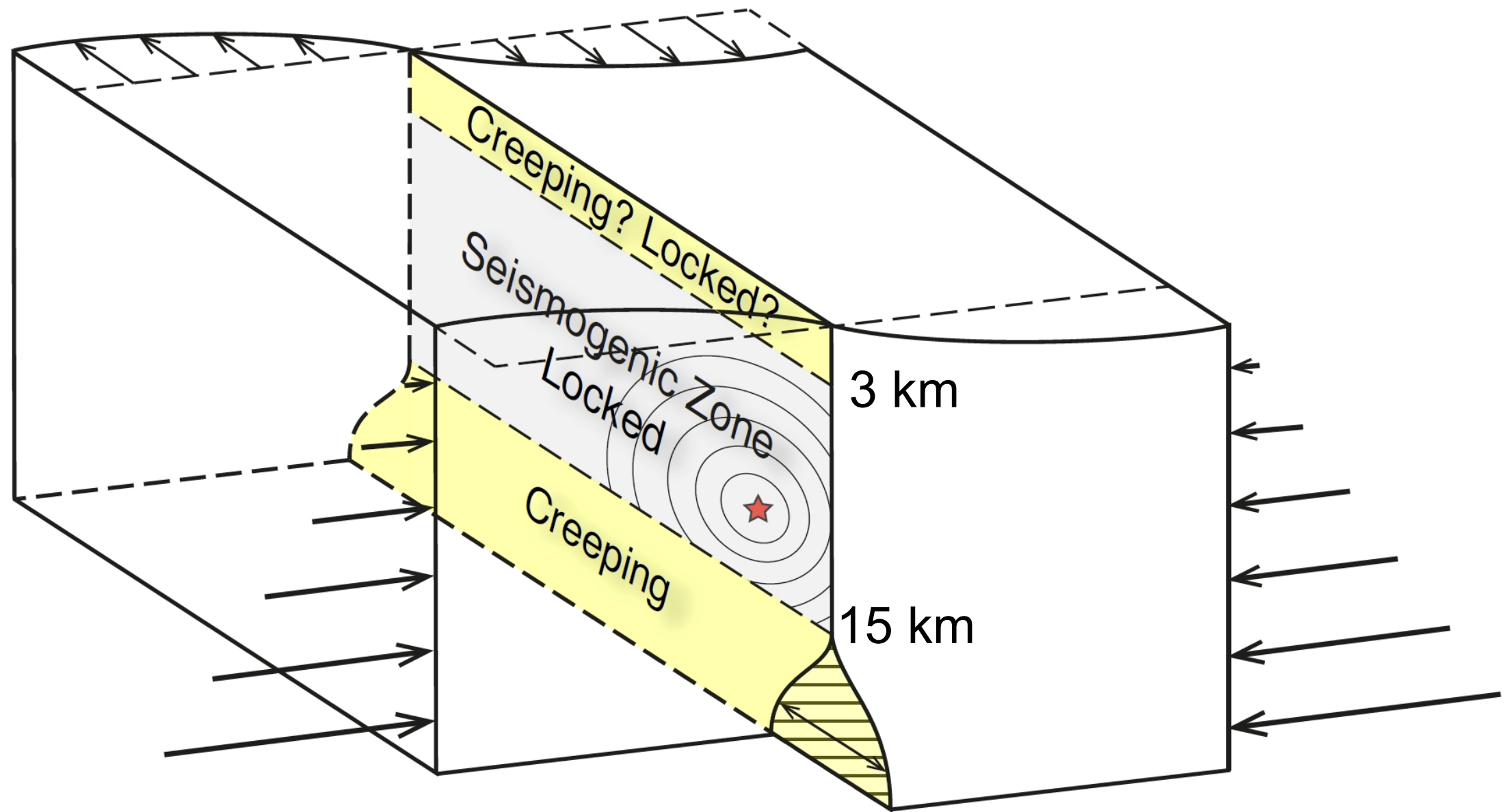
Nadia Lapusta

California Institute of Technology

- Potential dynamic weakening of stable (creeping) areas, thoughts about 2011 Tohoku
- Penetration of large events below the seismogenic zone

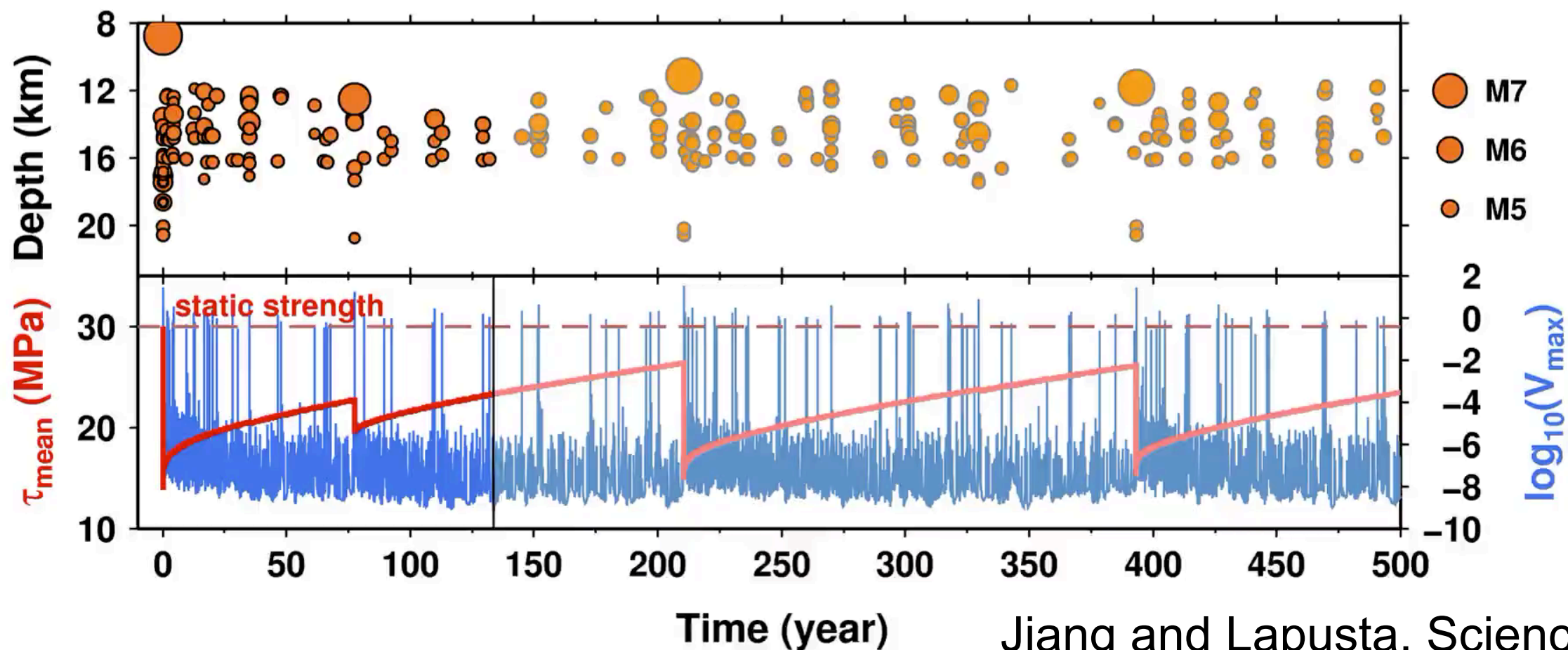
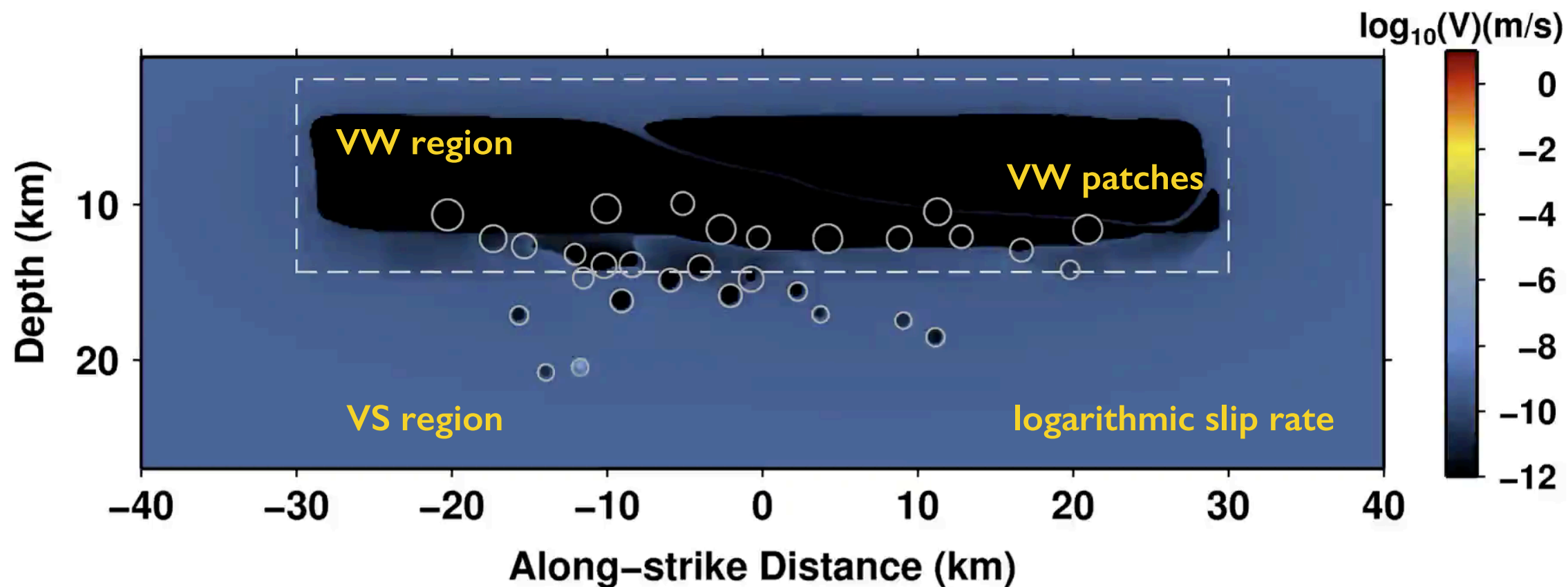


# Basic model of a plate-boundary strike-slip fault



Numerical simulation methodology for **long-term fault slip** punctuated by earthquakes with **all inertial (wave) effects resolved**: Lapusta, Rice, Ben-Zion, Zheng, JGR (2000); Lapusta and Liu JGR (2009); Noda and Lapusta, JGR (2010)

Years: 133 Days: 162 Seconds: 84113.9



# Low-velocity fault frictional resistance: Rate-and-state friction

Laboratory-derived (Dieterich, Ruina, Tullis, Marone, and others)

for **low slip velocities** ( $\sim 10^{-9} - 10^{-3}$  m/s) compared to the seismic range ( $\sim 1$  m/s).

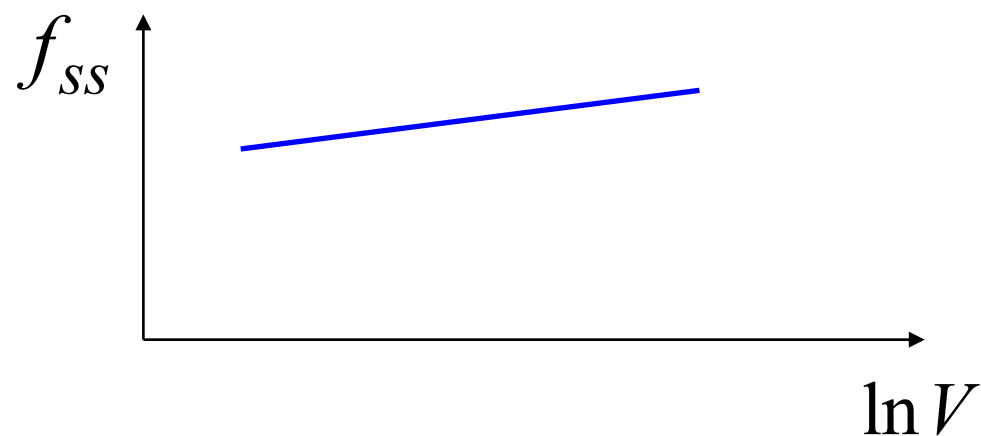
Numerous successful applications: earthquake nucleation, postseismic slip, earthquake triggering, aftershocks, slow slip transients, repeating earthquakes.

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

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

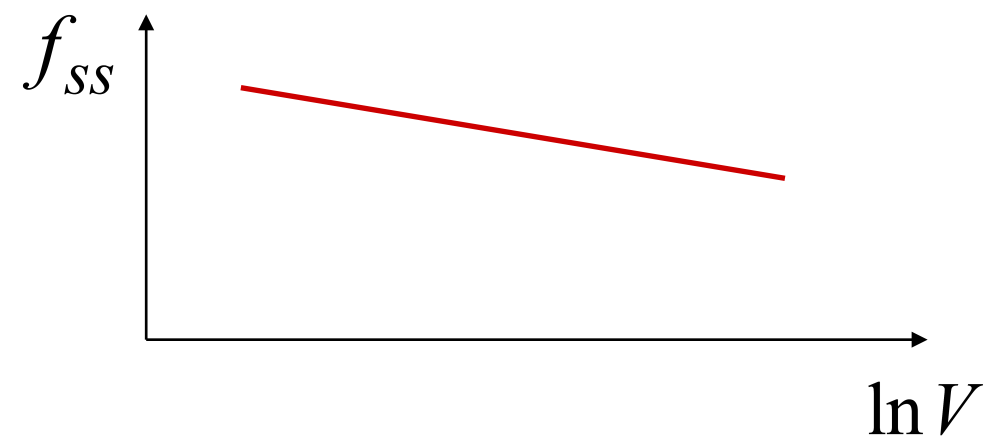
Key concept: **Velocity-strengthening** vs. **velocity-weakening** friction

**Velocity-strengthening:**  
**Friction *increases* with slip velocity**



**Slow slip under slow loading**

**Velocity-weakening:**  
**Friction *decreases* with slip velocity**



**Seismic slip in large enough regions**



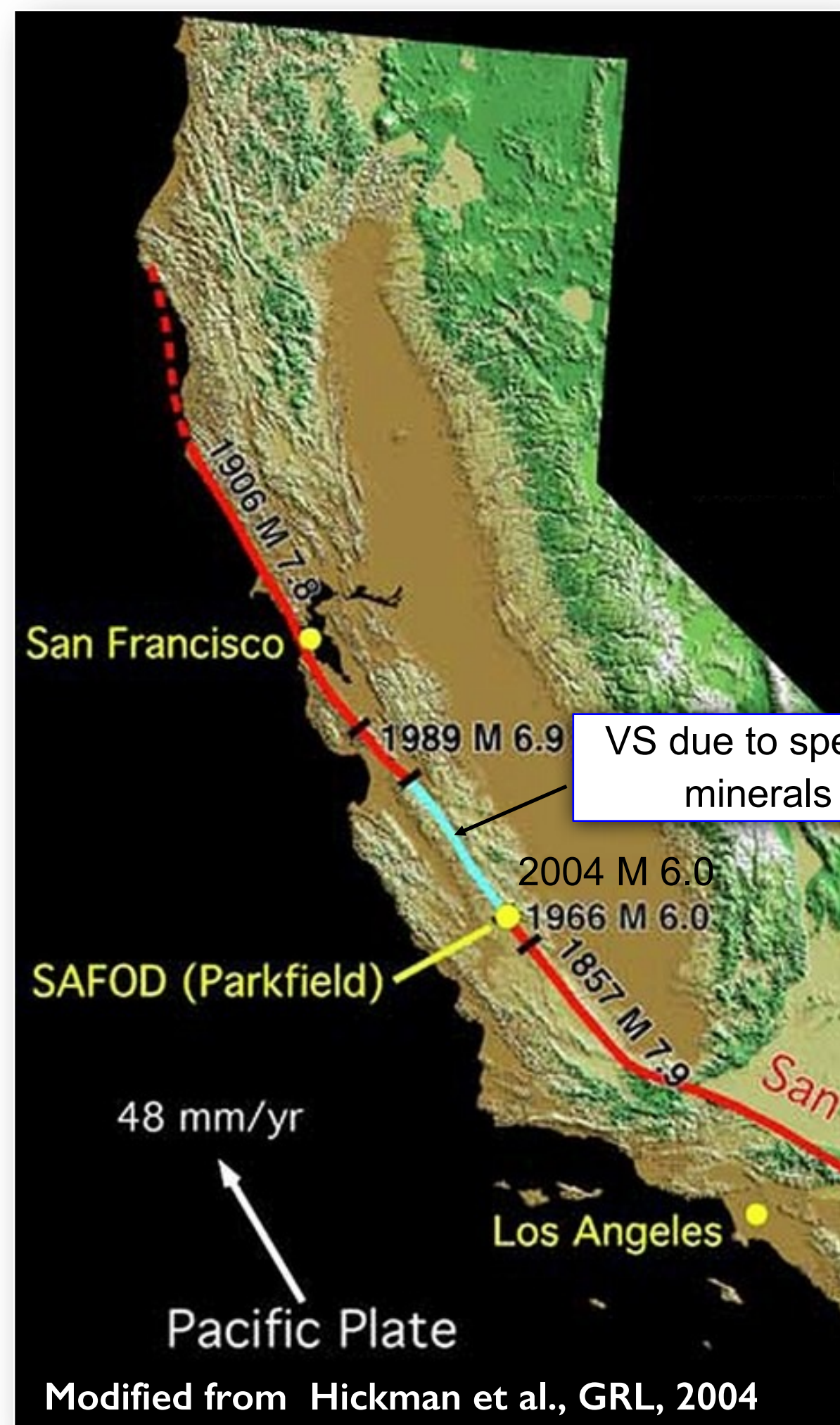
Conveniently explains  
observed variations in coupling

### Locked segments

- velocity-weakening friction
- earthquakes

### Slowly moving (creeping) areas

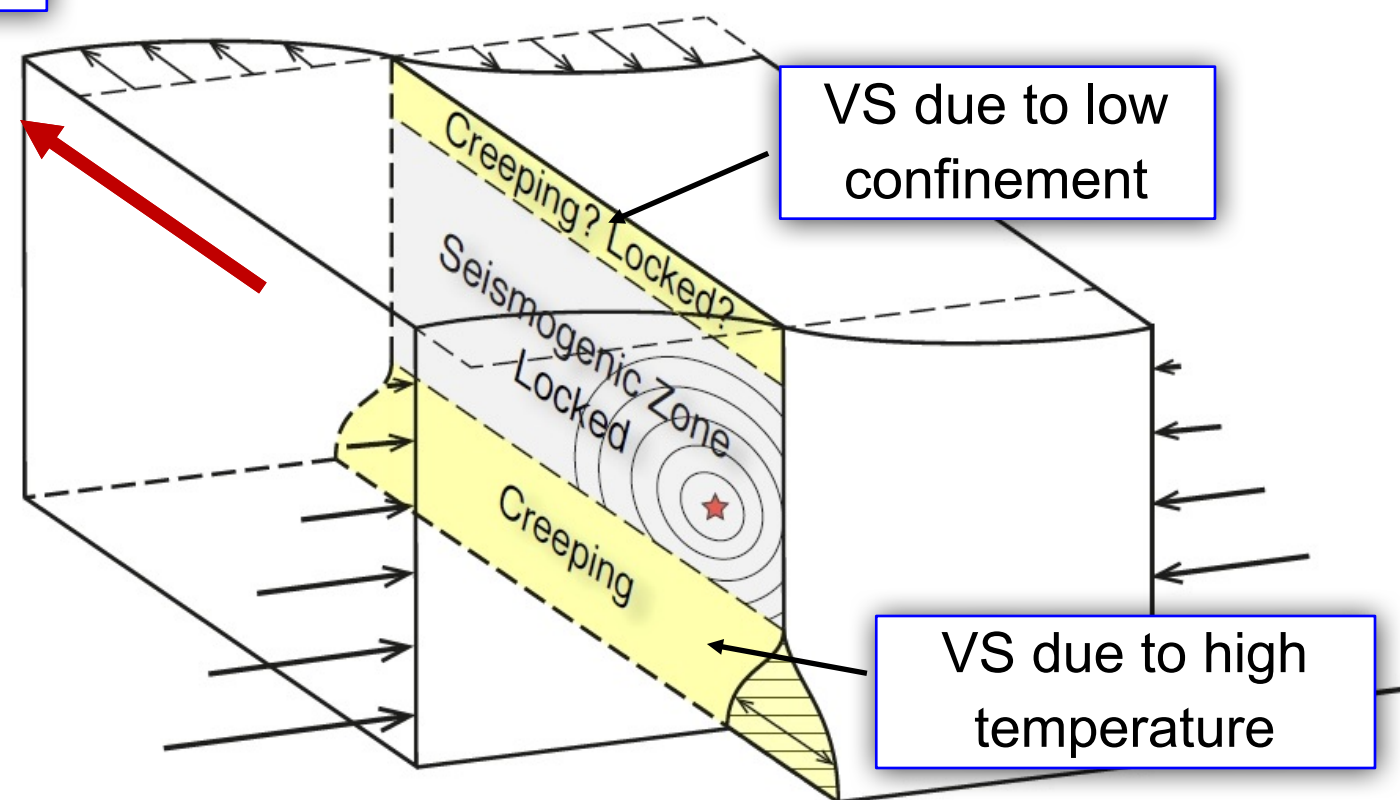
- velocity-strengthening friction
- “barriers” to earthquakes



VS due to special  
minerals

VS due to low  
confinement

VS due to high  
temperature



# Low-velocity fault frictional resistance: Rate-and-state friction

**Unique tool for simulating earthquake cycles** in their entirety,  
from accelerating slip in slowly expanding nucleation zones  
to dynamic rupture propagation (**turns into ~ linear slip weakening**)  
to post-seismic slip and interseismic creep  
to fault restrengthening between seismic events  
to steady slip in velocity-strengthening areas.

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

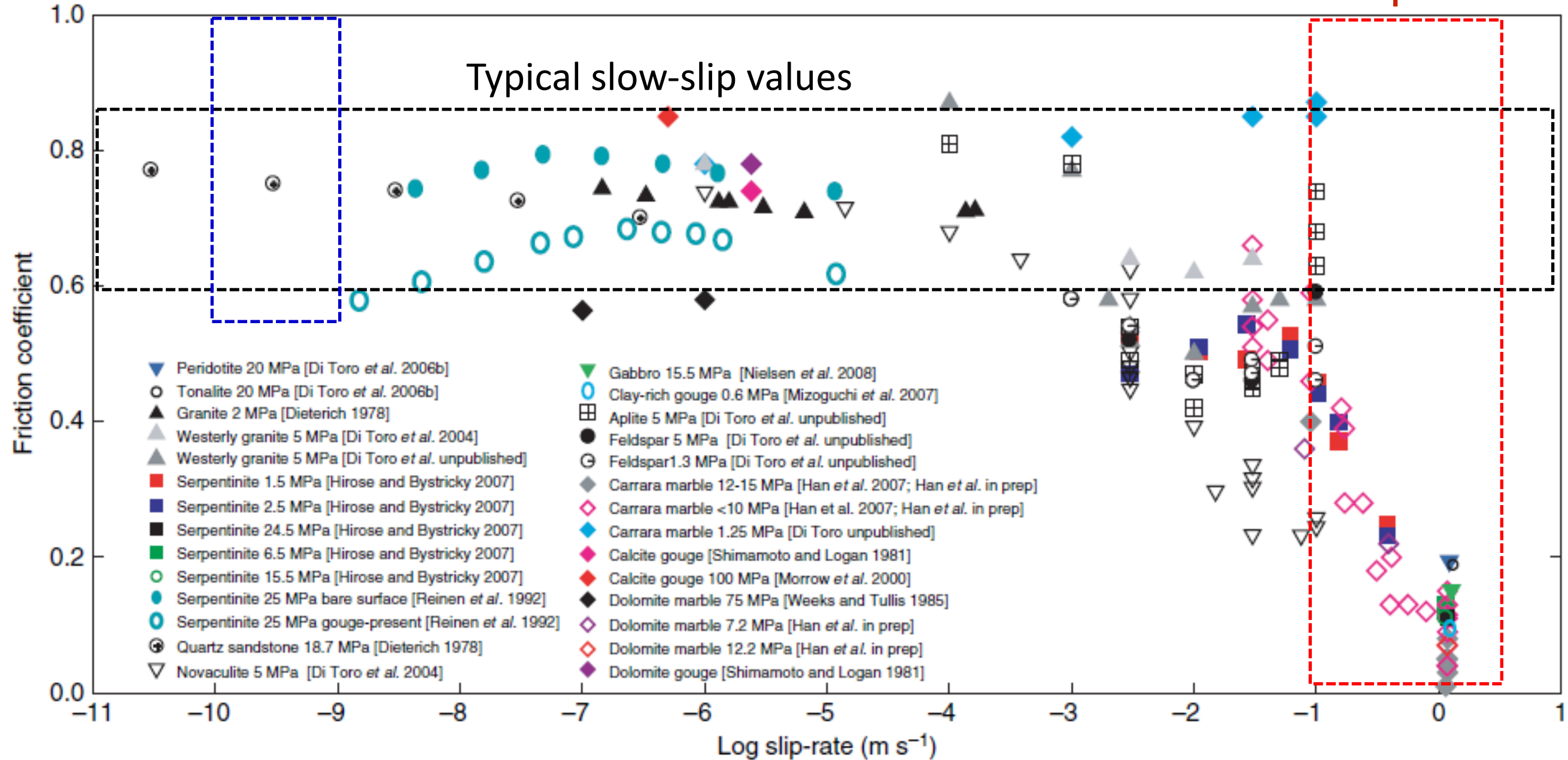
## A number of additional important effects

- **Rapid shear heating during seismic slip and associated changes, mostly weakening**
- Dilatancy (another state variable) and associated pore-pressure effects
- 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
- Fluid effects on rate-and-state parameters
- Recent experiments with velocity weakening even at high temperatures

# Rate and state friction is not the whole story: Dramatic weakening occurs at high slip rates

Plate motion

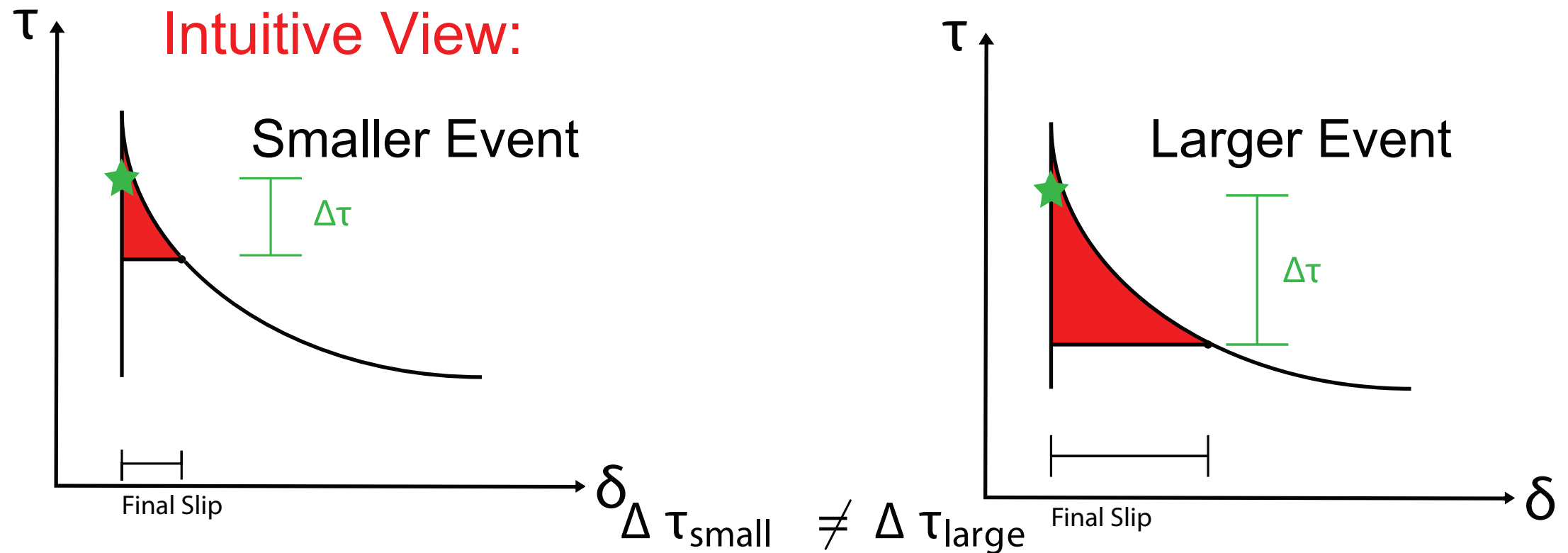
Earthquakes



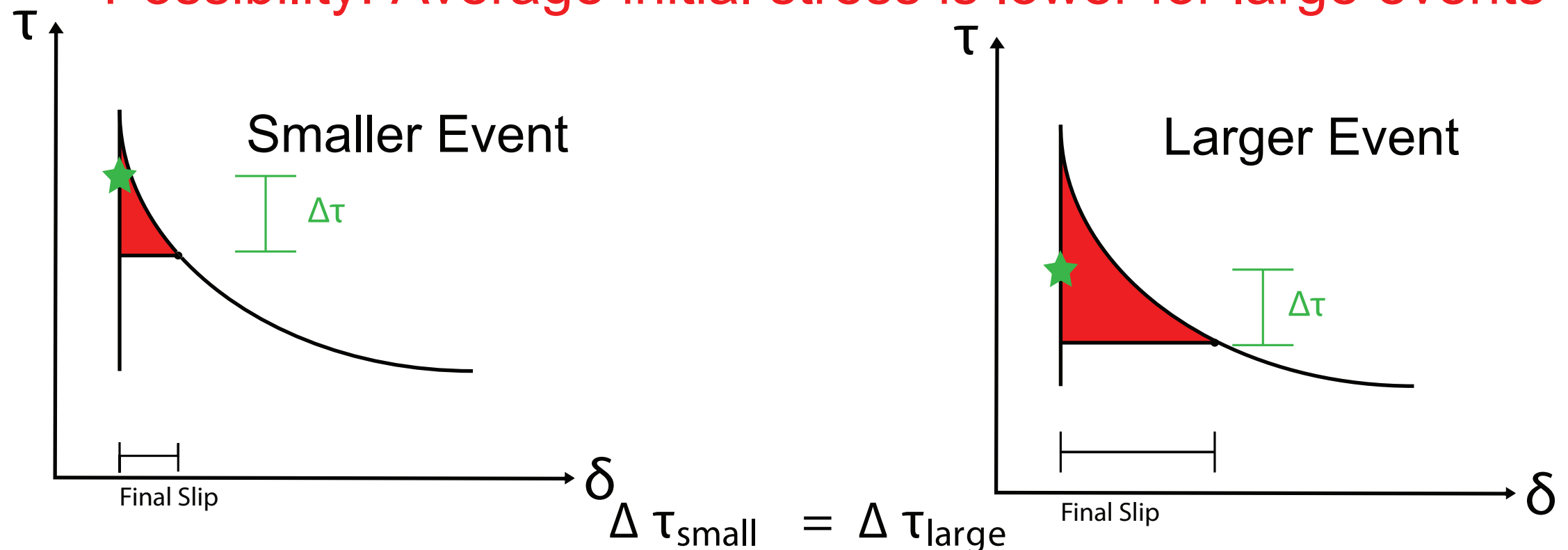


# Is dynamic weakening consistent with magnitude-independent stress drops?

Intuitive View:



Possibility: Average initial stress is lower for large events





# **Proposed physical mechanisms behind the dramatic weakening**

## **Shear heating mechanisms**

**Flash heating of contact asperities at small slips** (Lim and Ashby, 1987, Tsutsumi and Shimamoto, 1997; Rice, 1999, 2006; Goldsby and Tullis, 2011; and others)

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

**Thermal decomposition and subsequent fluid pressurization**

(Han, Shimamoto, Hirose, Ree, Ando, 2007; Brantut et al., 2010; 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)

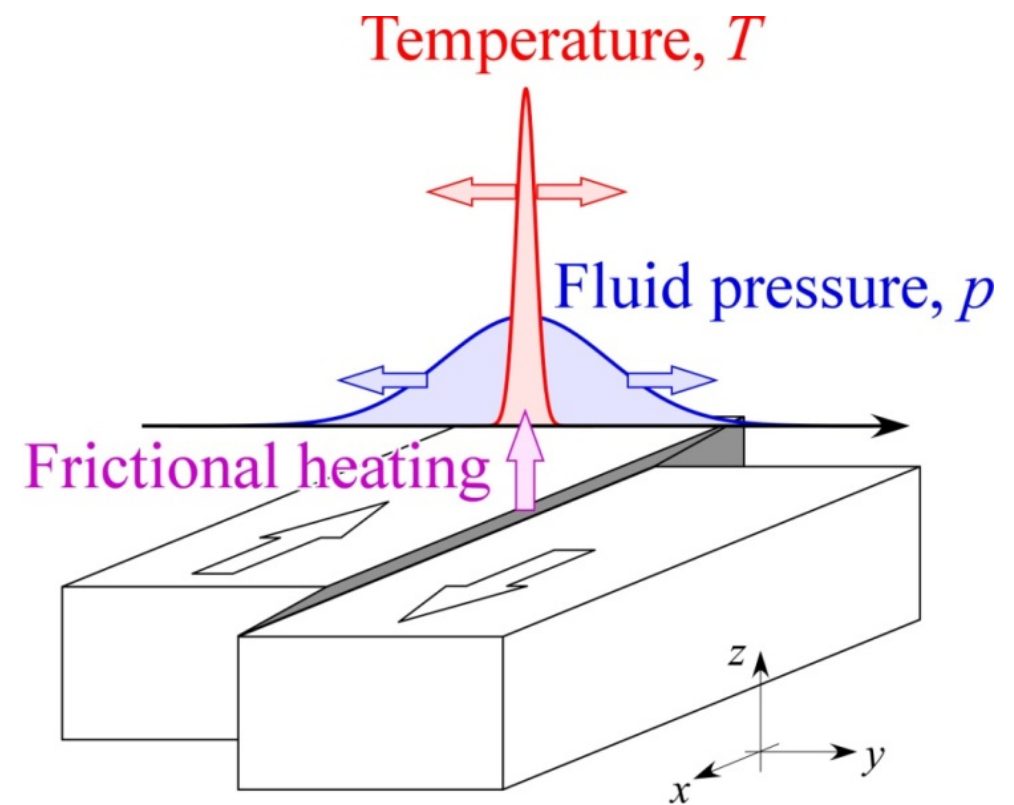
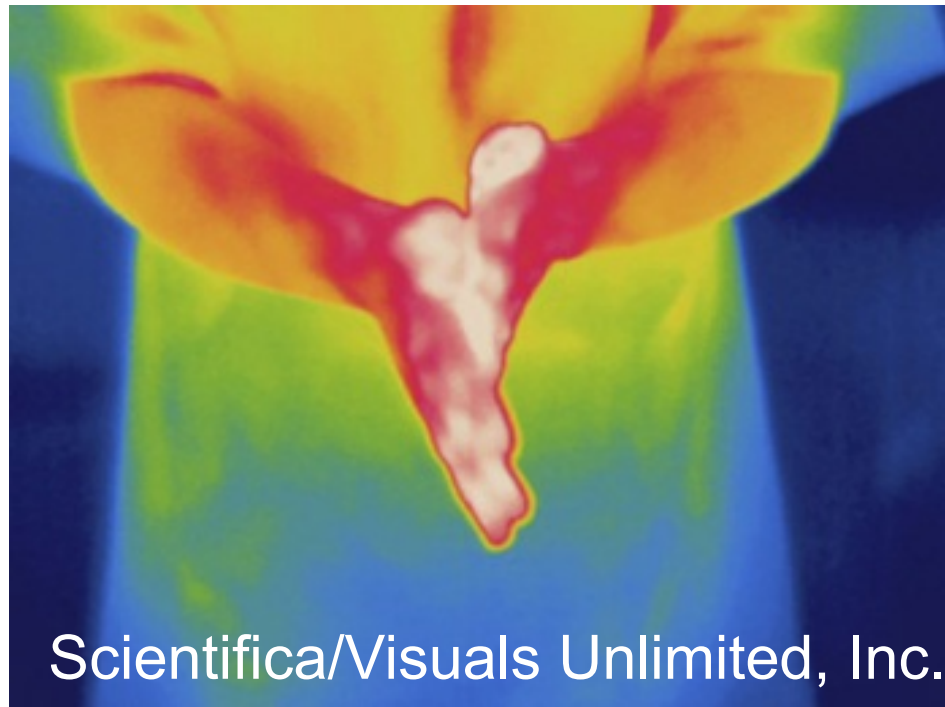
**Normal stress reduction from elastic mismatch** (Weertman, 1963, 1980; Andrews and Ben-Zion, 1997)

**Superplasticity, nanoparticle lubrication** (Green et al., 2015; De Paola et al., 2015)

**Acoustic fluidization, interface vibrations** (Melosh, 1979, 1996; Brune et al., 1993)

**Elastohydrodynamic lubrication** (Brodsky and Kanamori, 2001)

# Friction-induced shear heating, and associated fluid effects



$$\tau = f\bar{\sigma} = f(\sigma - p)$$

$f \equiv$  rate-and-state friction

$$\frac{\partial T}{\partial t} = \alpha_{th} \frac{\partial^2 T}{\partial y^2} + \frac{\tau V}{\rho c} \frac{\exp(-y^2/2w^2)}{\sqrt{2\pi}w}$$

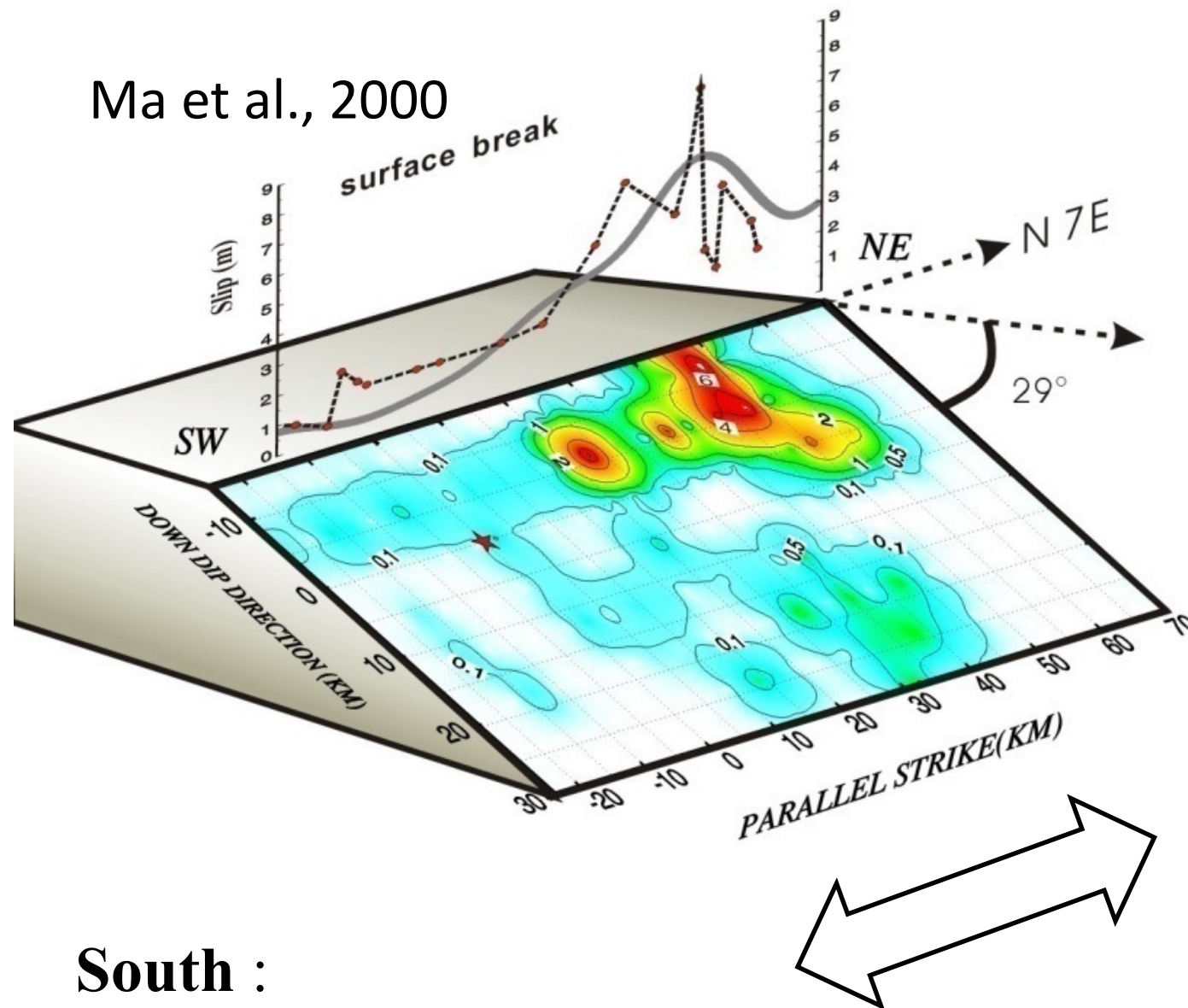
- Rapid shear heating raises temperature (for narrow **shear zone width**)

$$\frac{\partial p}{\partial t} = \alpha_{hy} \frac{\partial^2 p}{\partial y^2} + \Lambda \frac{\partial T}{\partial t}$$

- Fluids in the fault zone (water, CO<sub>2</sub>) expand
- Pore fluid pressure  $p$  may increase, depending on **permeability**
- Fault resistance  $\tau$  decreases (dynamic weakening) or not

# Lab measurements of fault properties for 1999 (Mw 7.6) Chi-Chi earthquake

Ma et al., 2000



South :

**Velocity-weakening,  
susceptible to nucleation**

**Higher permeability**

Its fault properties have been measured in the lab using samples obtained by drilling (**Tanikawa and Shimamoto, 2009**).

North :

**Velocity-strengthening,  
“stable”**

**Lower permeability,  
susceptible to dynamic  
weakening through  
pore fluid pressurization**

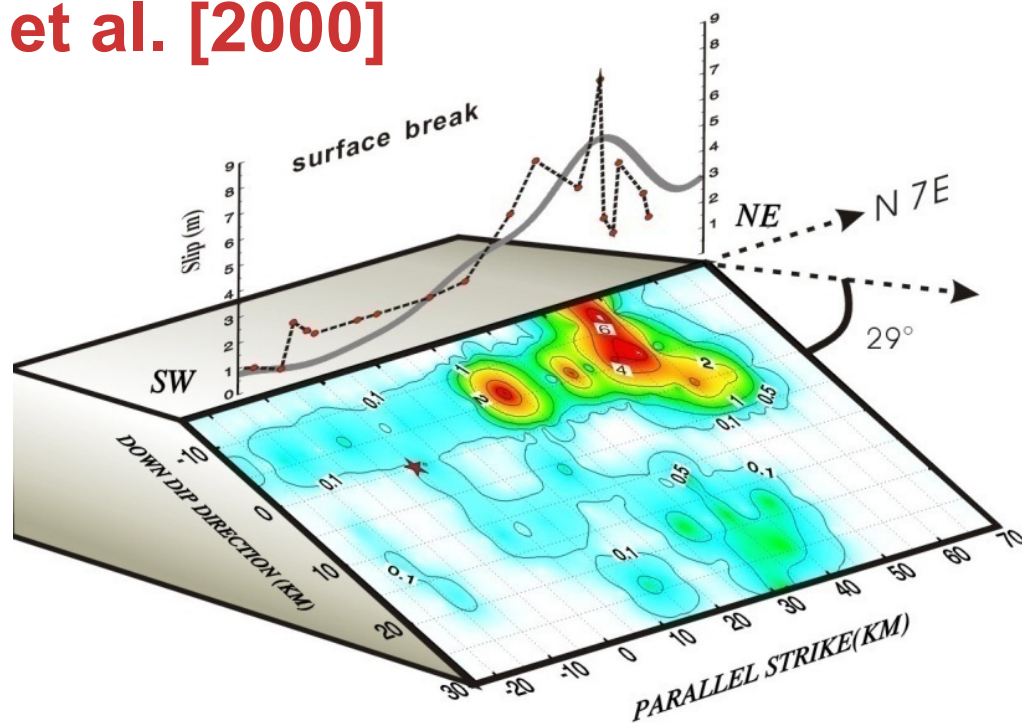
Caution:

The data is based on samples from shallow depths (200-300 m).



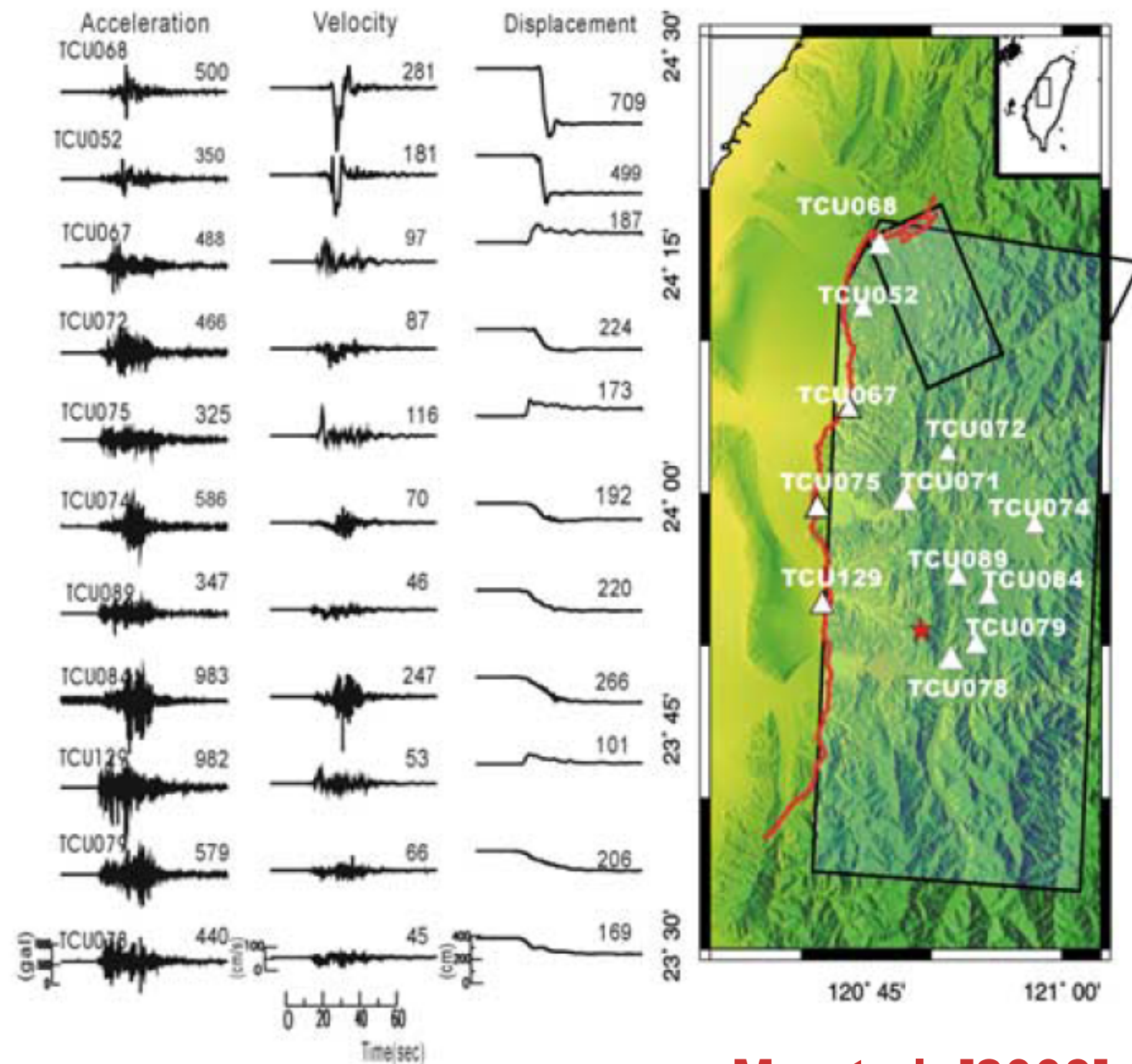
# Variations in radiation for the 1999 ( $M_w$ 7.6) Chi-Chi earthquake

Ma et al. [2000]



Fault area with lower slip generated more high-frequency radiation [e.g. Ma et al., 2003].

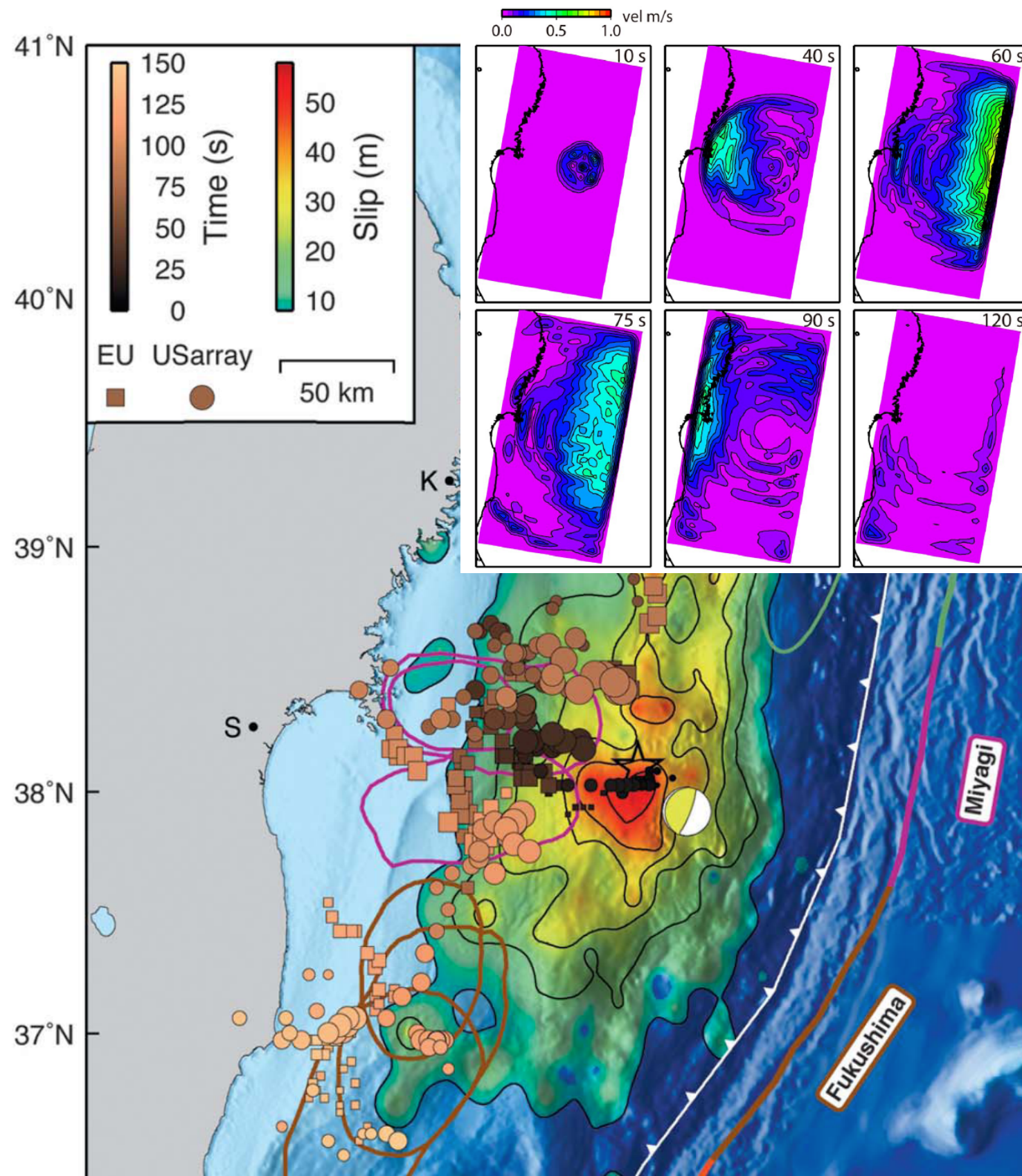
Qualitatively the same behavior as in Tohoku-Oki!



Ma et al. [2003]



# Observations from 2011 Mw 9.0 Tohoku-Oki earthquake



- **Extremely large unexpected seismic slip** ( $> 50$  m) in shallower areas which had been assumed to be stably moving (and hence barriers to earthquake rupture).
- **Prior smaller ( $\sim$ Mw 8) events** at the bottom of the subducting interface.
- **Areas of lower slip generated more high-frequency radiation.**
- **Complex pattern of rupture:** first down, then up, then down again (Ide et al., Science, 2011).

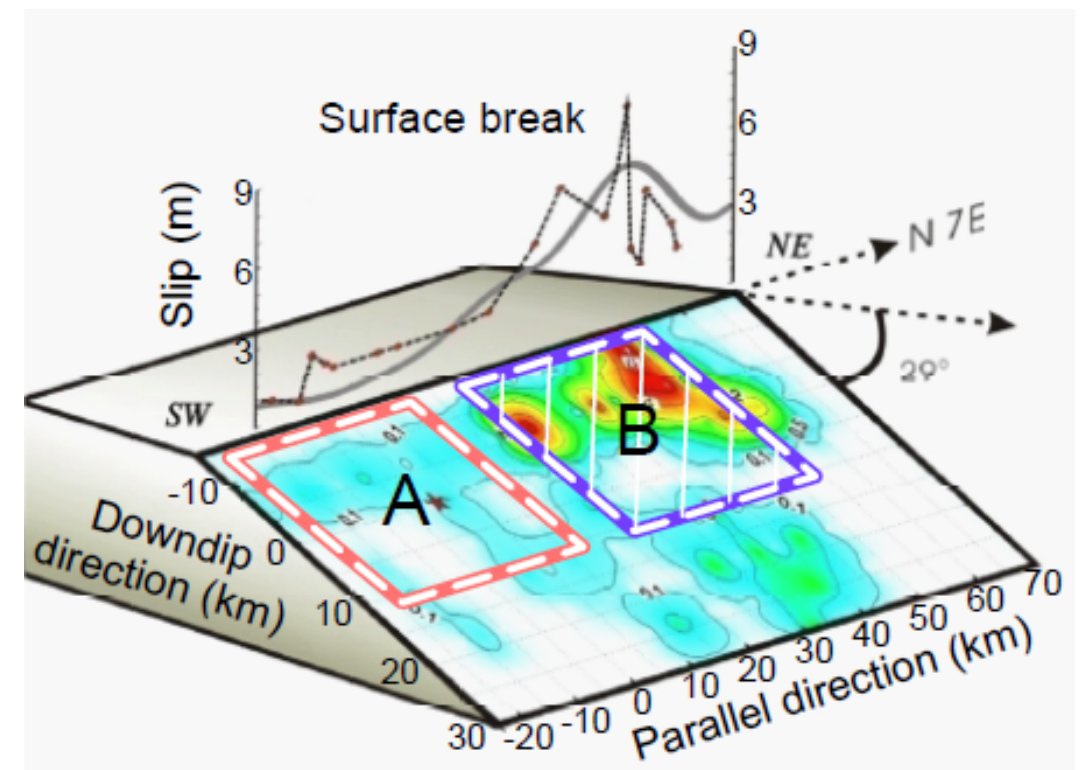
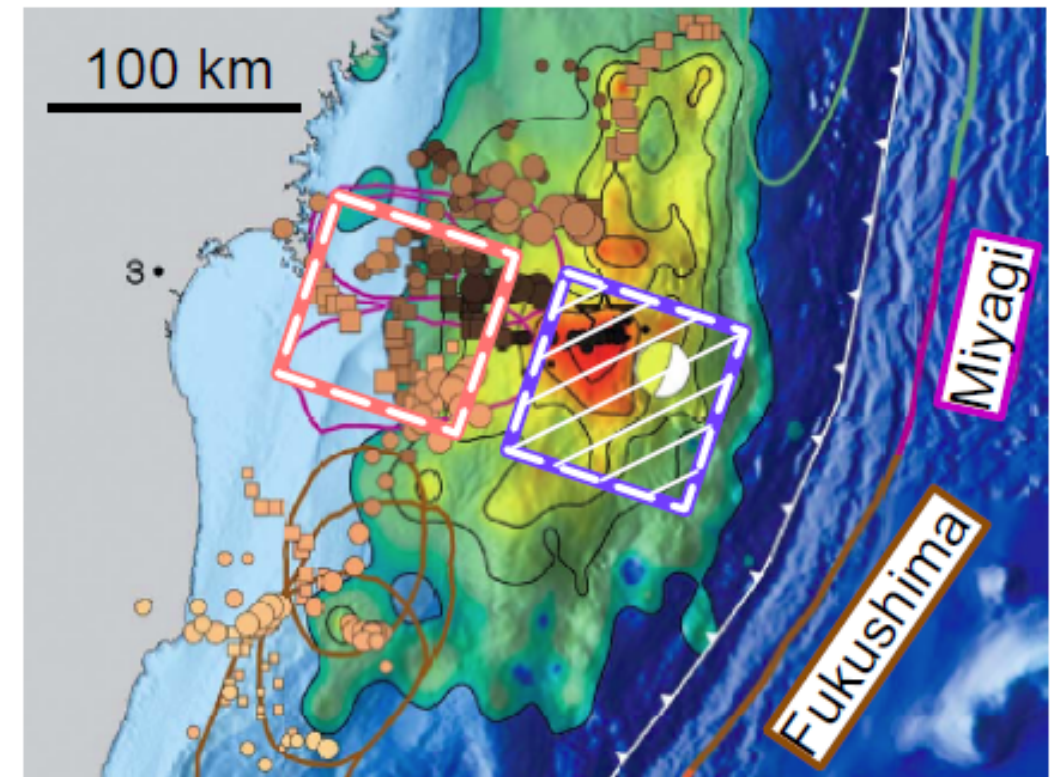
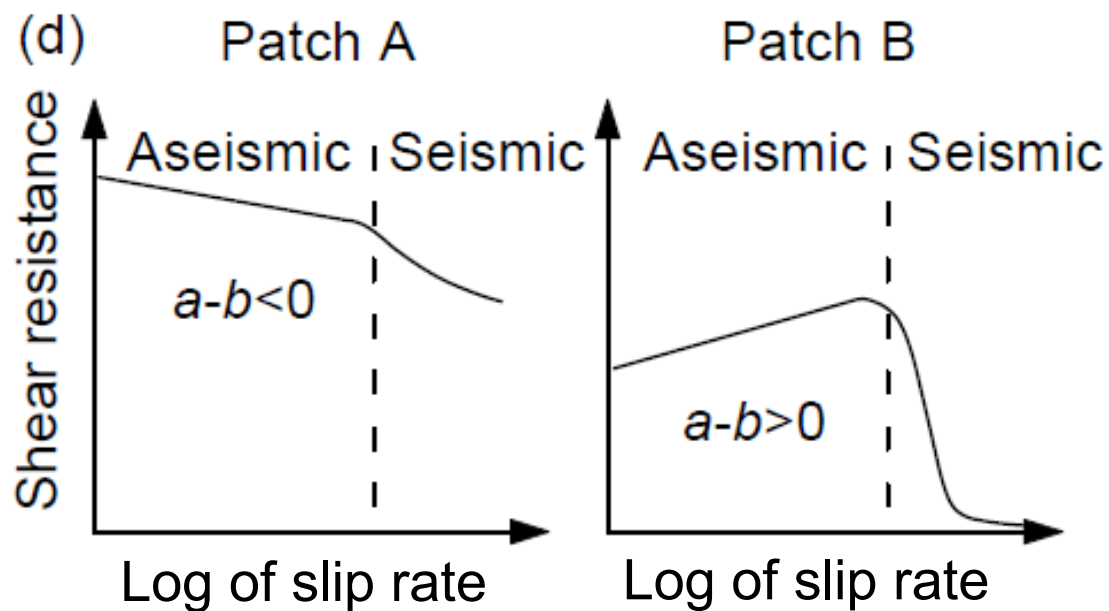
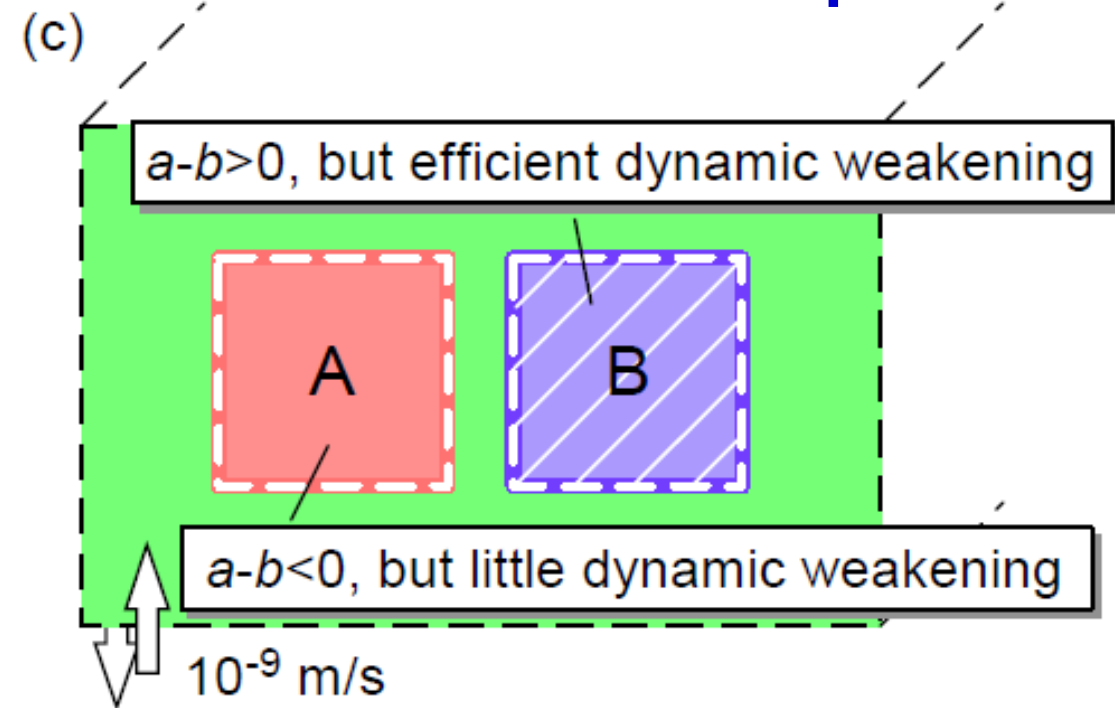
*We can qualitatively reproduce all these observations in a single physical model with dynamic weakening of creeping regions*

**Noda and Lapusta, Nature, 2013**

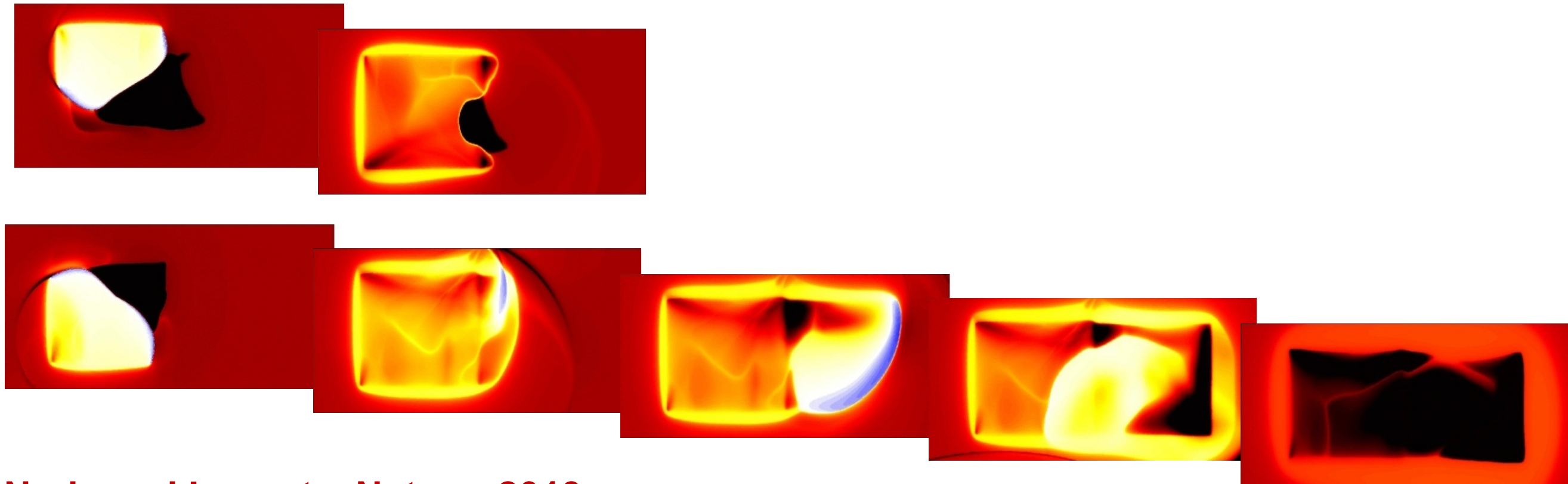
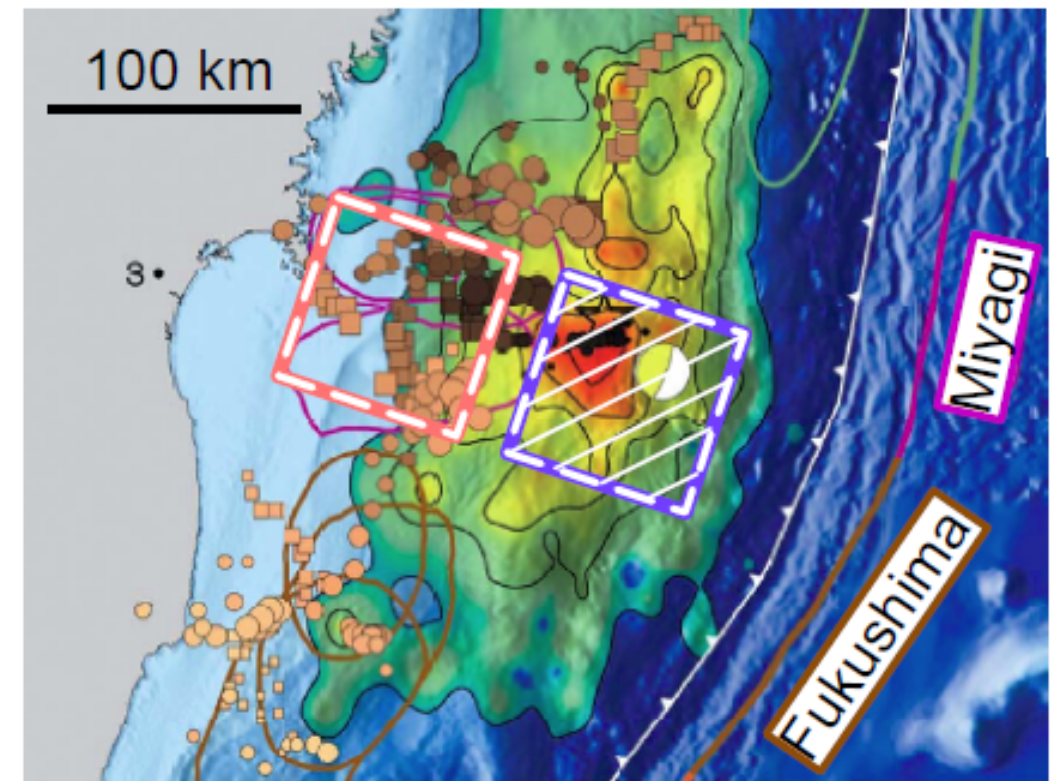
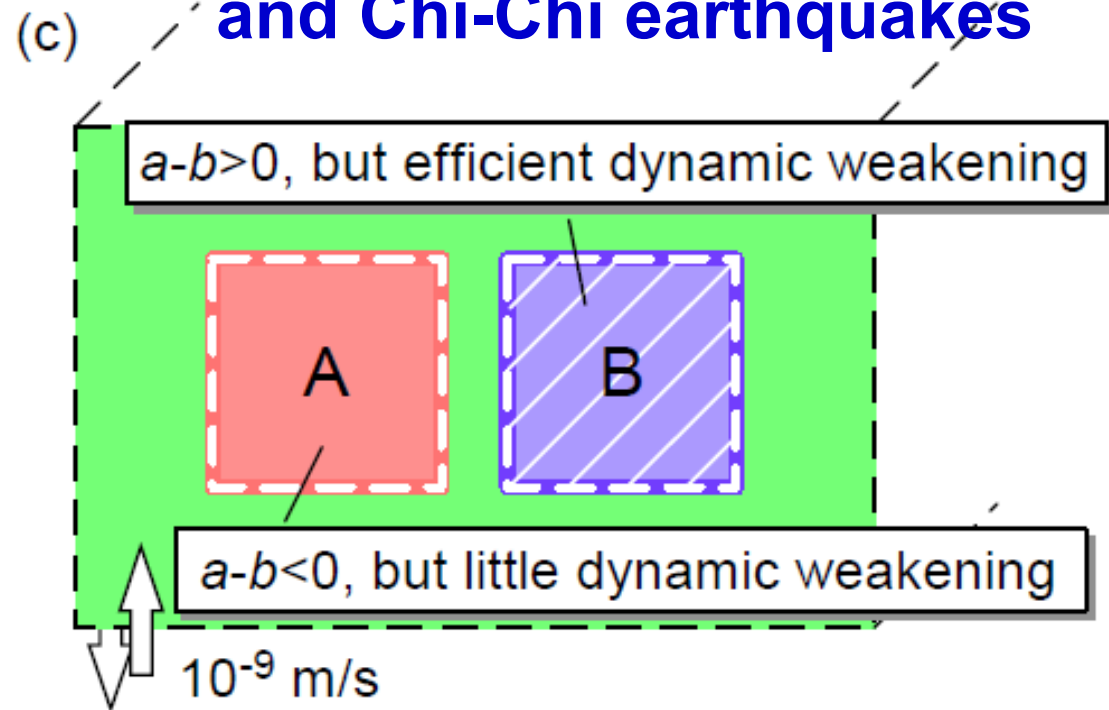
Simons et al., Science, 2011



**Model with simple geometry but realistic, lab-measured fault rheology and its correspondence to Tohoku-Oki and Chi-Chi earthquakes**



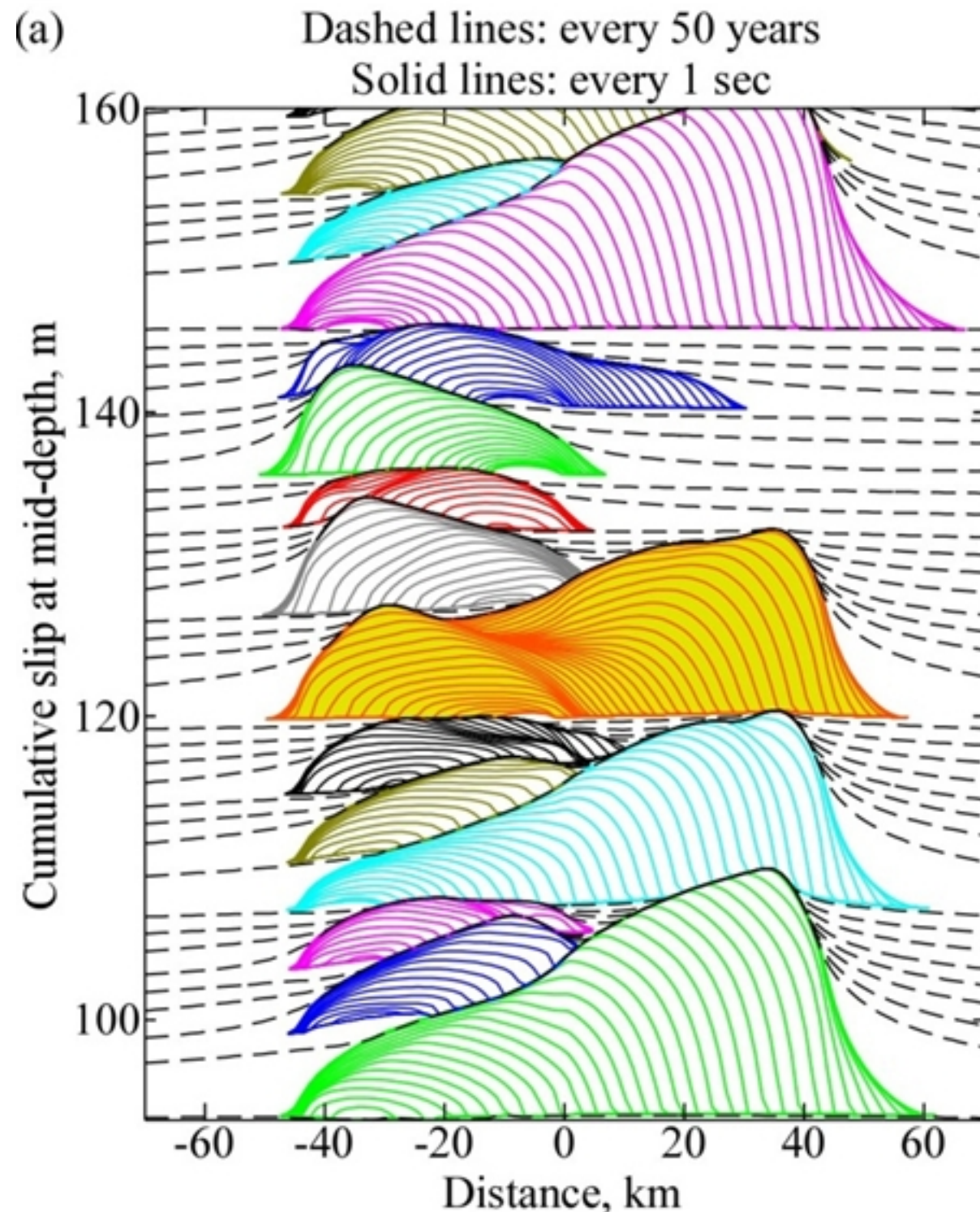
**Model with simple geometry but realistic, lab-measured fault rheology and its correspondence to Tohoku-Oki and Chi-Chi earthquakes**





# Qualitative match of long-term earthquake sequence behavior

Accumulation of fault slip



- A number of smaller events in the left patch per each event spanning both patches (as for both Tohoku-Oki and Chi-Chi faults)
- Large coseismic slip in the right patch which can also be creeping



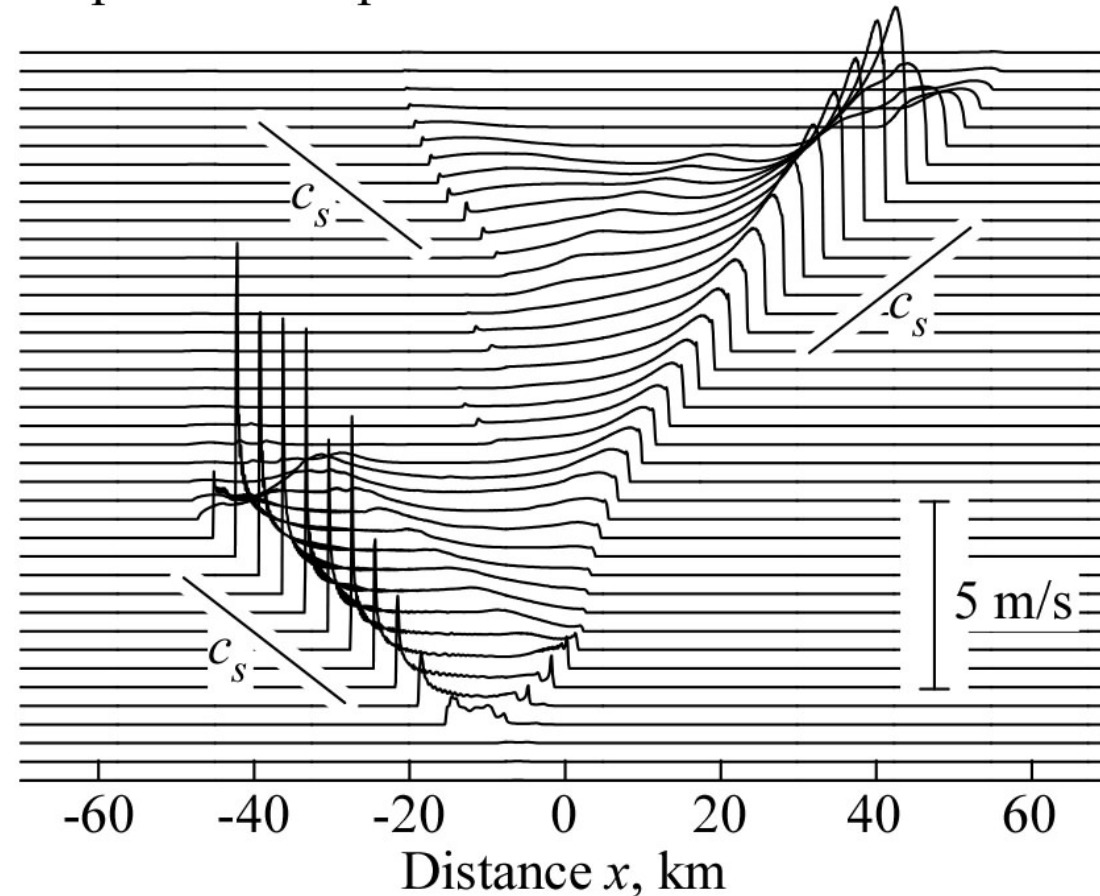
**Noda and Lapusta, Nature, 2013**

Prior smaller events in relation to Tohoku-Oki,  
from Simons et al., 2011



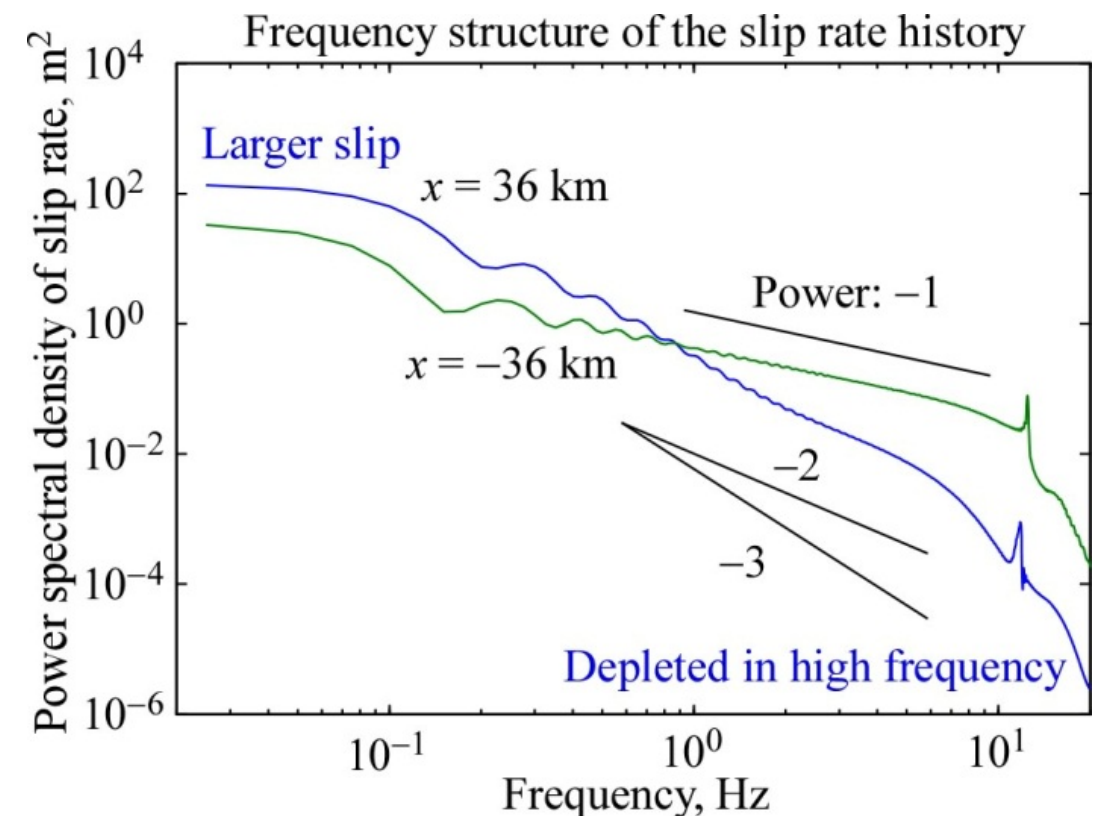
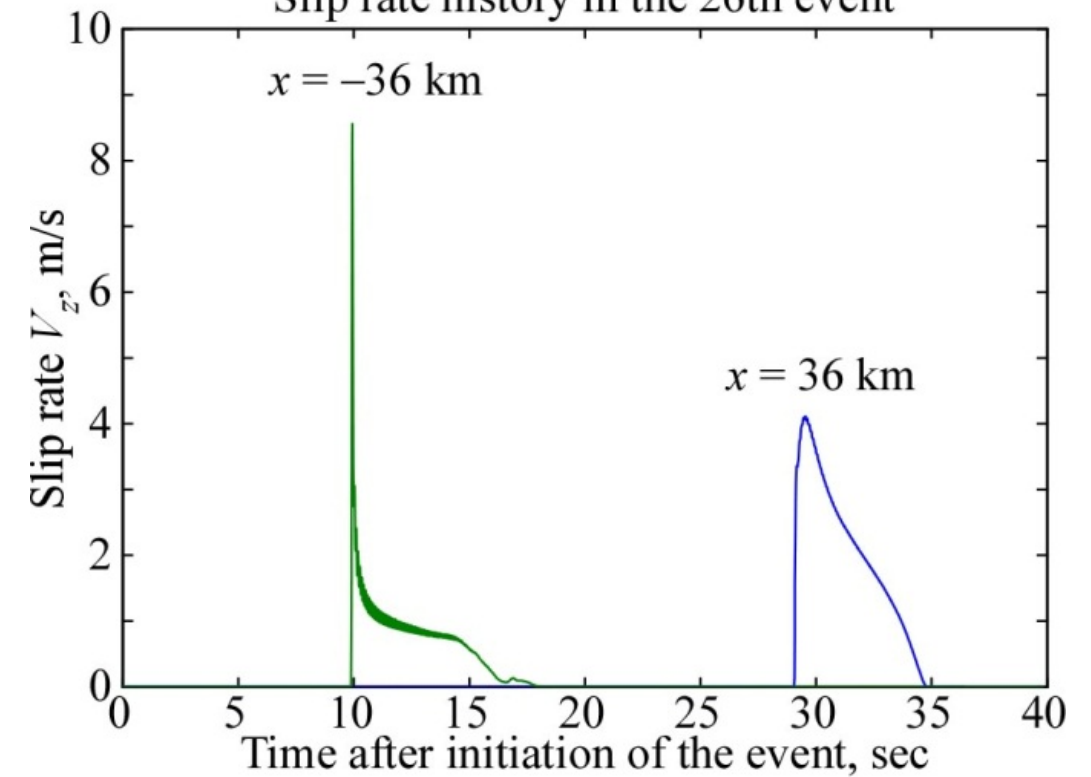
# Frequency contrast between the two patches as observed

Snapshots of slip rate in the 26th event

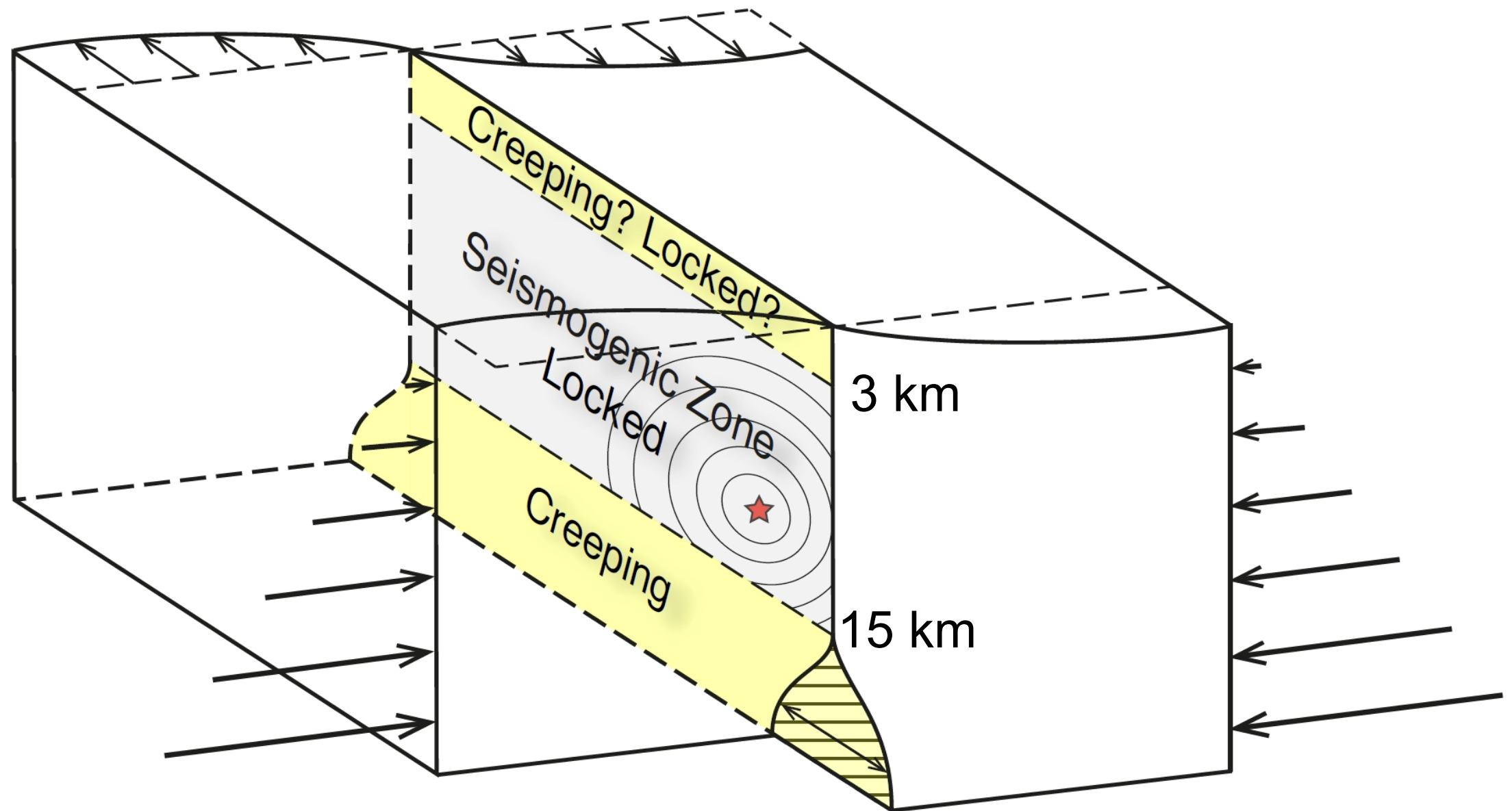


Patch A has smaller slip but more high-frequency content, reproducing observations for Chi-Chi [Ma et al., 2003] and Tohoku-Oki earthquake [Meng et al., 2011].

Slip rate history in the 26th event



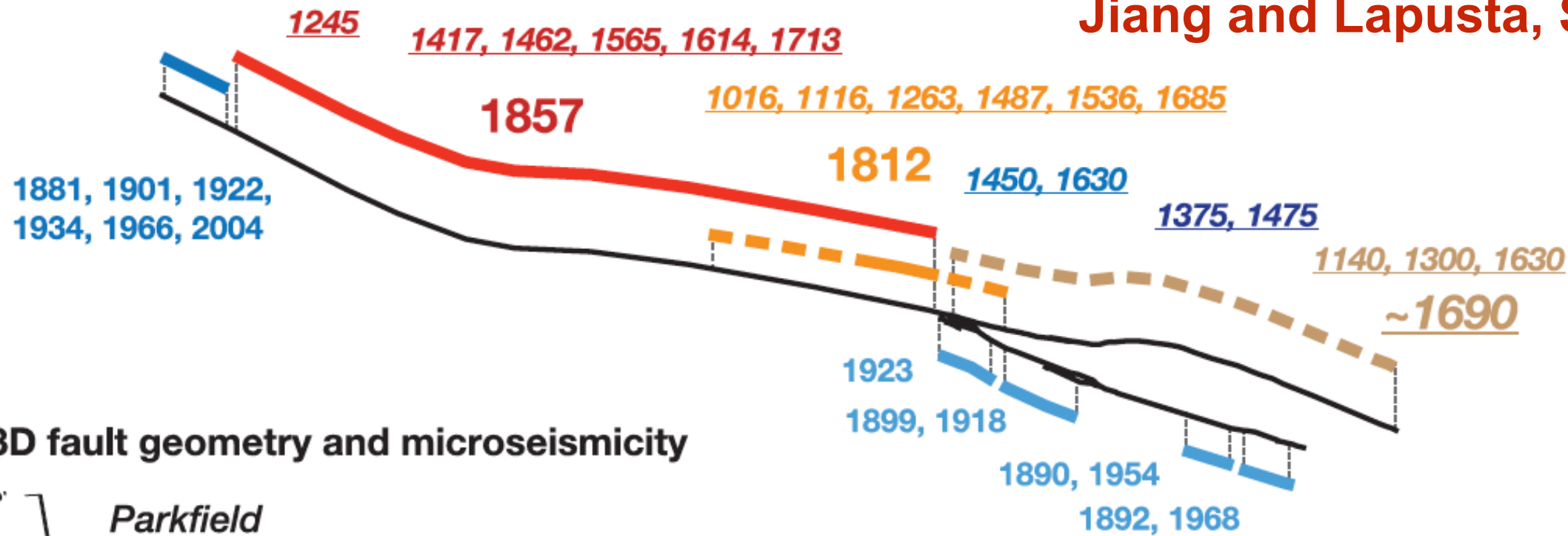
**What if dynamic rupture dynamically penetrates into the deeper creeping fault extensions? Evidence of such penetration?**



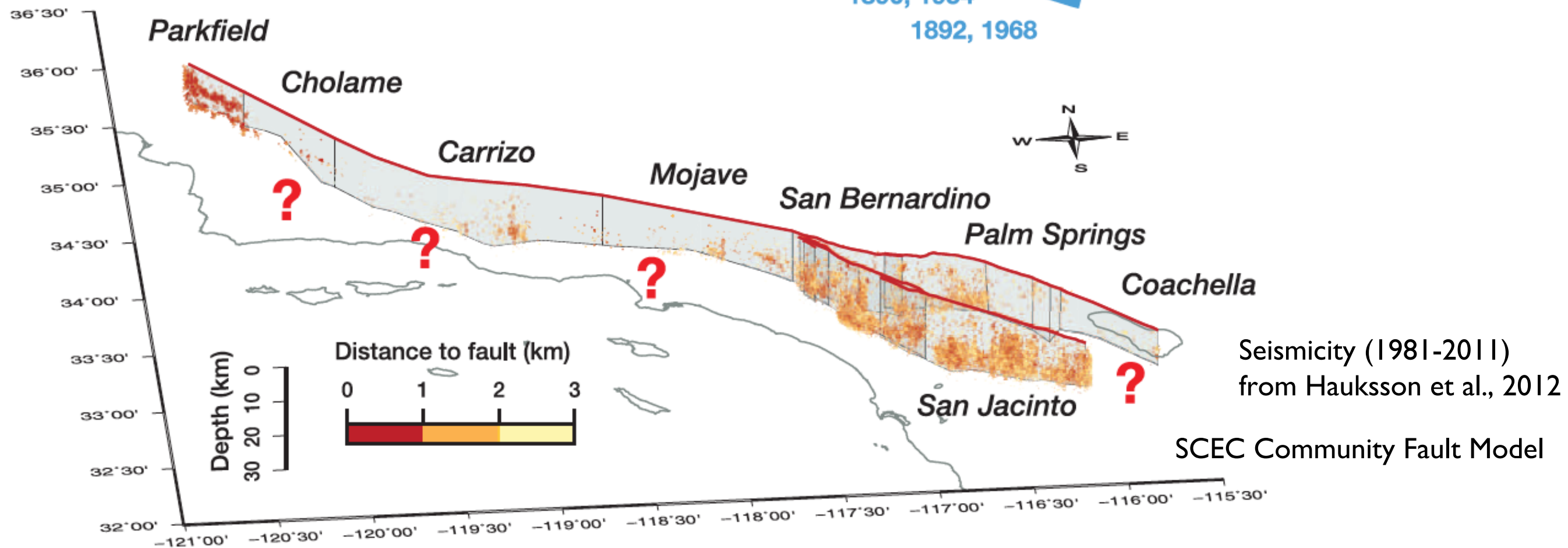
# Observation: Seismic quiescence (absence of microseismicity) on some fault segments, i.e. on San Andreas Fault in California

## A Historical and *prehistorical* earthquakes on the SAF and SJF

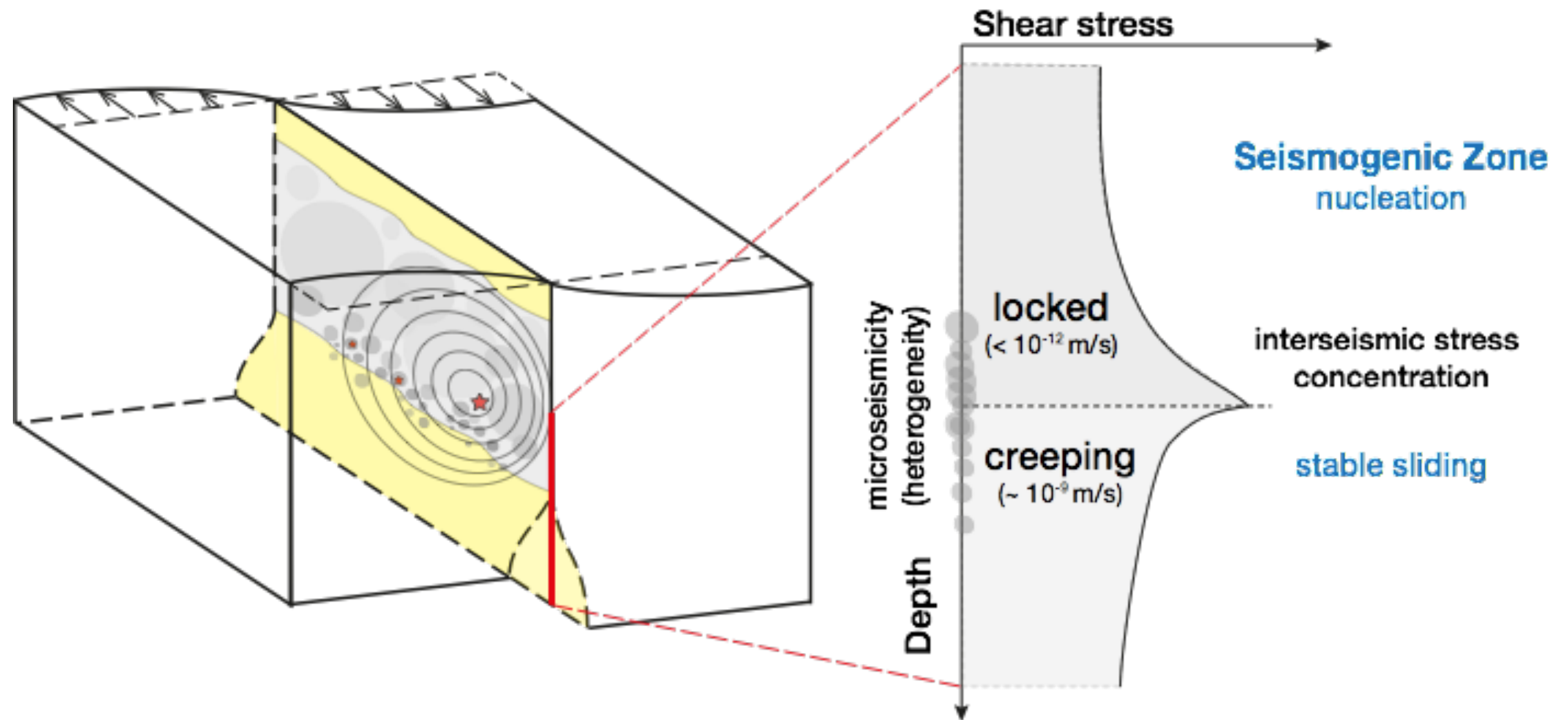
Jiang and Lapusta, Science, 2016



## B 3D fault geometry and microseismicity



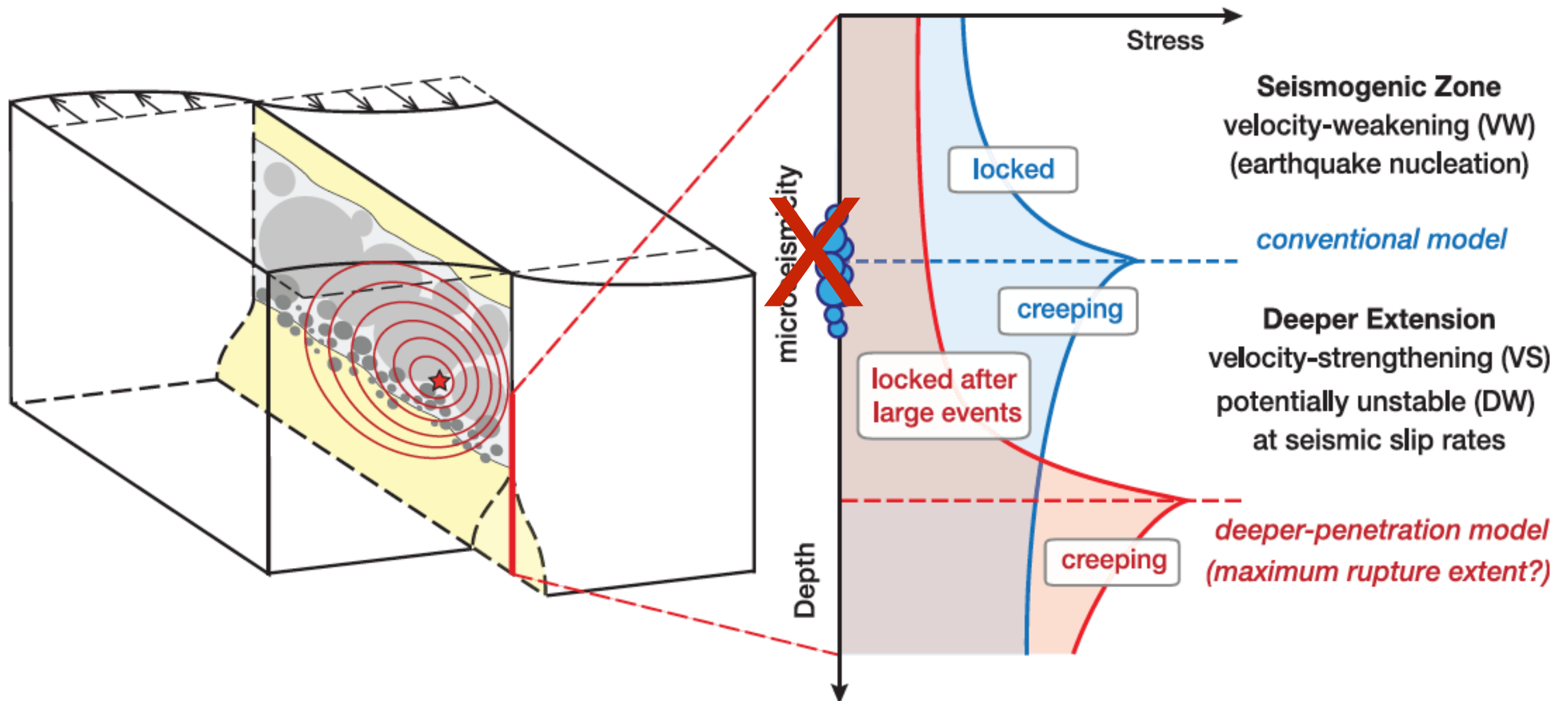
**Microseismicity is expected at the transition between locked (seismogenic) zone and creeping deeper extensions ...**



Deeper creeping fault extensions of mature faults are supported by a number of observations: deep tectonic tremor (Shelly, 2010); afterslip needed to explain postseismic deformation (Bruhat et al., 2011); Studies of exhumed faults (Cole et al., 2007).



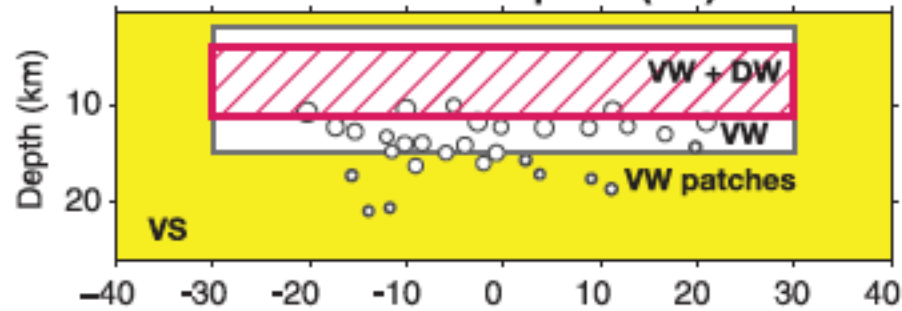
... unless large earthquakes penetrate into the creeping regions and put locked/creeping transition below the seismogenic zone



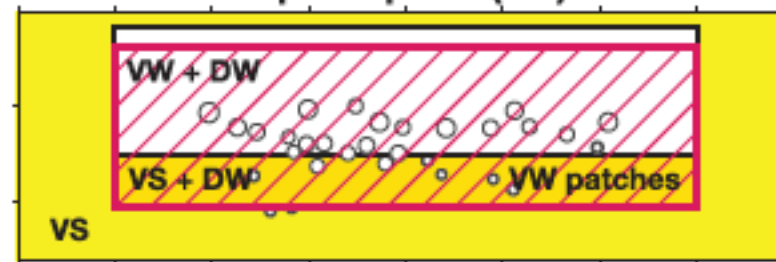
Jiang and Lapusta, Science, 2016

## A Fault models

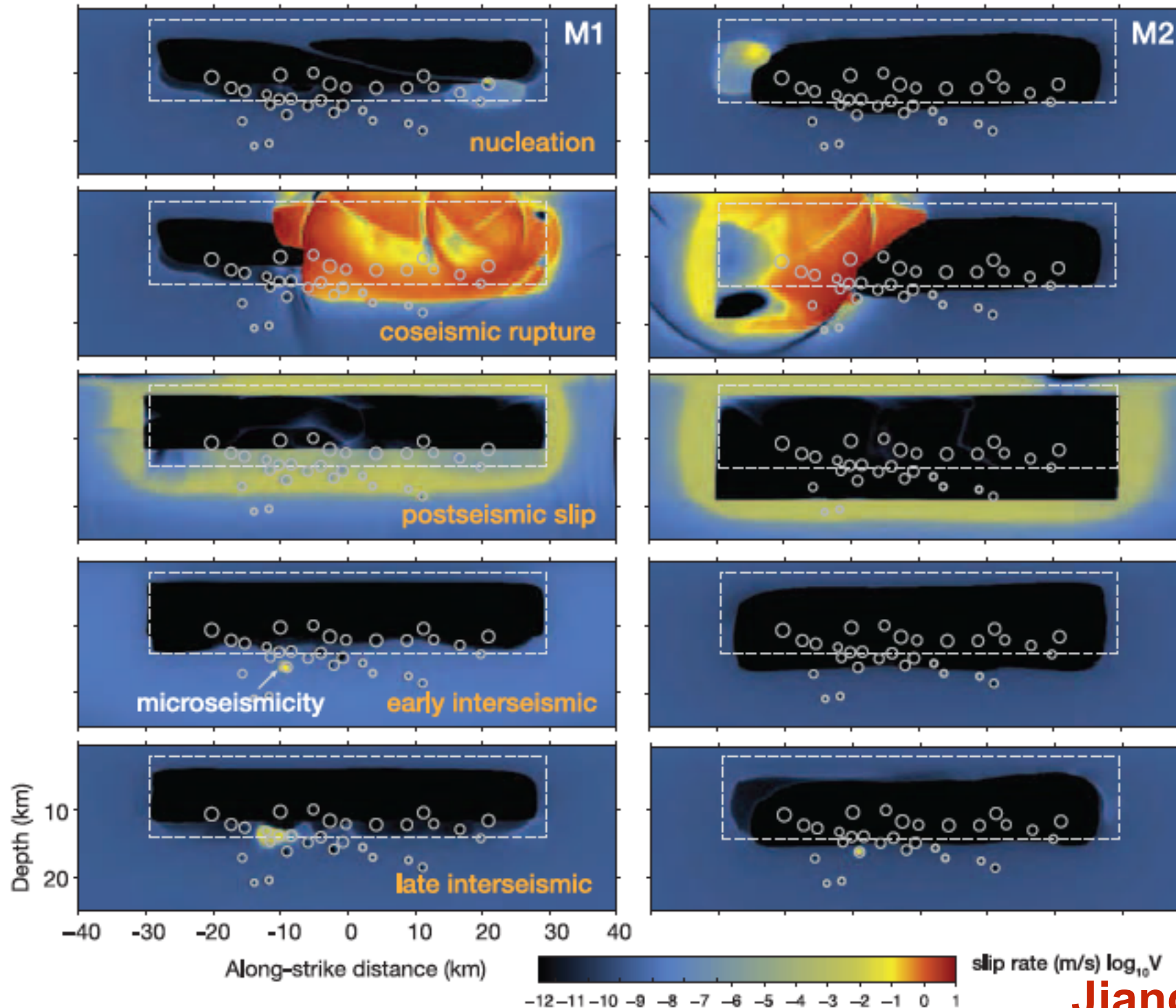
SZ-confined rupture (M1)



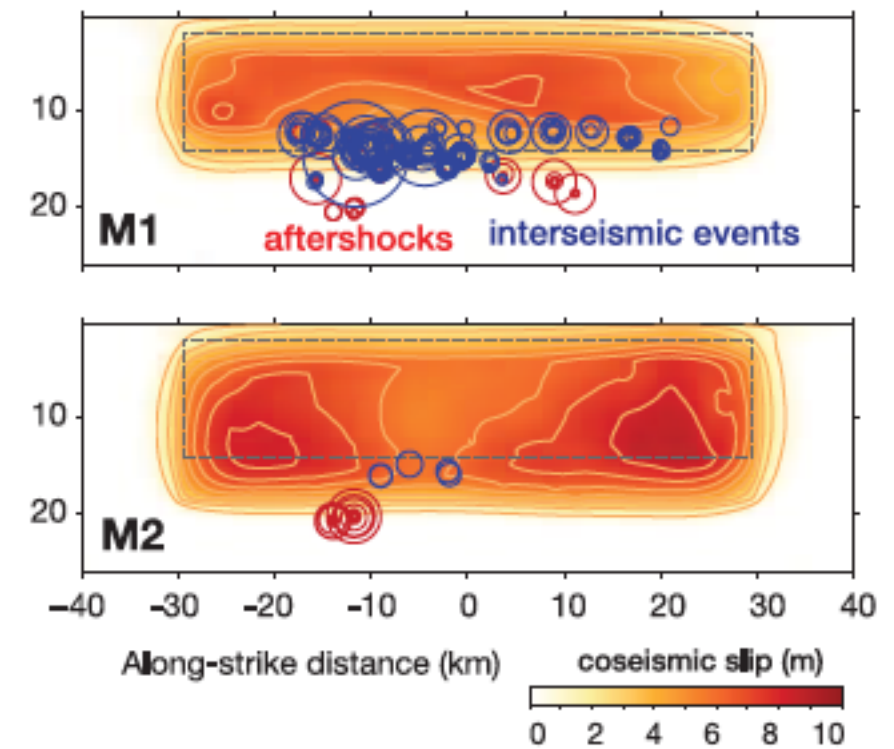
deeper rupture (M2)



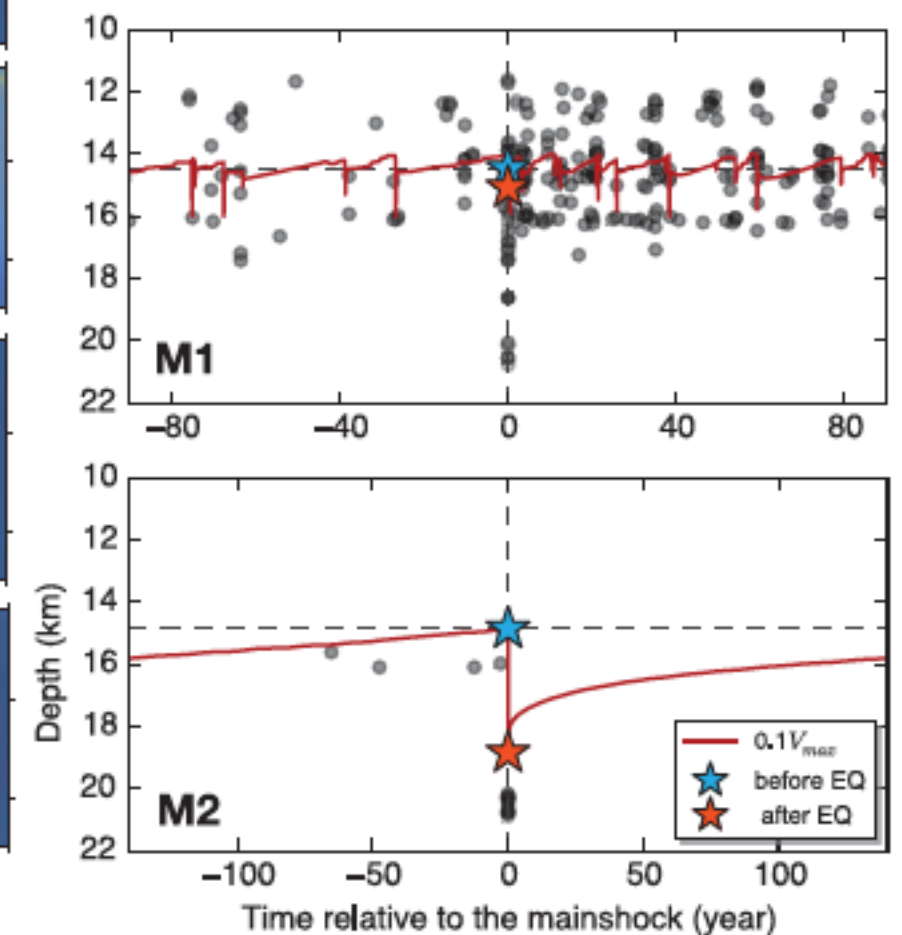
## B Earthquake sequences and aseismic slip



## C Spatial patterns



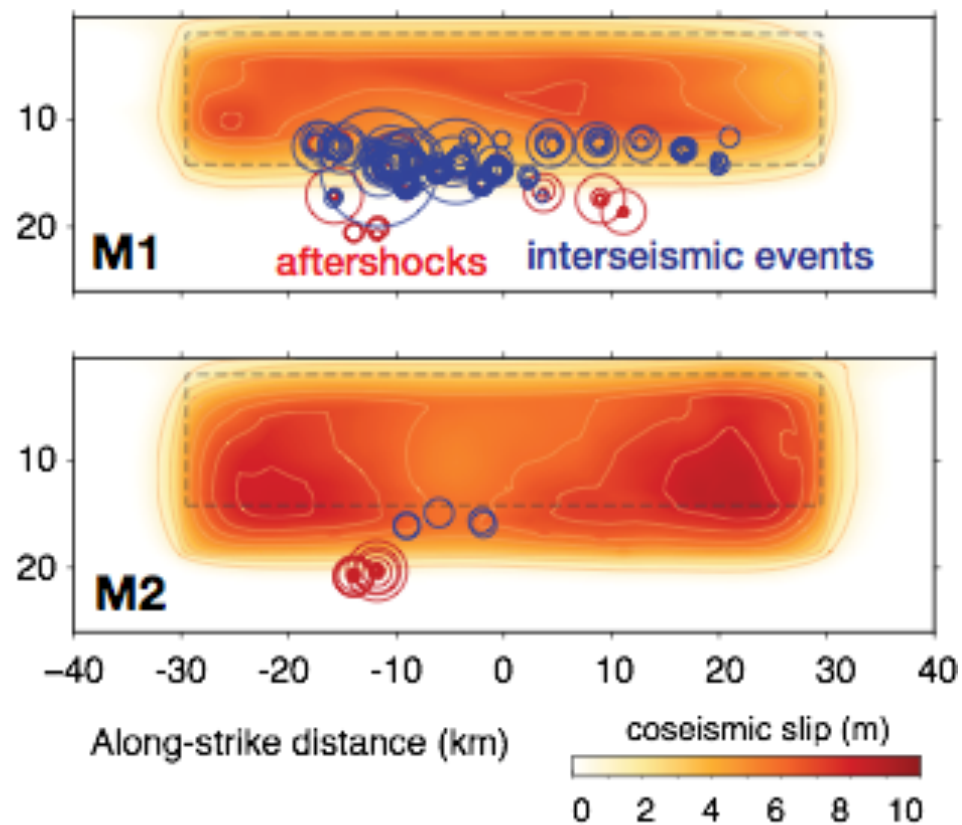
## D Temporal evolution



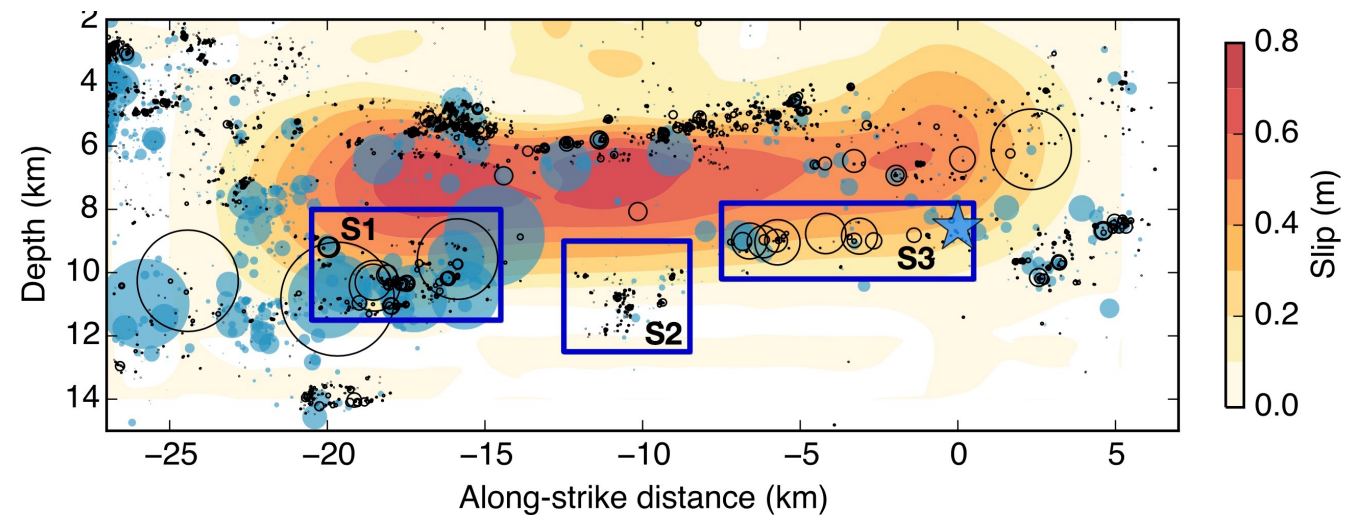
Jiang and Lapusta, Science, 2016



# No microseismicity at the base of the seismogenic zone may point to deeper penetration of large events due to dynamic weakening



2004 Mw 6.0 Parkfield earthquake

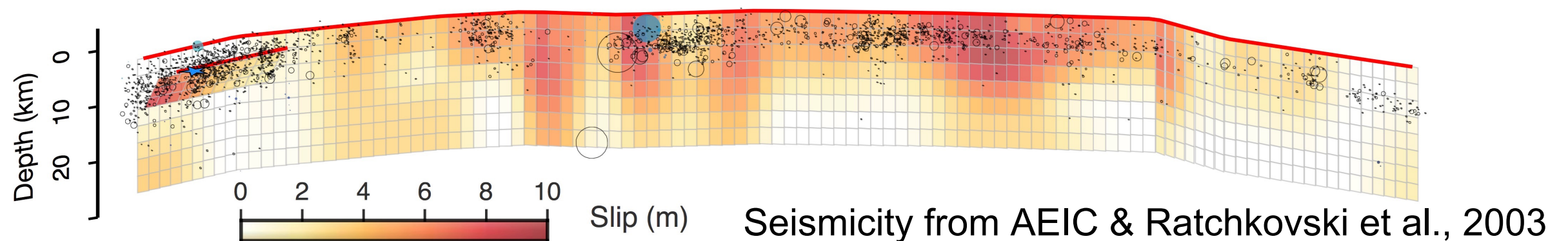


Slip model/seismicity from Barbot and Lapusta, 2012; Waldhauser and Schaff, 2008

**Shallower rupture => microseismicity at depth**  
**Deeper rupture => seismic quiescence**

2002 Mw 7.9 Denali, Alaska earthquake

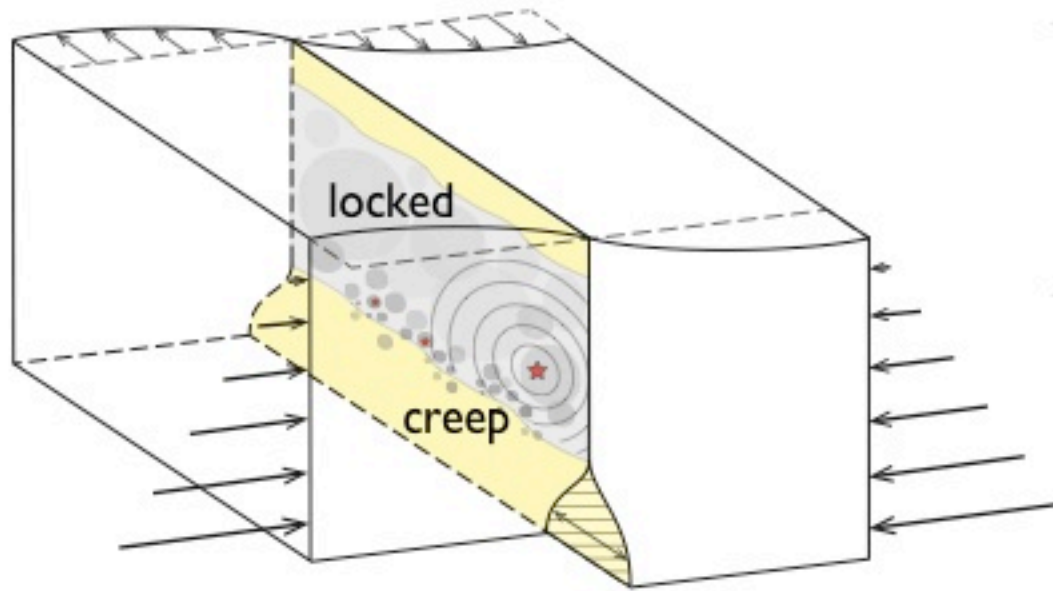
Slip model from Elliott et al., 2007



**Jiang and Lapusta, Science, 2016**



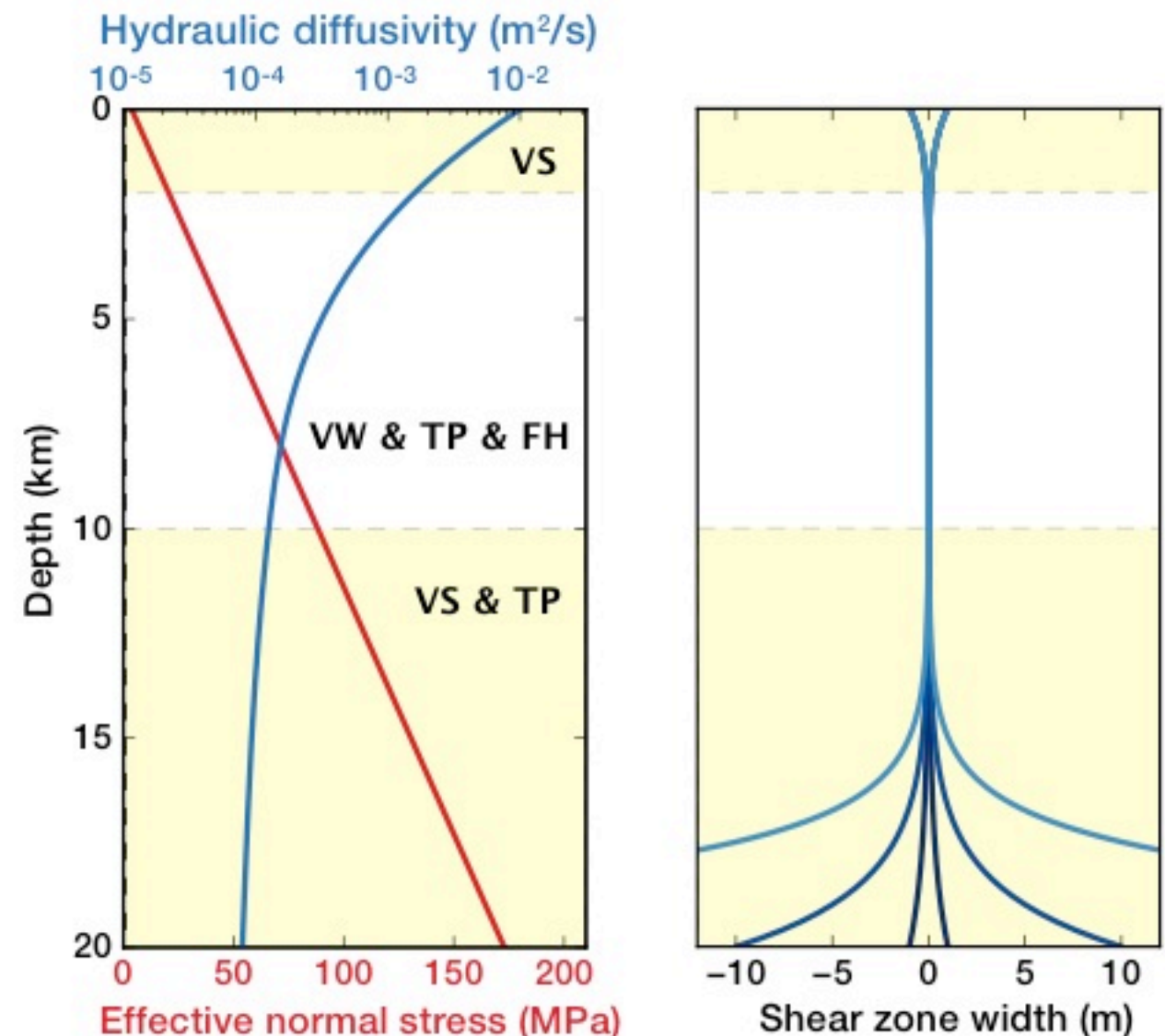
# What controls the depth of earthquake slip?



- **Conventional assumption:** seismic slip arrests at a fixed depth near locked/creeping transition (or VW/VS rate-and-state boundary)
- **Our hypothesis:** Arresting depth is affected by co-seismic weakening and hence depends on both fault properties and rupture evolution

For thermal pressurization of pore fluids:

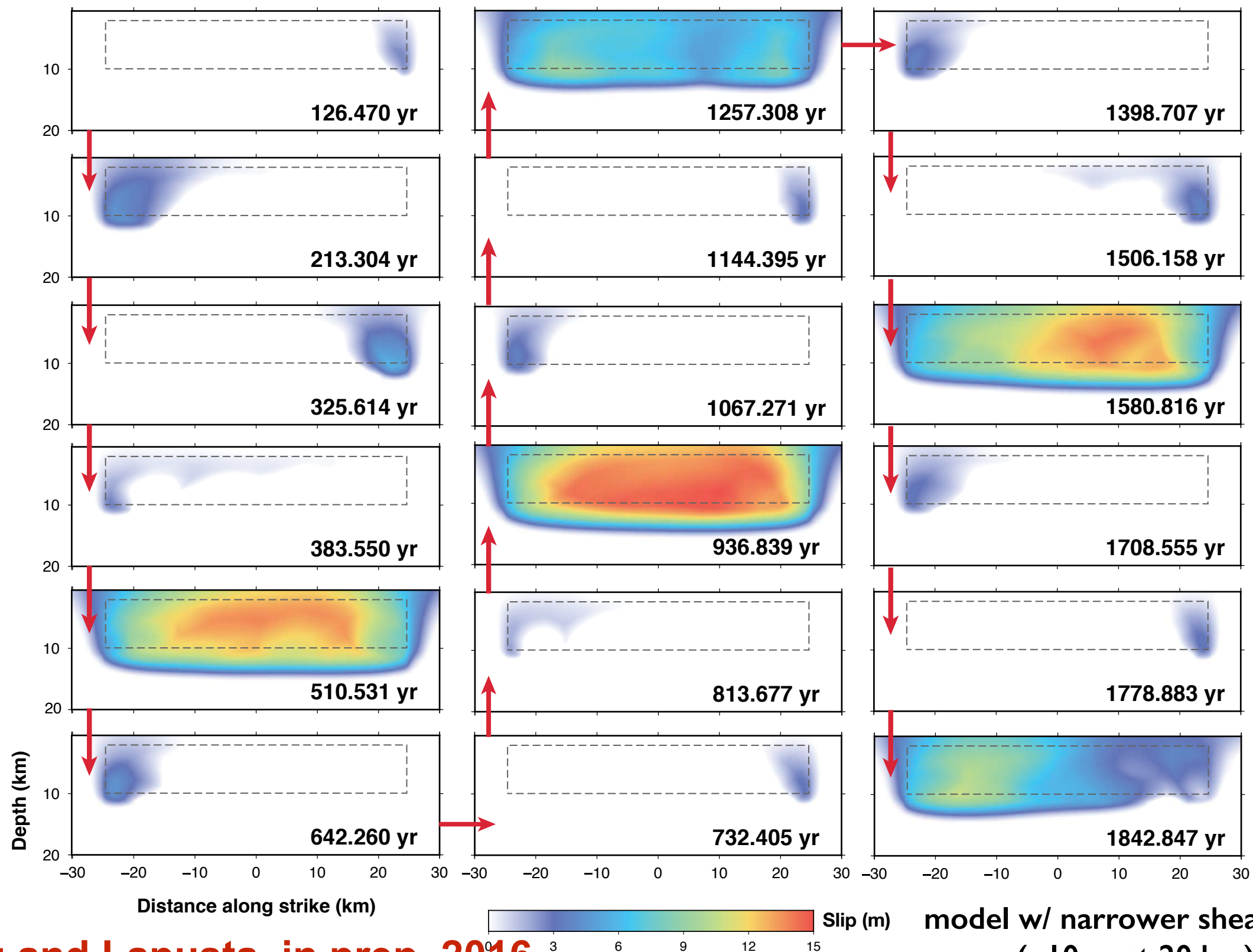
- Hydraulic diffusivity decreases with depth (e.g., *Wibberley & Shimamoto, 2003*)
- Shearing zone width increases with depth from mm to meters (e.g., *Cole et al., 2007*)
- The competition, together with the shear heating imposed by the rupture dynamics, determines the depth of seismic slip.



**Jiang and Lapusta, in prep, 2016**

# Variable slip depth in space and for different events

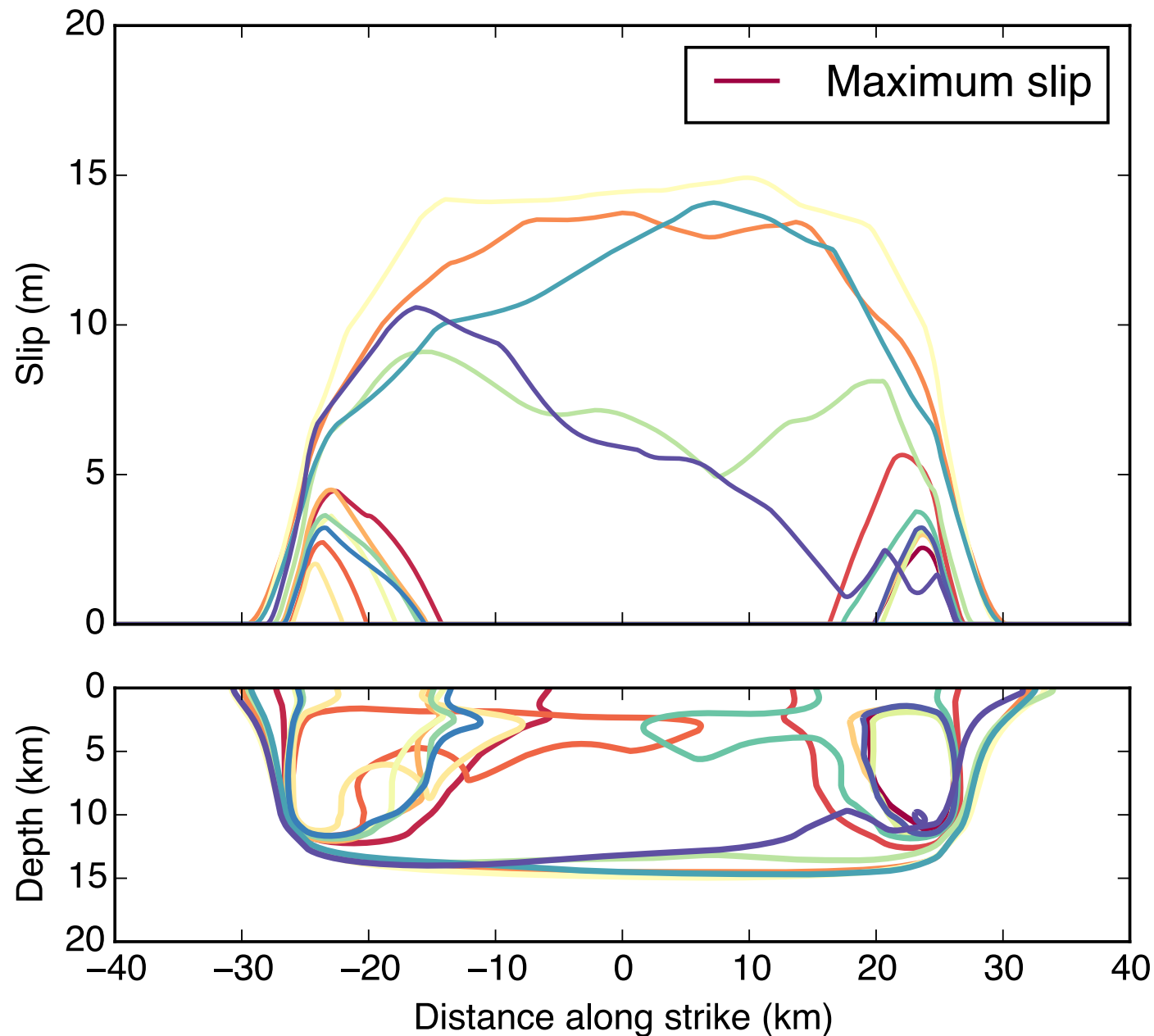
*No lateral variations in fault properties*



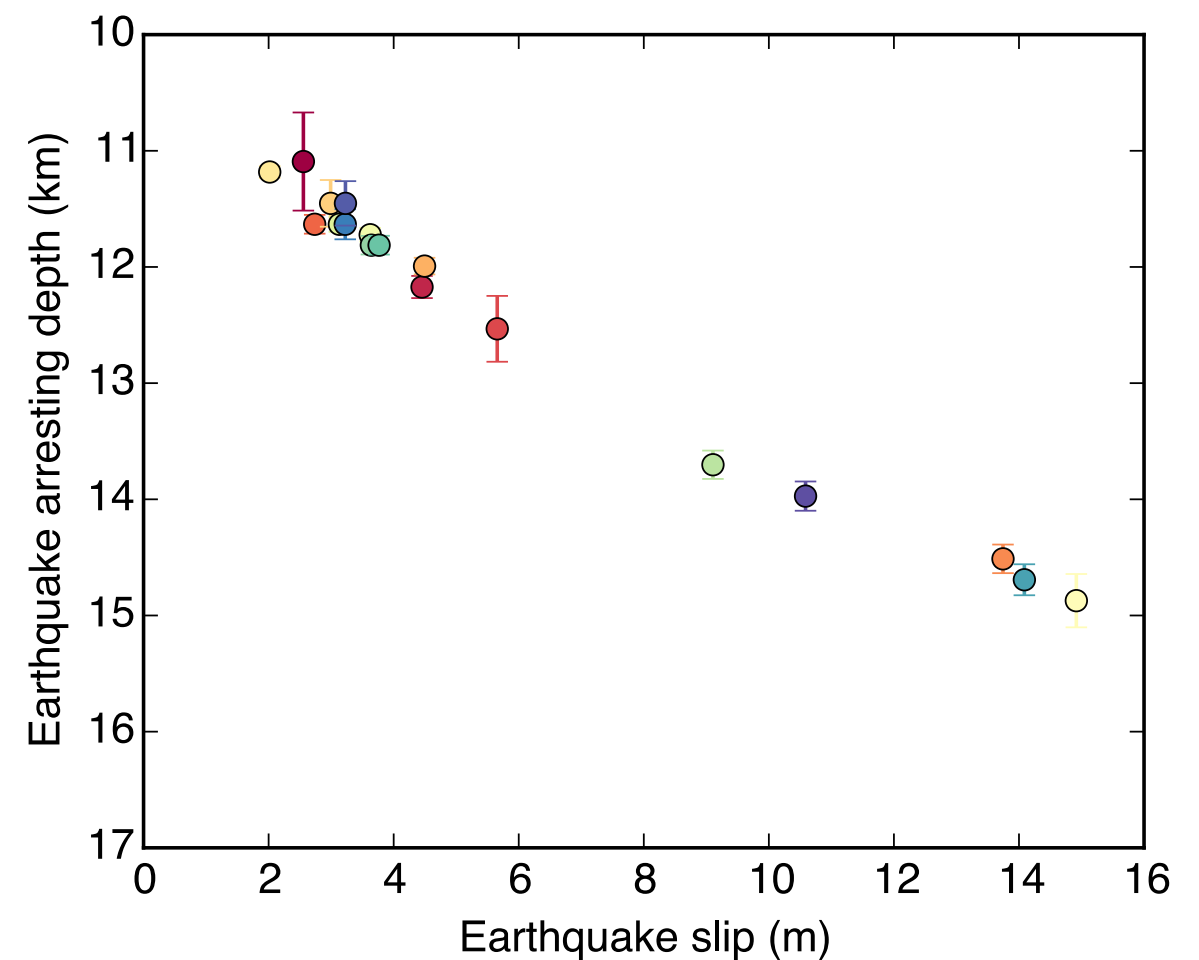
Jiang and Lapusta, in prep, 2016

# Depth of slip increases with earthquake slip

slip varies along strike



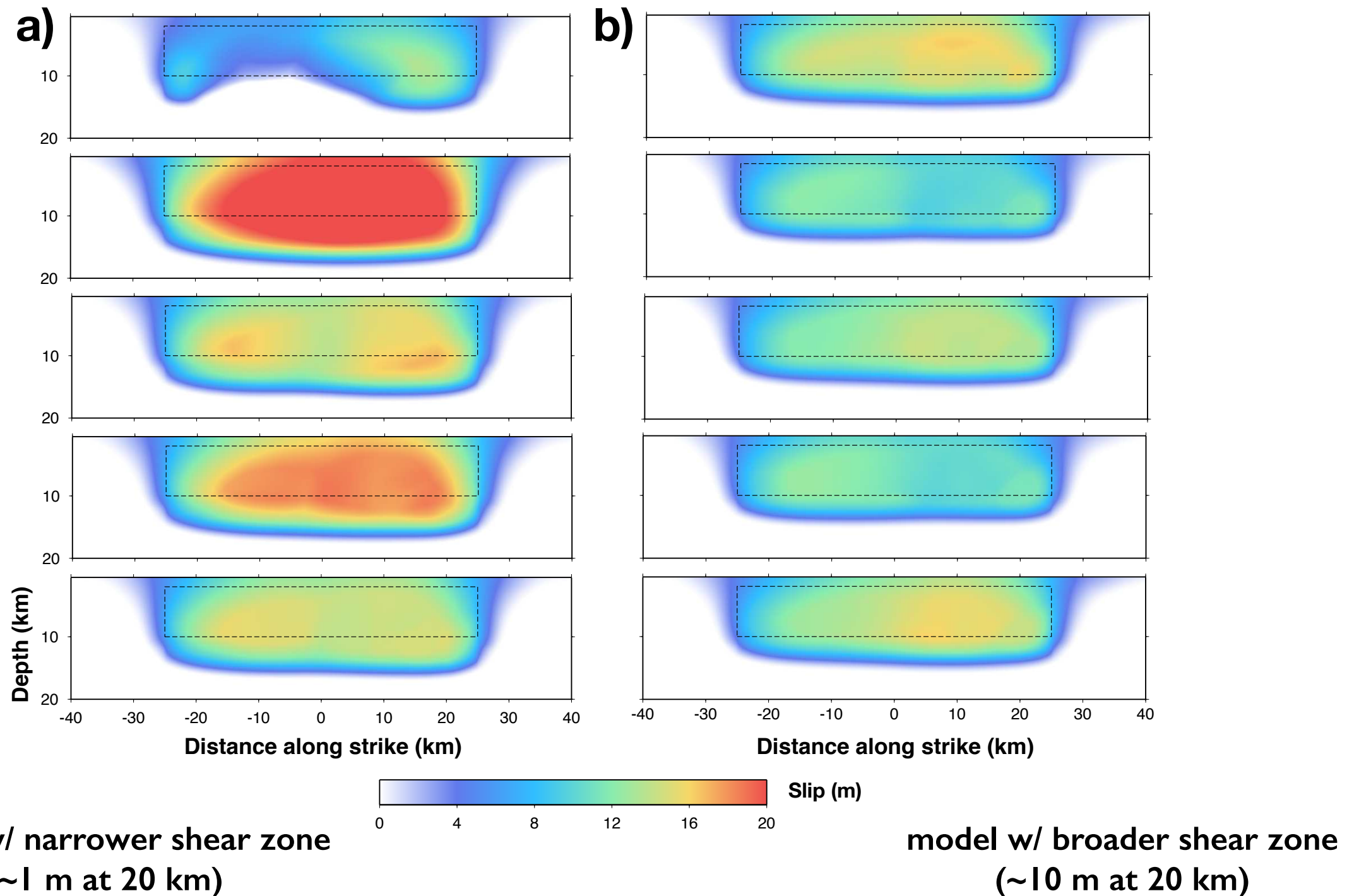
arresting depth increases with max earthquake slip





# Depth dependence of shear zone width is quite important

Both earthquake arresting depths and patterns are affected



Jiang and Lapusta, in prep, 2016

## Creeping regions may host large seismic slip due to co-seismic weakening, reproducing:

- A range of observations from the area of the 2011 Tohoku earthquake, qualitatively
- Quiescence of some major strike-slip faults (due to deeper large events)

★ No microseismicity on mature segments may indicate deeper large events ★

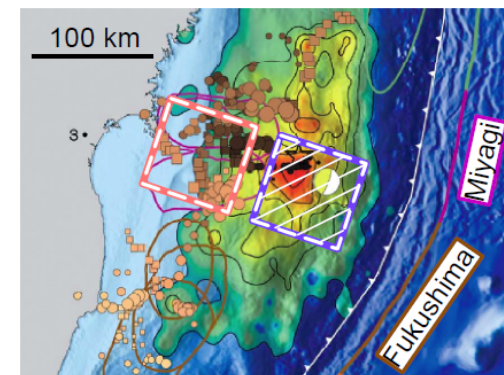
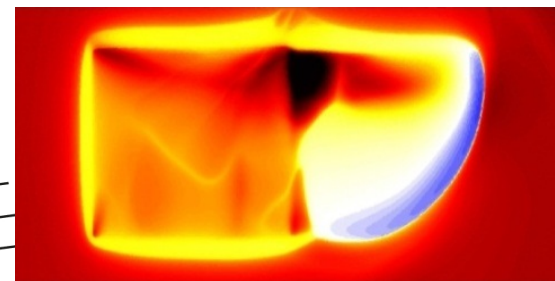
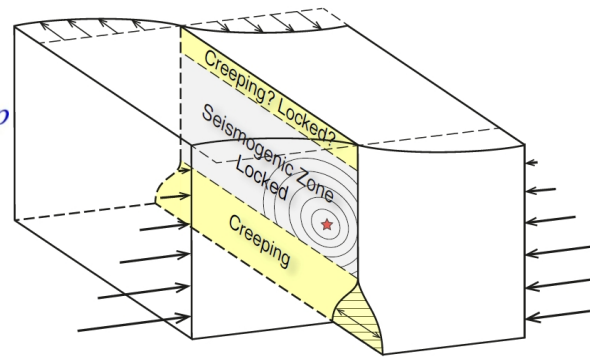
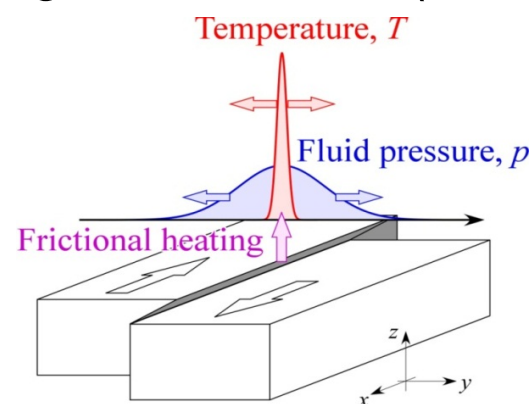
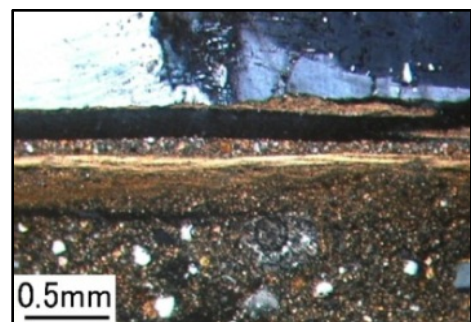
## The depth limit of seismic slip depends on both fault properties and rupture dynamics:

- For thermal pressurization of pore fluids, competition between decreasing permeability and increasing shear-zone width, with shear heating determined by rupture properties.
- Even for fault properties constant in time and uniform along strike, the depth limit of seismic slip varies along strike and changes from one large earthquake to the next.
- The depth extent of seismic slip increases with slip.

★ Similar behaviors should occur for other co-seismic weakening mechanisms ★

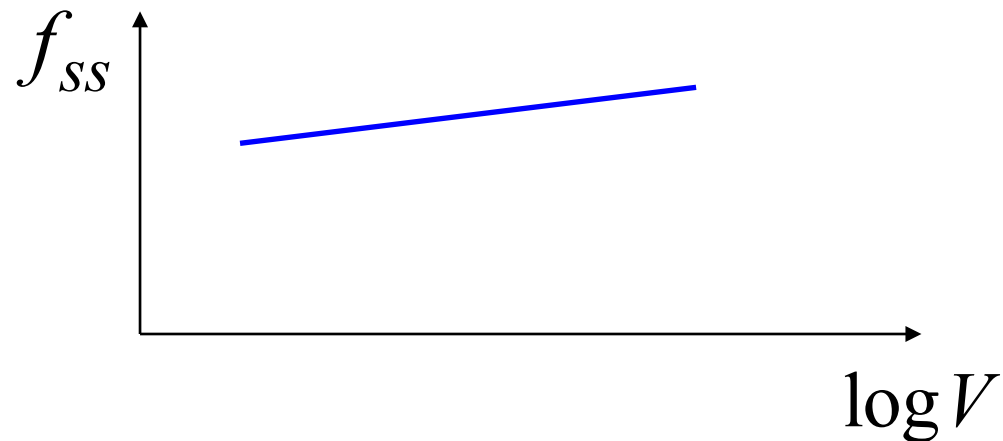
## Questions

- Shear-zone width at depth? Its evolution with seismic slip? Effect of inelastic off-fault behavior?
- Applicability of poroelasticity, def. of effective stress (Hirth and Beeler, 2015; Beeler et al., 2016)?
- Other weakening mechanisms (melting, thermal decomposition, superplasticity)?



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

**$a - b > 0$ , velocity strengthening**



**Aseismic slip under slow loading**

Factors that favor VS in experiments:

High temperatures (  $\sim 300$  C)

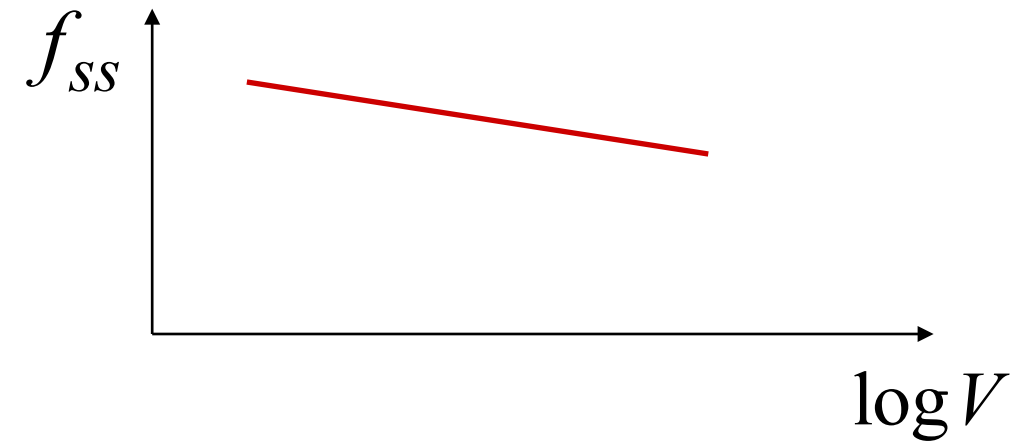
Aseismic faults below certain depth

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):

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

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



**Long-term fault behavior in such models:  
deeper penetration of seismic slip in large events  
that changes in time and varies along strike**

