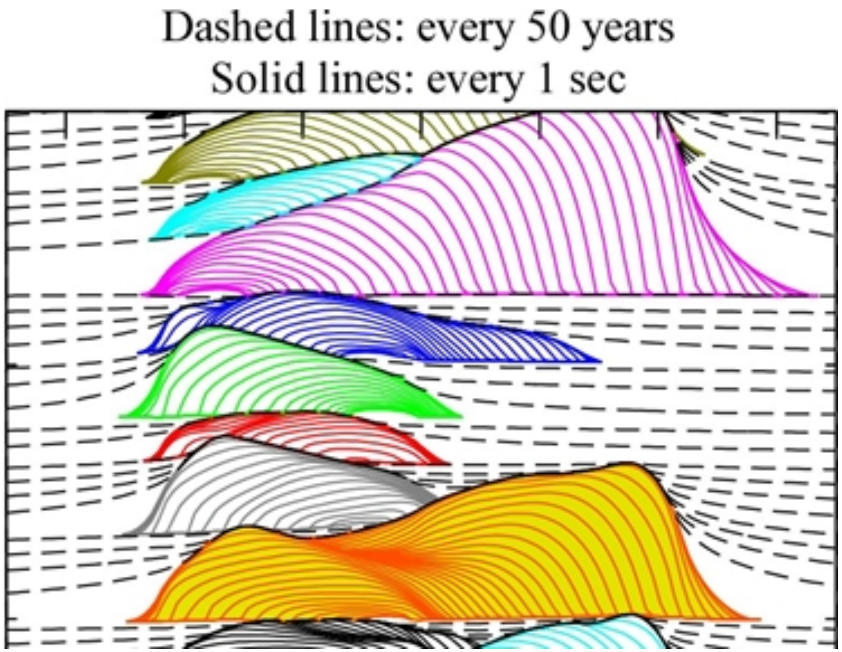
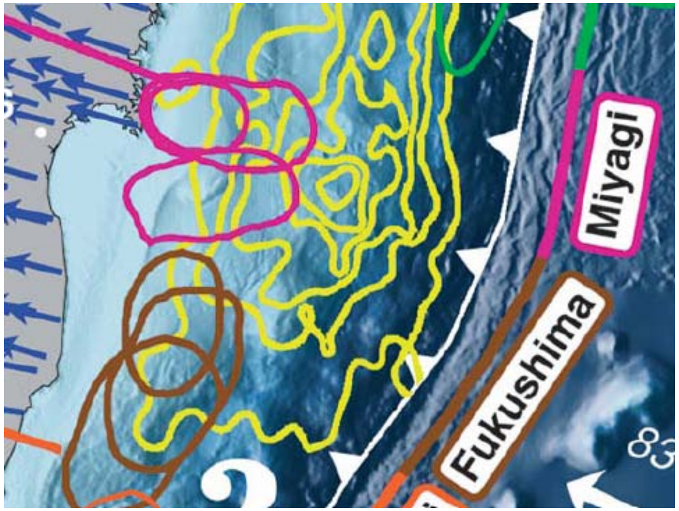
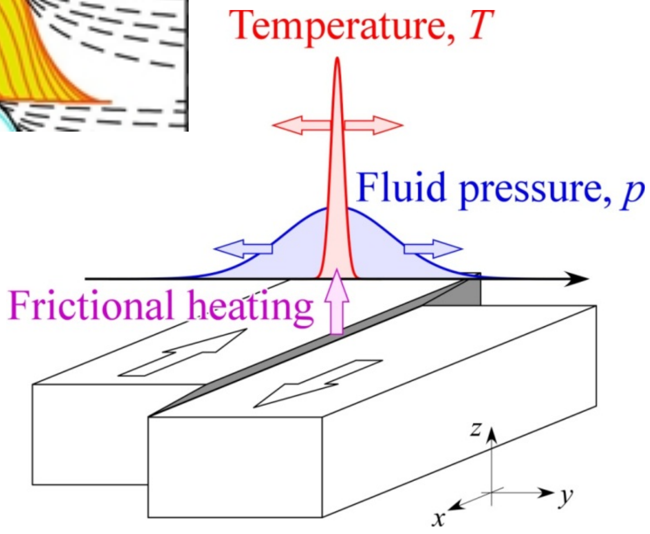
Qualitative modeling of earthquakes and aseismic slip in the Tohoku-Oki area

Nadia Lapusta, Caltech

Hiroyuki Noda, JAMSTEC







SEISMOLOGICAL LABORATORY
California Institute of Technology

Constitutive law on the fault: Rate-and-state friction at low slip rates + Potential co-seismic weakening due to pore pressure

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

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

$a - b > 0$, velocity strengthening

$a - b < 0$, velocity weakening

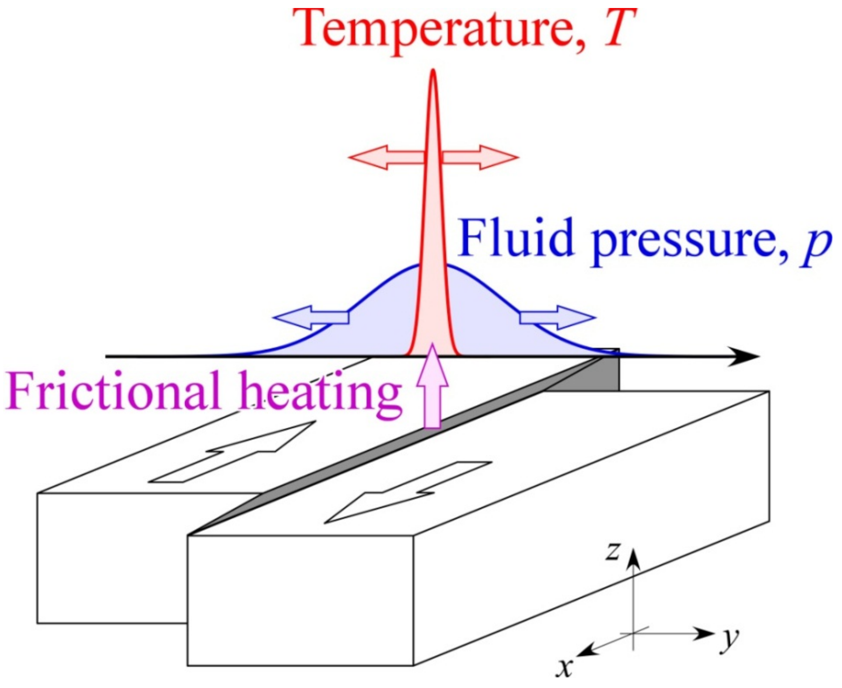
Aseismic slip under slow loading

Seismic slip in *large enough* regions

Aseismic slip in smaller regions

Potential co-seismic weakening due to shear heating and pore fluids

- Rapid shear heating during seismic slip causes expansion of pore fluids.
- This expansion may lead to increased pore pressure, depending on permeability .
- This could lead to **co-seismic fault weakening**, additional to any slow-slip friction behavior.



$$\tau = f(\sigma - p)$$

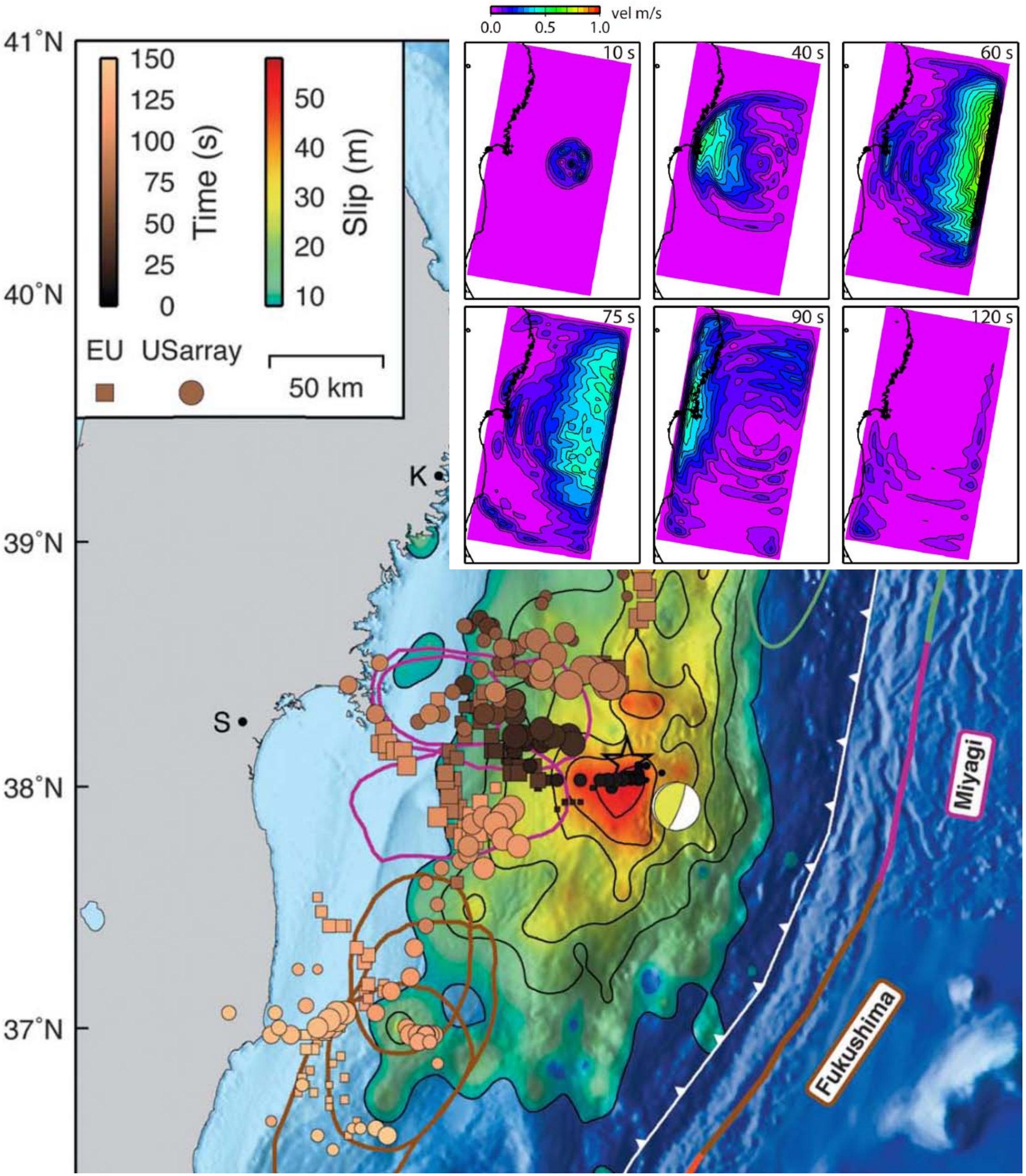
Pore fluid pressure evolution
(with diffusion normal to the fault):

$$\frac{\partial p(x,y,z,t)}{\partial t} = -\alpha_{hy} \frac{\partial^2 p}{\partial y^2} + \Lambda \frac{\partial T}{\partial t}$$

α_{hy}: **Hydraulic diffusivity (depends on permeability)**
Λ : Fluid pressure change / temperature change

Hibab [1967]; Sibson [1973], Lachenbruch [1980]; Mase & Smith [1985,1987]; Segall & Rice [1995]; Andrews [2002]; Garagash & Rudnicki [2003a,b]; Rice [2006]; Noda, Dunham, & Rice [2008]; Noda and Lapusta [2010], and others.

Rare unexpected event: 2011 Mw 9.0 Tohoku-Oki earthquake



Simons et al., Science, 2011

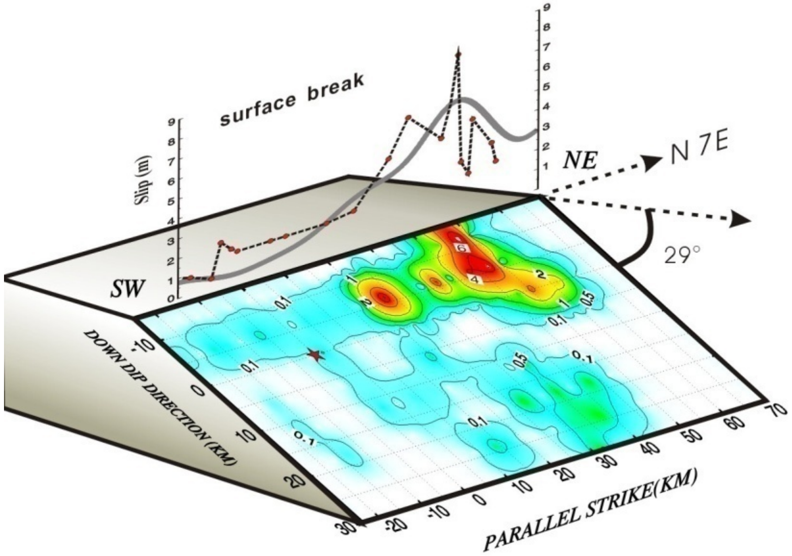
- **Extremely large unexpected seismic slip** (> 50 m) in shallower areas *which had been assumed to be stably moving (and hence barriers to earthquake rupture)*.
- **Inconsistency with prior ~Mw 8 events** at the bottom of the subducting interface.
- **Areas of lower slip generated more high-frequency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

Can we understand these observations in a single physical model?

Yes!

Noda and Lapusta, Nature, 2013

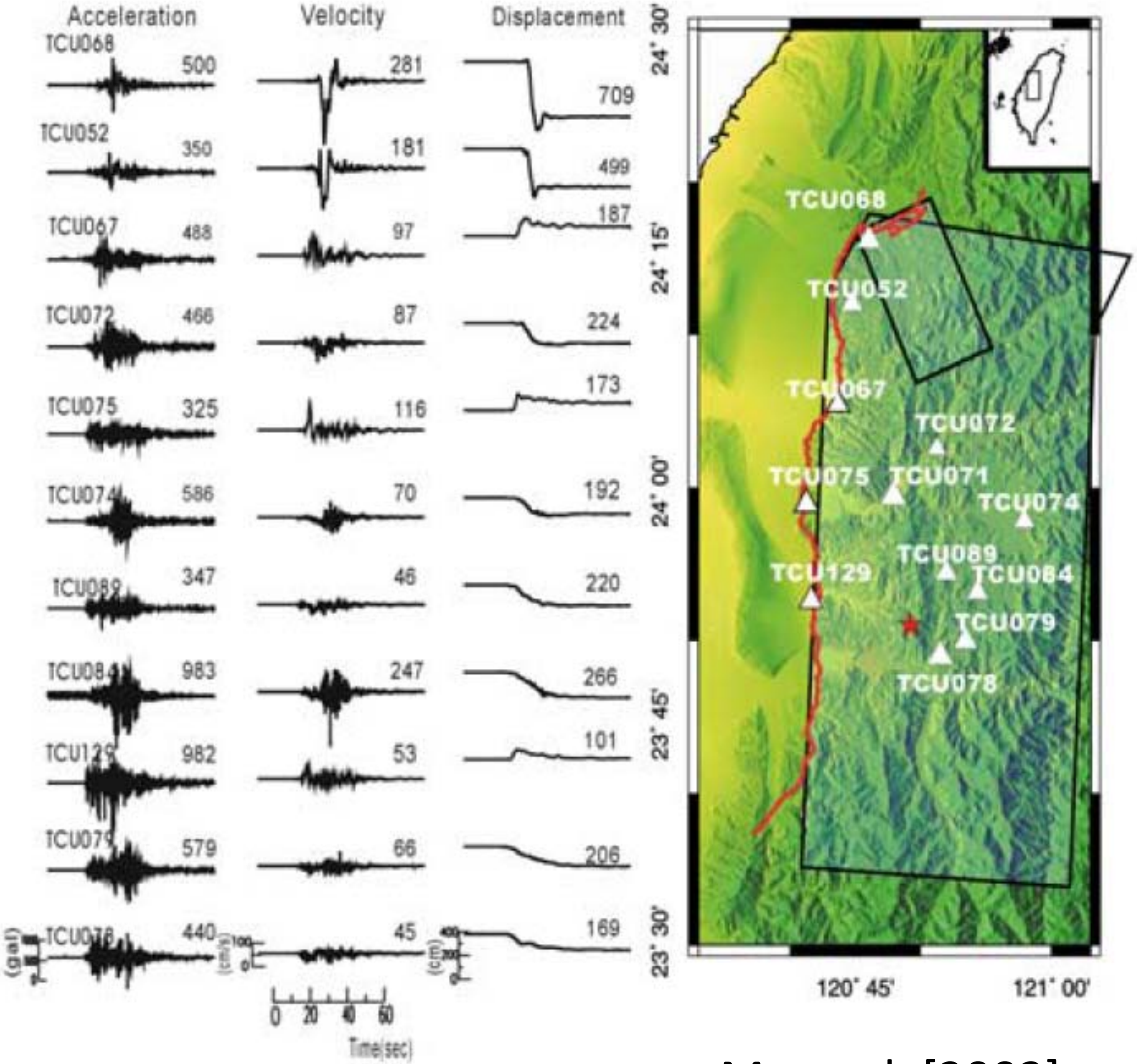
1999 (M_w 7.6) Chi-Chi earthquake in Taiwan



Ma et al. [2000]

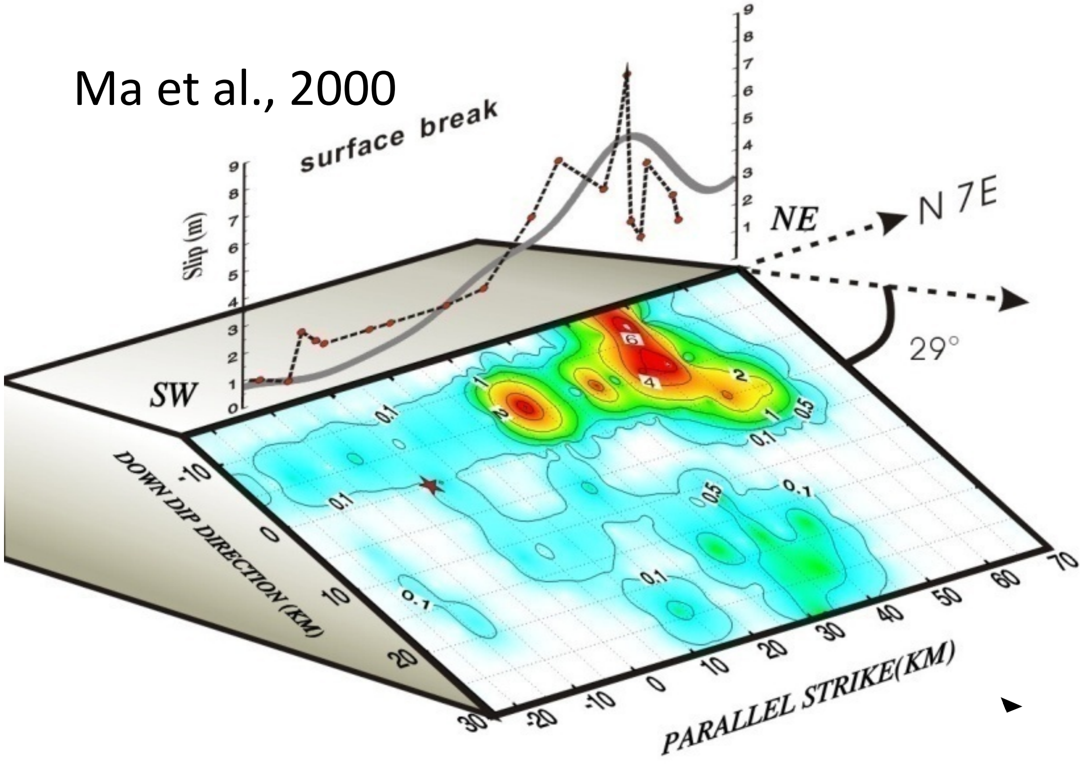
- Fault area with lower slip generated more high-frequency radiation [e.g. Ma et al., 2003].

Qualitatively the same behavior as in Tohoku-Oki!



Ma et al. [2003]

1999 (M_w 7.6) Chi-Chi earthquake in Taiwan



Ma et al., 2000

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 weakening through pore fluids

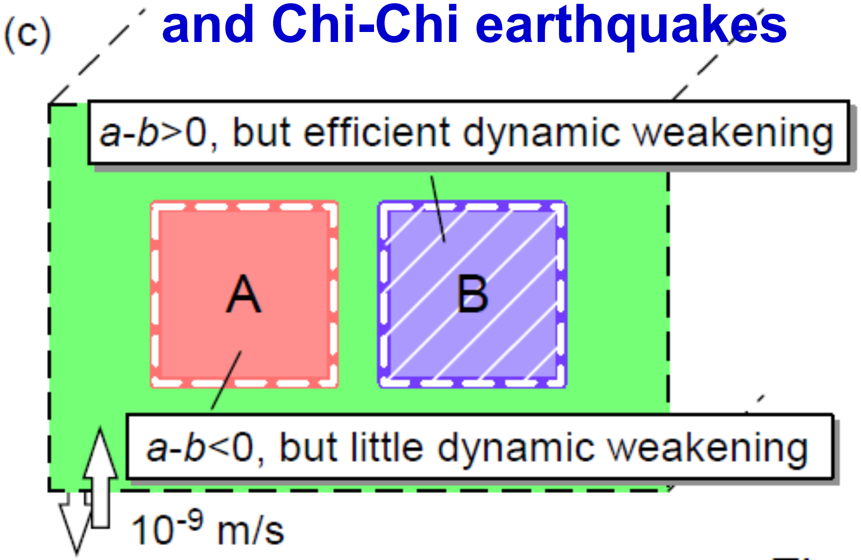
South :

Velocity-weakening, susceptible to nucleation

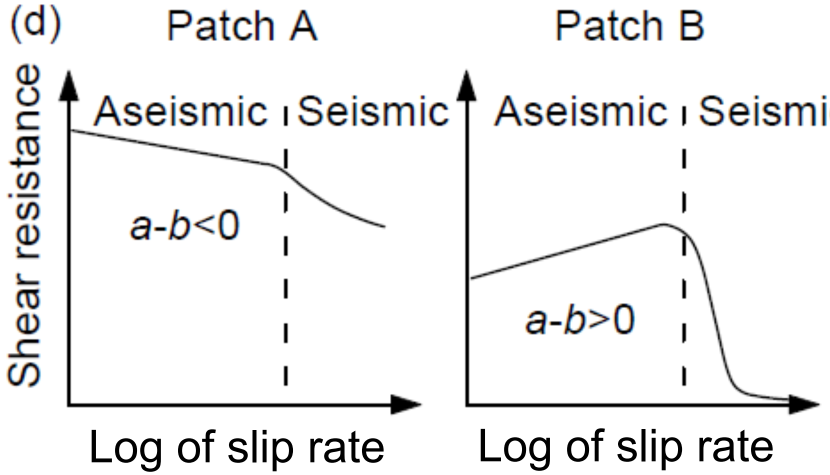
Higher permeablility

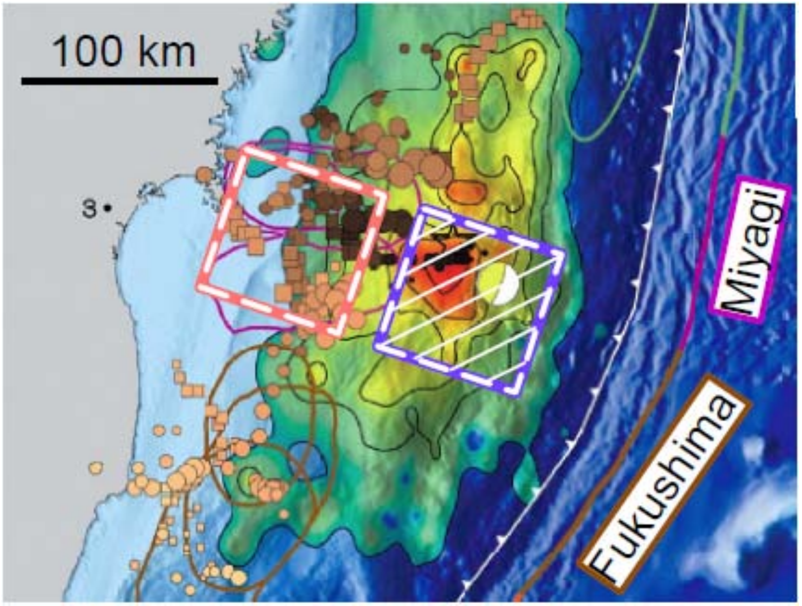
Caution:
The data is based on samples from shallow depths (200-300 m).

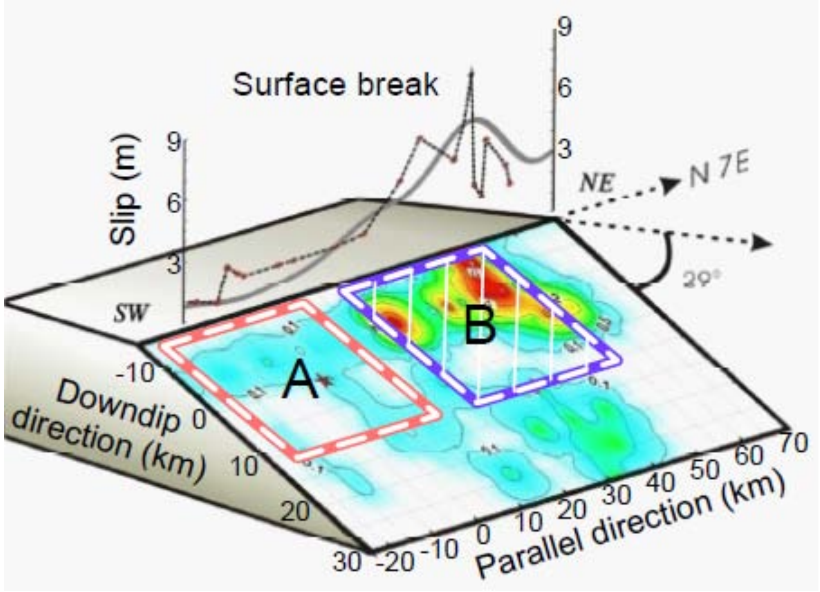
Model with simple geometry but realistic, lab-measured fault rheology and its correspondence to Tohoku-Oki and Chi-Chi earthquakes



Noda and Lapusta, Nature, 2013

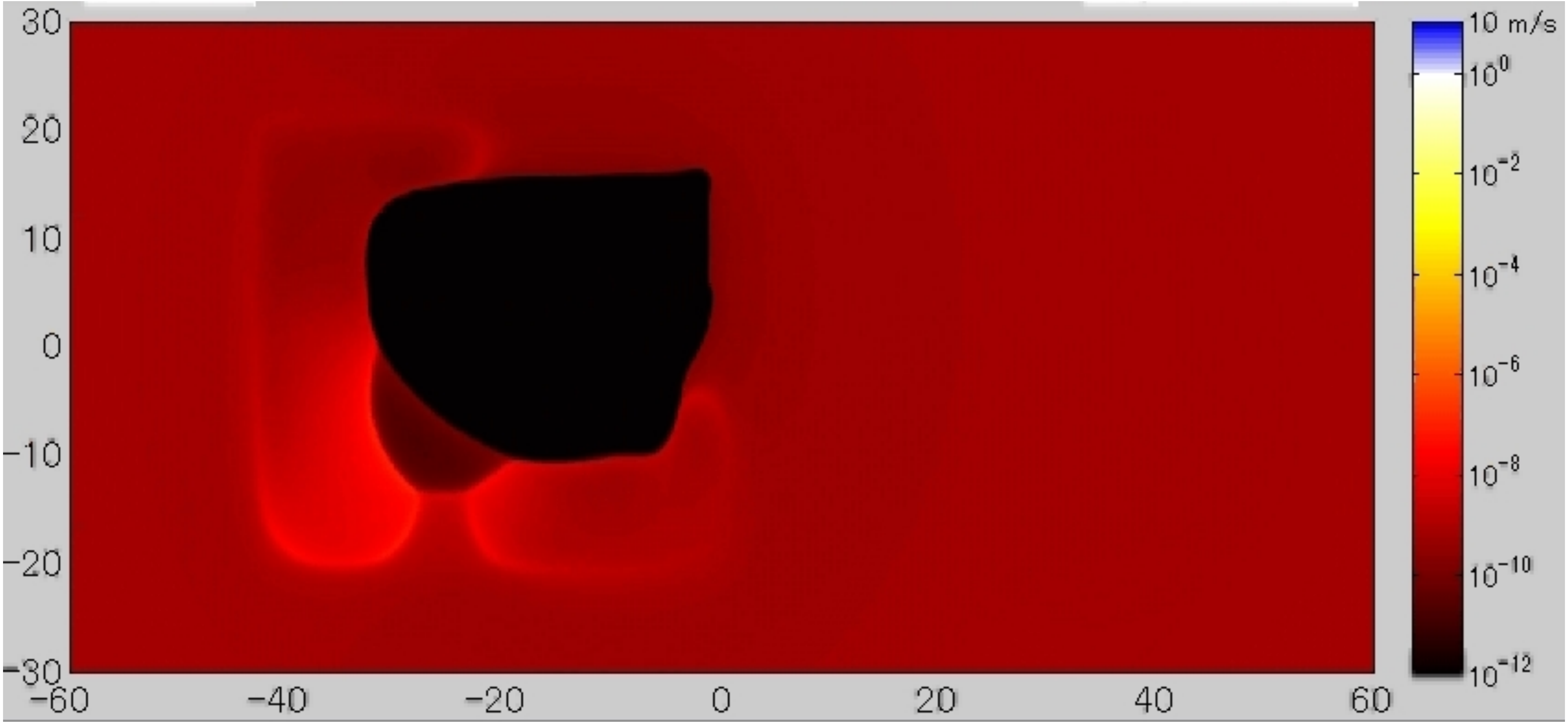






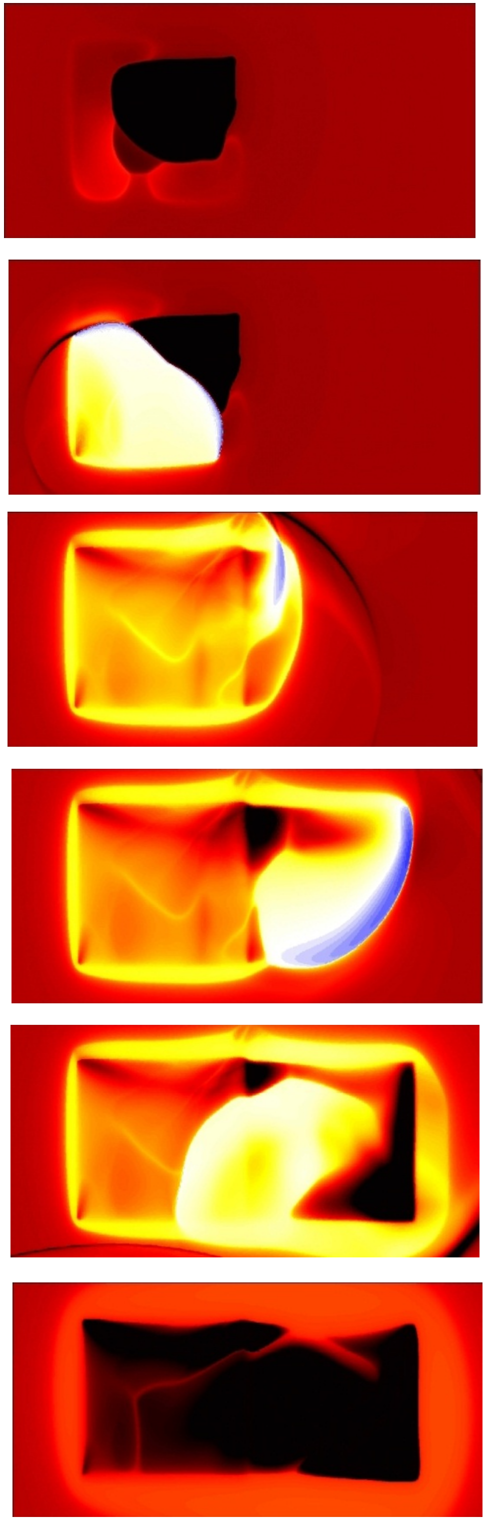
Numerical simulation methodology for long-term fault slip punctuated by earthquakes with all wave effects: Lapusta et al., 2000; Lapusta and Liu (2009); Noda and Lapusta (2010)

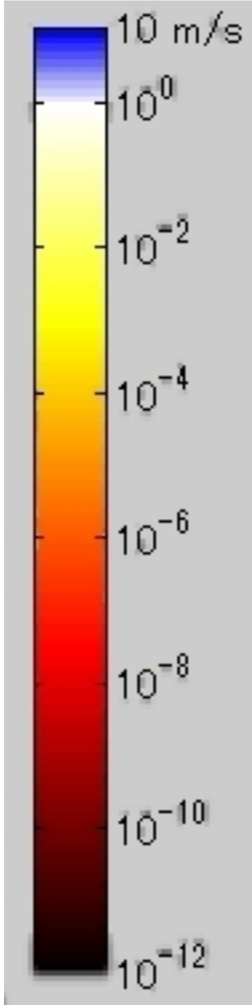
Snapshots of slip rate distribution on the fault



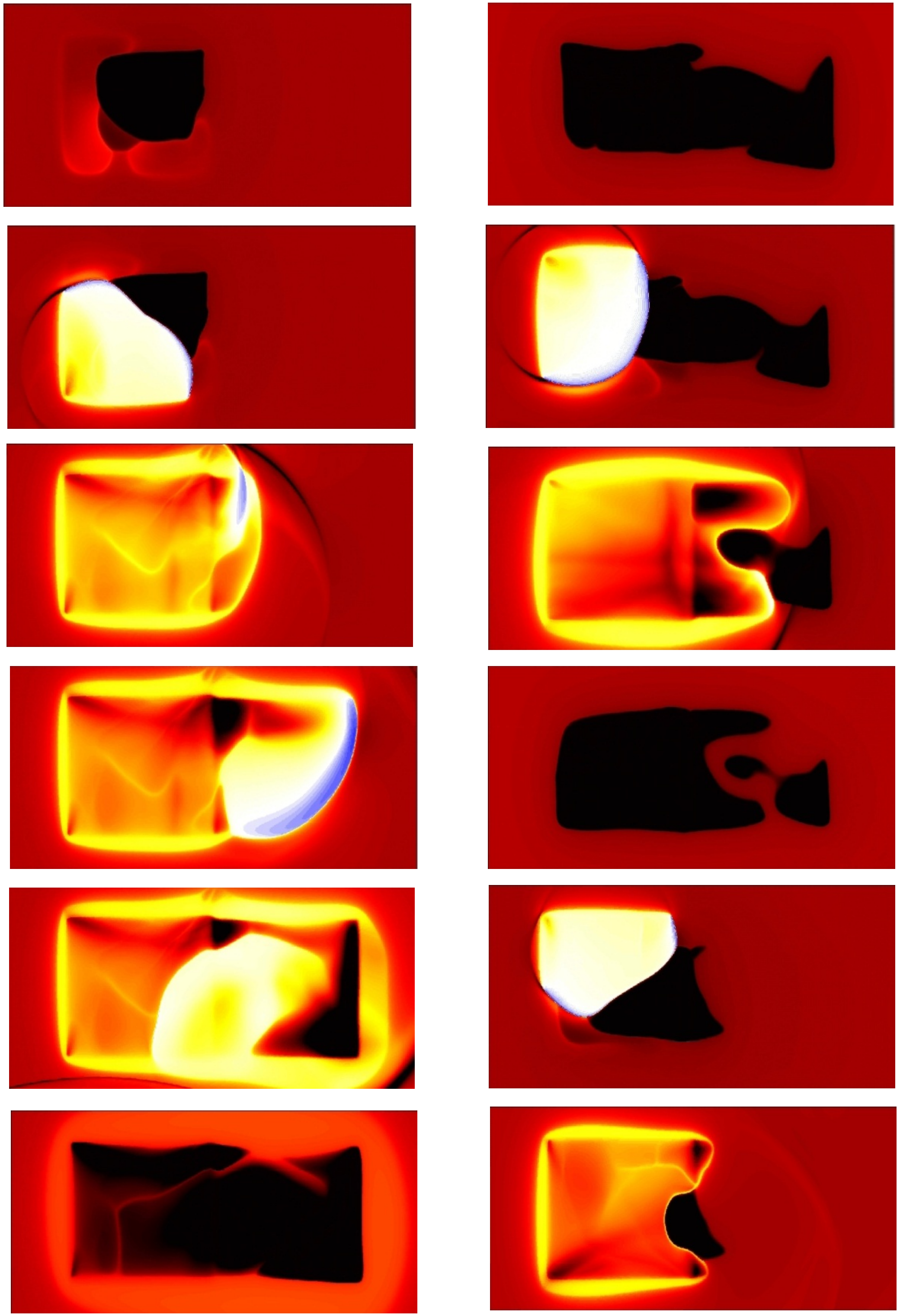
Movie

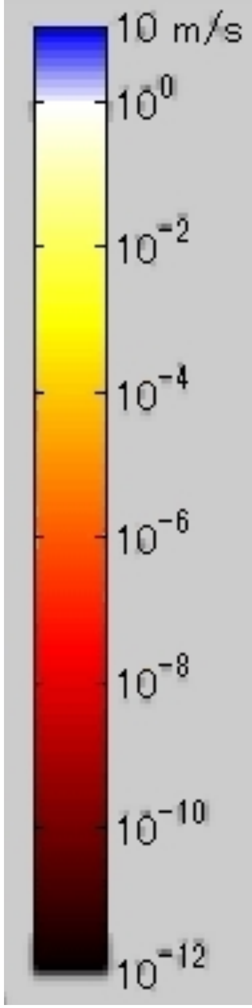
Snapshots of slip rate on the fault



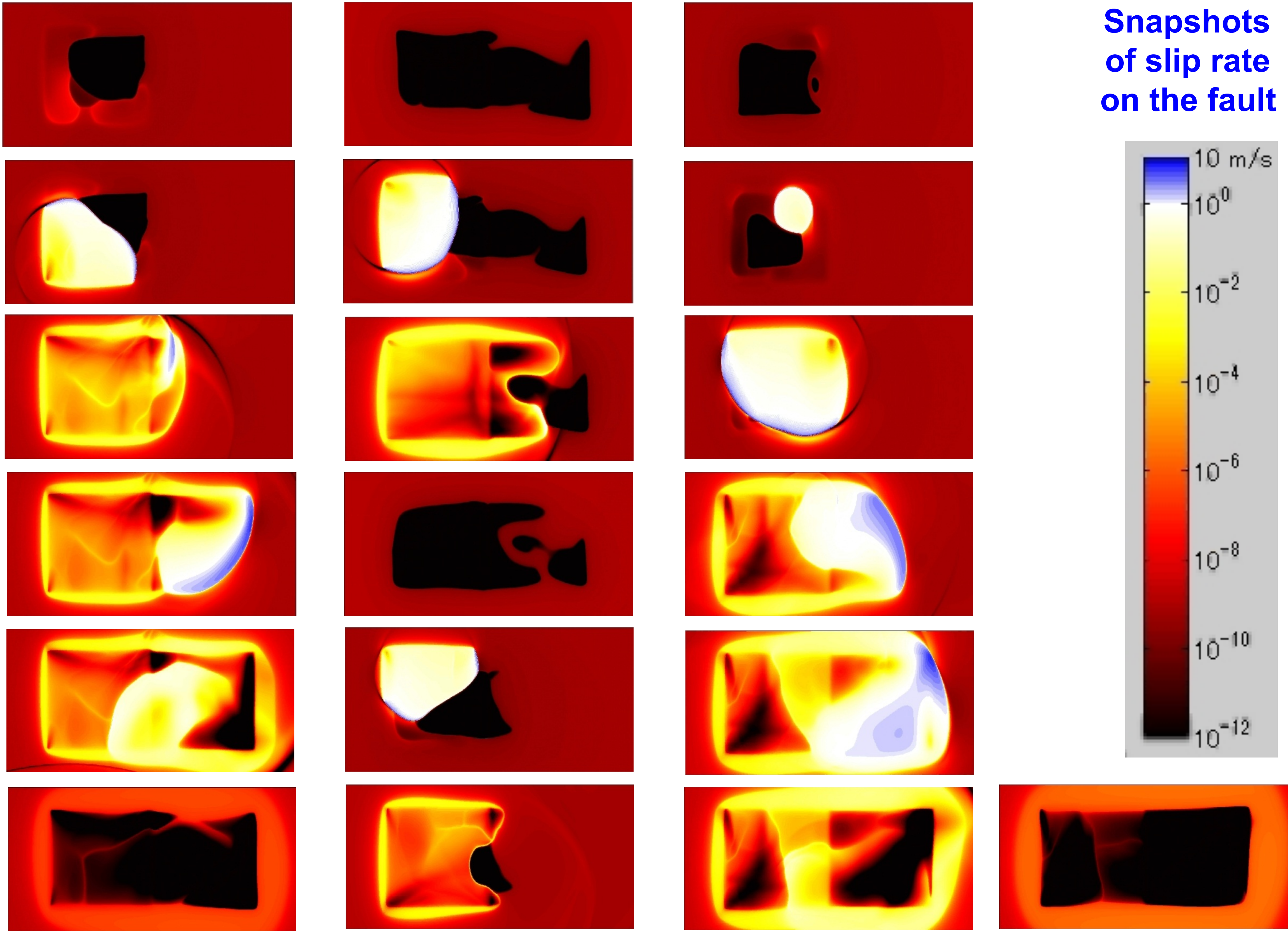


Snapshots of slip rate on the fault



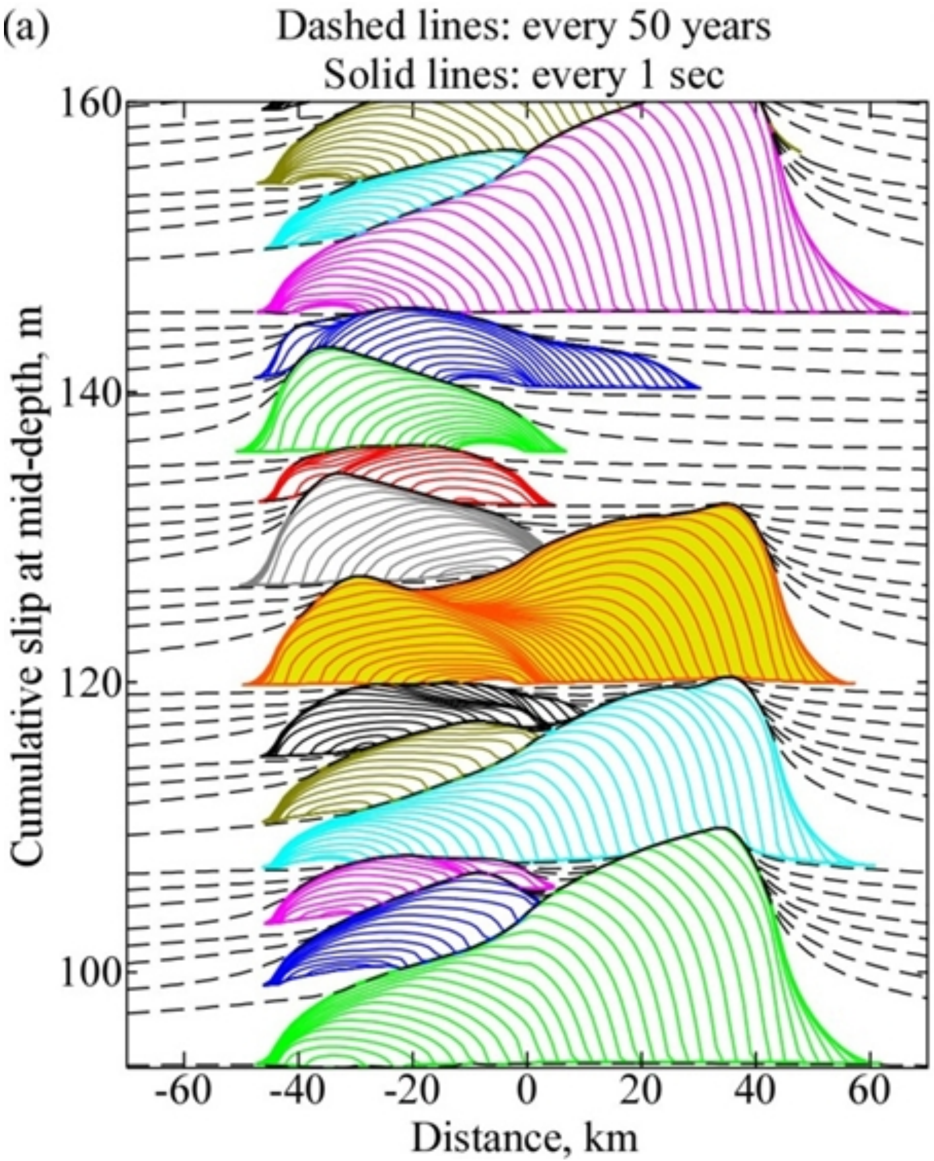


Snapshots of slip rate on the fault



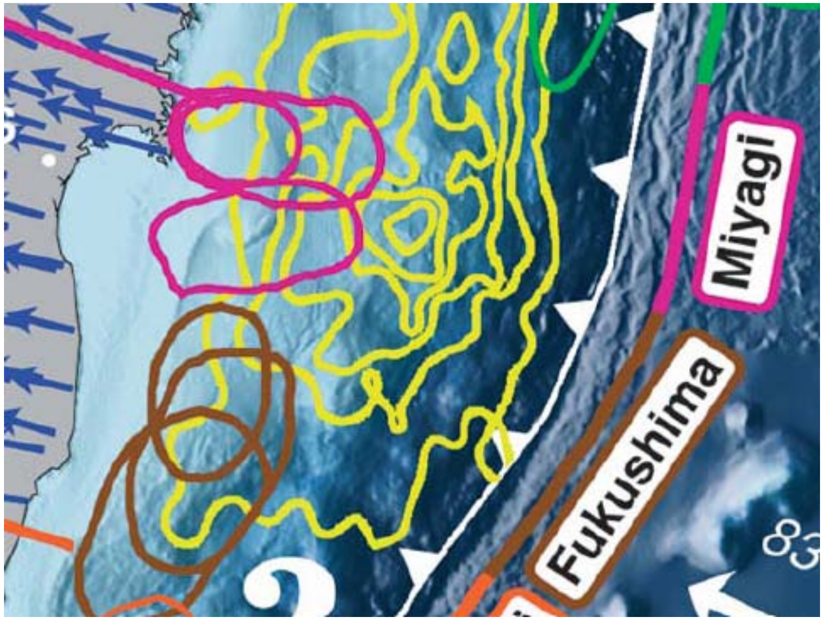
Qualitative match of long-term earthquake sequence behavior

Accumulation of fault slip



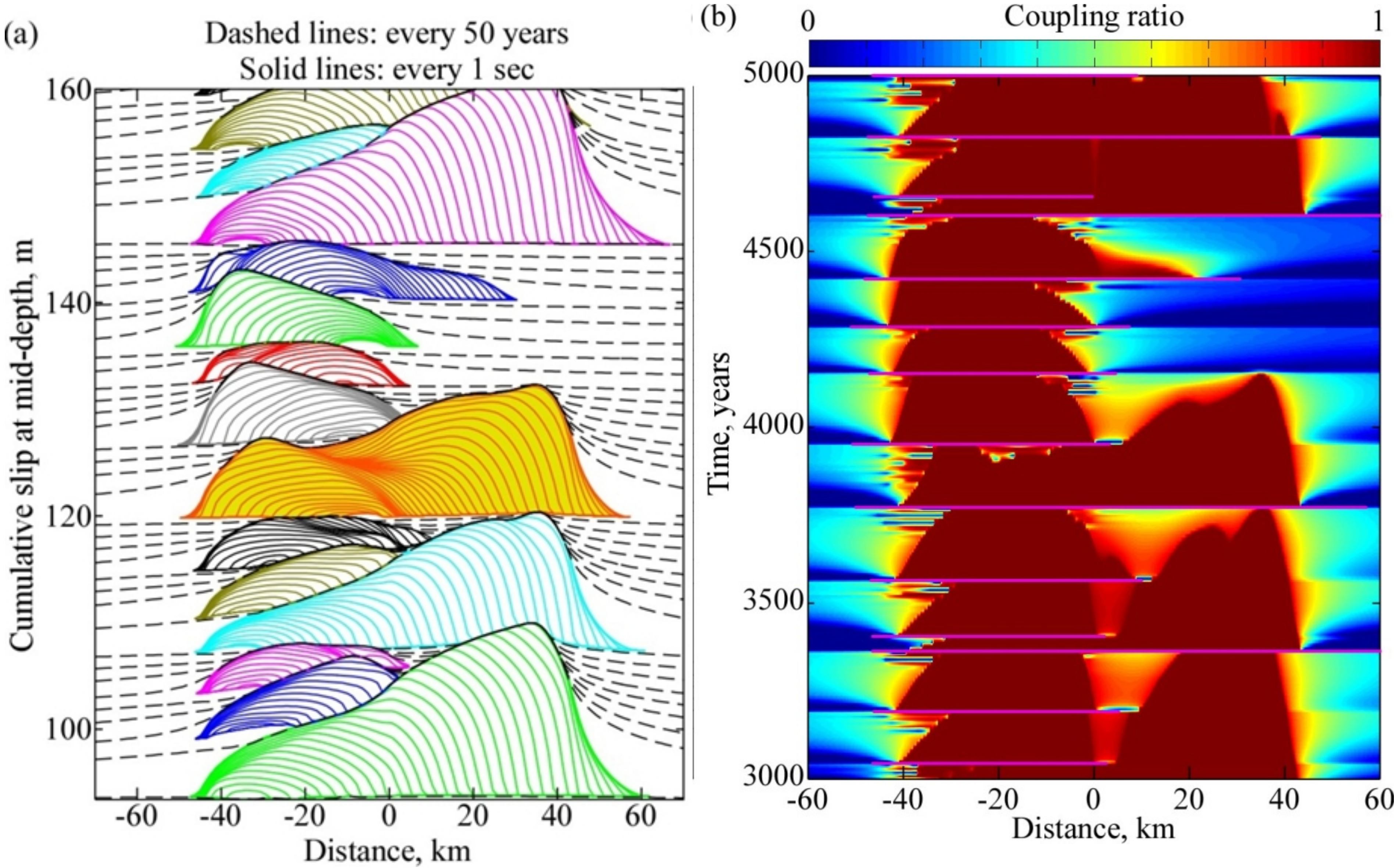
- A number of smaller events in the left patch per each event spanning both patches (as for both Tohoku-Oki and Chi-Chi faults)

- Large coseismic slip in the right patch which can also be creeping



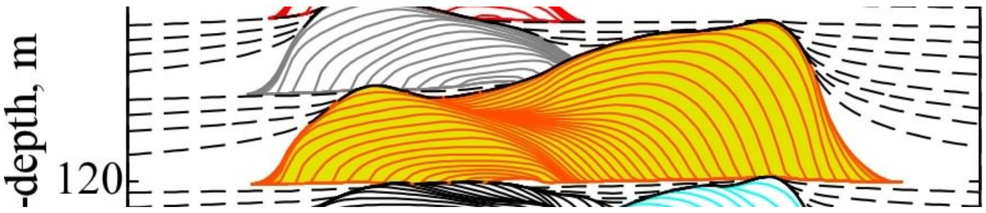
Prior smaller events in relation to Tohoku-Oki, from Simons et al., 2011

Rich behavior of the patch which is stable at low velocities but potentially unstable co-seismically



The area of largest slip can be creeping (“stable”, “decoupled”) beforehand.

Complex rupture pattern during largest events

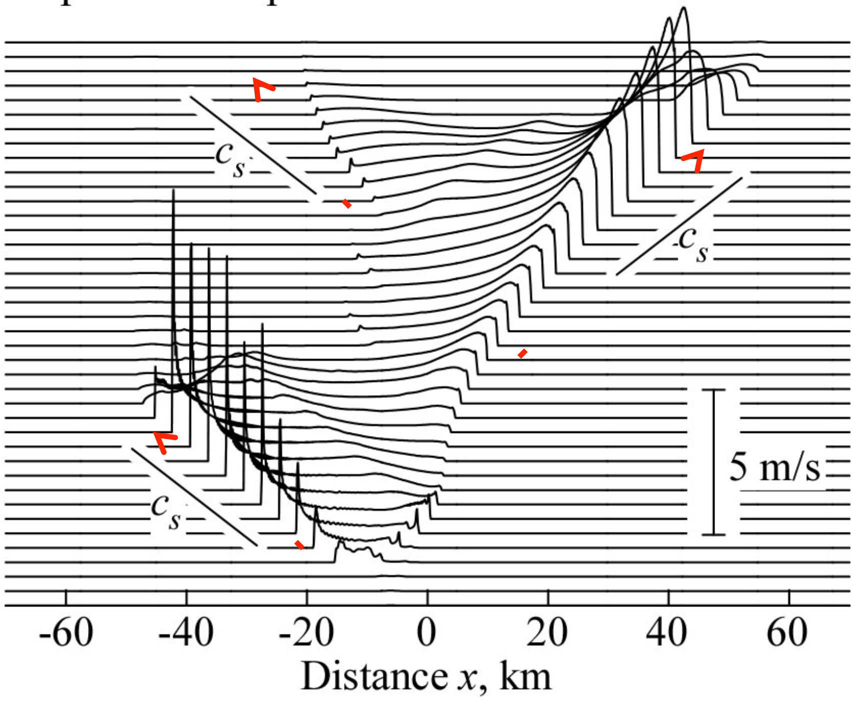


1. Rapid rupture with a sharp peak in patch A

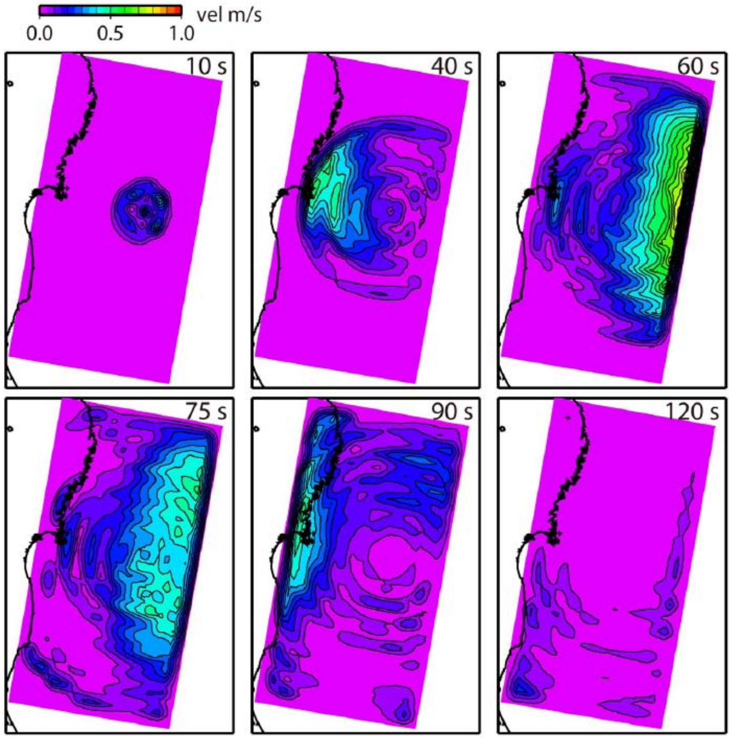
2. Acceleration of a slower rupture without a sharp peak in patch B

3. Secondary backward-propagating rupture in patch A

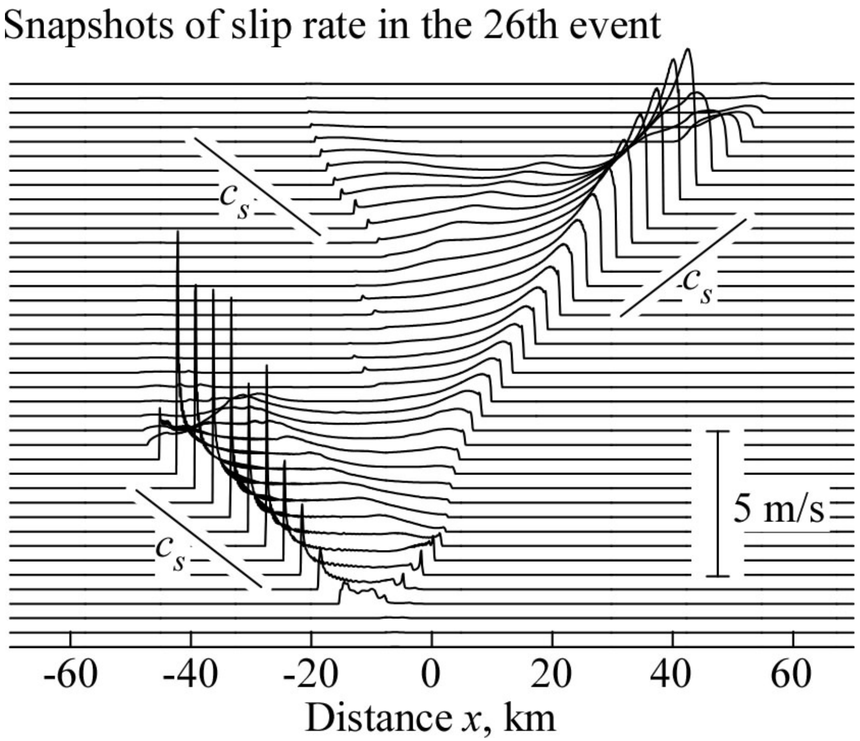
Snapshots of slip rate in the 26th event

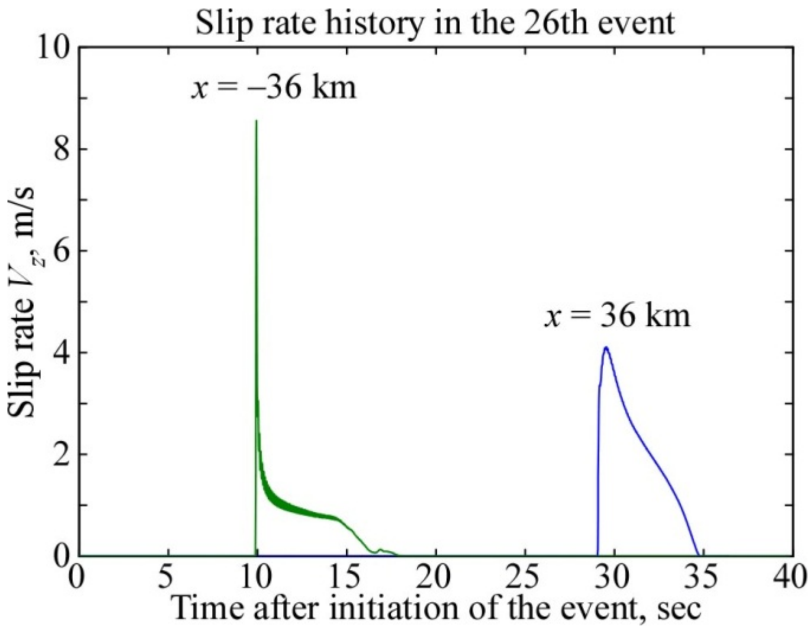


Qualitatively similar to Ide et al. [2011]



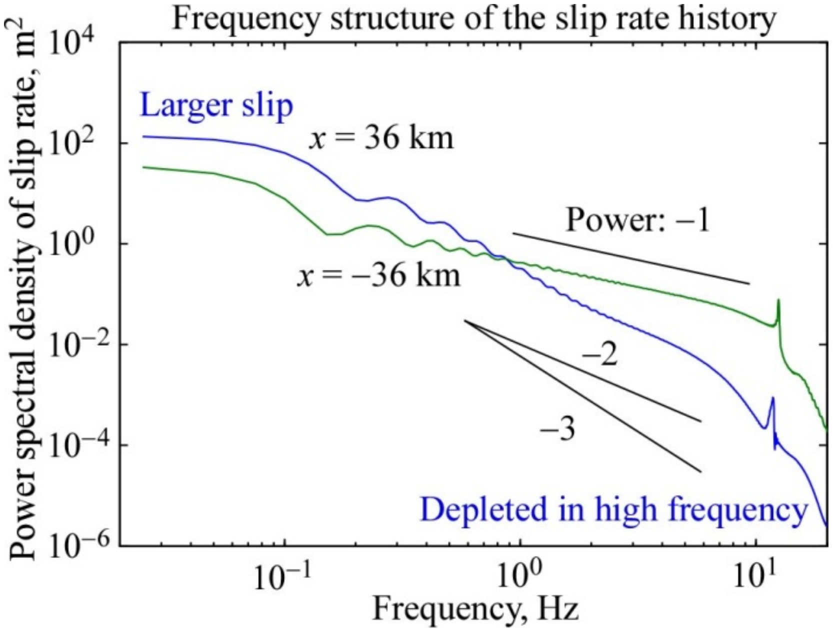
Frequency contrast between slip in the two patches





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].

This effect could act alone or in combination with other mechanisms for variations in frequency content, such as heterogeneity of friction properties [Meng et al., 2011].



Conclusions

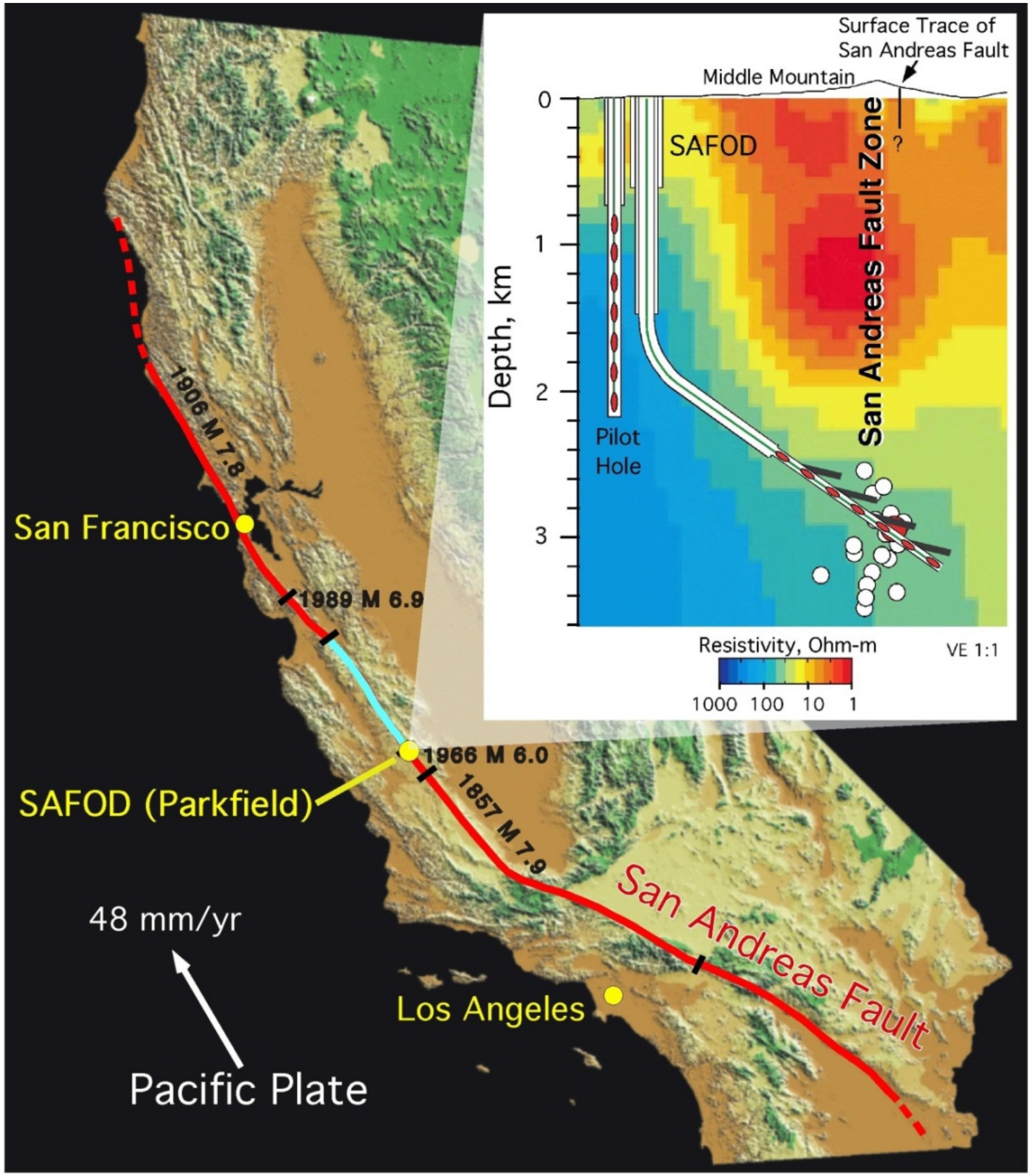
- The model qualitatively explains observations on a range of temporal scales for two well-studied earthquakes (Chi-Chi and Tohoku-Oki).
  - Largest slip in the segment that may have been creeping interseismically
  - More frequent smaller events in the other segment
  - More high-frequency radiation from lower-slip areas; variations in rupture direction
- Patches stable at low velocities but susceptible to high-velocity (co-seismic) weakening show rich behavior in numerical simulations.

Implication for seismic hazard: The fact that a fault segment is creeping may not automatically make it a barrier or preclude large co-seismic slip.

Implications for Tohoku-Oki: The shallow fault region with the largest co-seismic slip may well have been creeping before the earthquake.

- We need more laboratory and theoretical studies to understand which materials/fault structures are/may be susceptible to co-seismic weakening and more field studies of whether creeping segments have had seismic events.

Can a large earthquake propagate through the creeping section of San Andreas fault?



Hickman, Zoback, Ellsworth, 2004

Such a scenario is possible if we have:

- Velocity-strengthening friction at (low) interseismic slip rates
- Co-seismic weakening at (high) seismic slip rates

Evidence for such behavior from

Chi-Chi and Tohoku-Oki earthquakes

Model ingredients and parameters

3D elastodynamics represented by a spectral boundary integral equation method

$c_s = 3$ km, $\upsilon = 1/4$, $\mu = 30$ GPa [Lapusta and Liu, 2009]

Ambient effective normal stress $\sigma_{e0} = 60$ MPa

Rate- and state-dependent friction coefficient (aging law)

State-evolution distance $L = 8$ mm (A and B)

Direct effect parameter $a = 0.0066$ (A and B)

[Tanikawa and Shimamoto, Personal communication]

Steady-state rate dependency $a - b = 0.004$ (A), -0.002 (B)

Friction coefficient at a reference ($V_0 = 10^{-6}$ m/s) $f_0 = 0.4$ (A), 0.7 (B)

[Tanikawa and Shimamoto, 2009]

Frictional heating and resulting pore-pressure evolution (thermal pressurization) with diffusion of heat and pore fluids away from the fault [Noda and Lapusta, 2010]

Hydraulic diffusivity $\alpha_{hy} = 7\times10^{-5}$ m^2 (A), 3.5×10^{-2} m^2 (B)

Undrained pore pressure change / temperature change

$\Lambda = 0.036$ MPa/K (A),0.069 MPa/K (B) [T&S, 2009]

Half-width of the shear zone $w = 8$ mm (A and B)

We treat the lab measurements as motivational rather than precise values, since they are based on samples from two boreholes at shallow depths (200-300 m).

Temperature and pore pressure evolution

Temperature evolution (with diffusion normal to the fault):

$$\frac{\partial T(x,y,z,t)}{\partial t} = -\alpha_{th}\frac{\partial^2 T}{\partial y^2} \quad \frac{\omega}{\rho c}$$

T : Temperature
α_{th} : Thermal diffusivity
ω : Heat generation per unit volume
ρ : Density
c : Heat capacity per unit mass

Heat source:

$$\omega = \frac{\tau V}{w\sqrt{2\pi}}\exp\left(-\frac{y^2}{2w^2}\right)$$

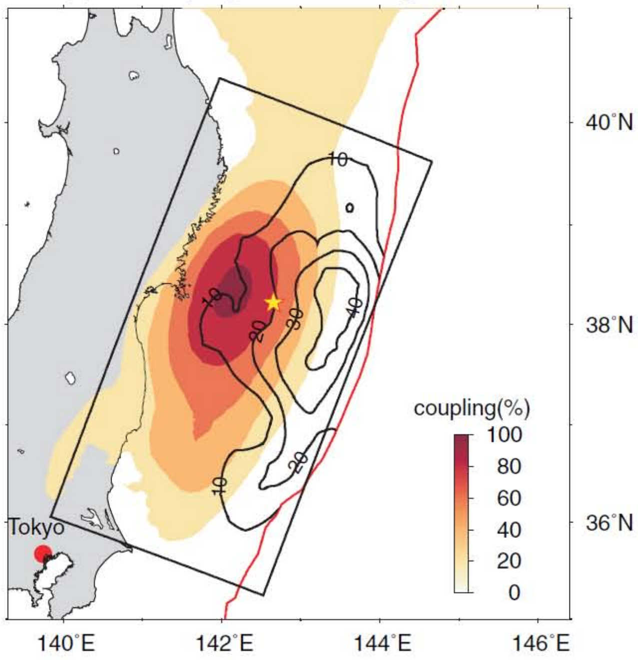
w : Half width of the shear zone

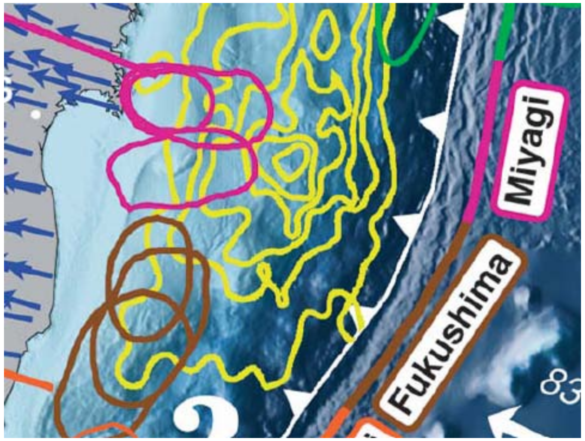
Pore fluid pressure evolution (with diffusion normal to the fault):

$$\frac{\partial p(x,y,z,t)}{\partial t} = -\alpha_{hy}\frac{\partial^2 p}{\partial y^2} + \Lambda\frac{\partial T}{\partial t}$$

α_{hy} : **Hydraulic diffusivity (depends on permeability)**
Λ : Fluid pressure change / temperature change

2011 Great Tohoku-Oki earthquake


(a) old coupling model and slip model

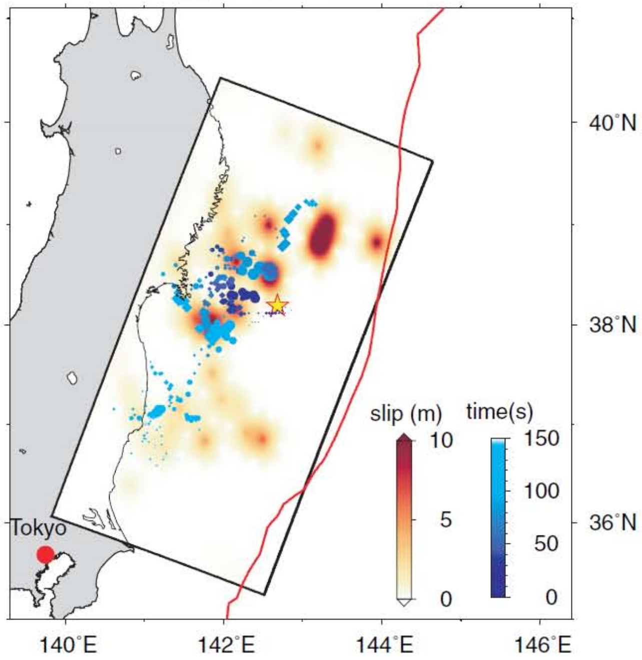


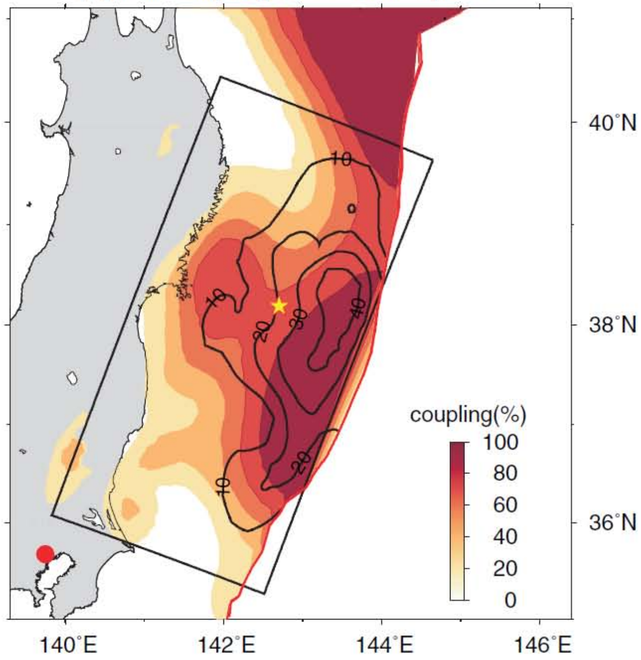
Simons et al., 2011

- Extremely large seismic slip (> 60 m) in shallower areas where the fault was assumed to be creeping.

- Inconsistency with prior events: Smaller events at the bottom of the subducting interface.

- Areas of lower slip generated more high-frequency radiation.


(c) rise time ≤10s


(d) new coupling model and slip model

Seismic slip / slip rate:
Wei et al., 2012

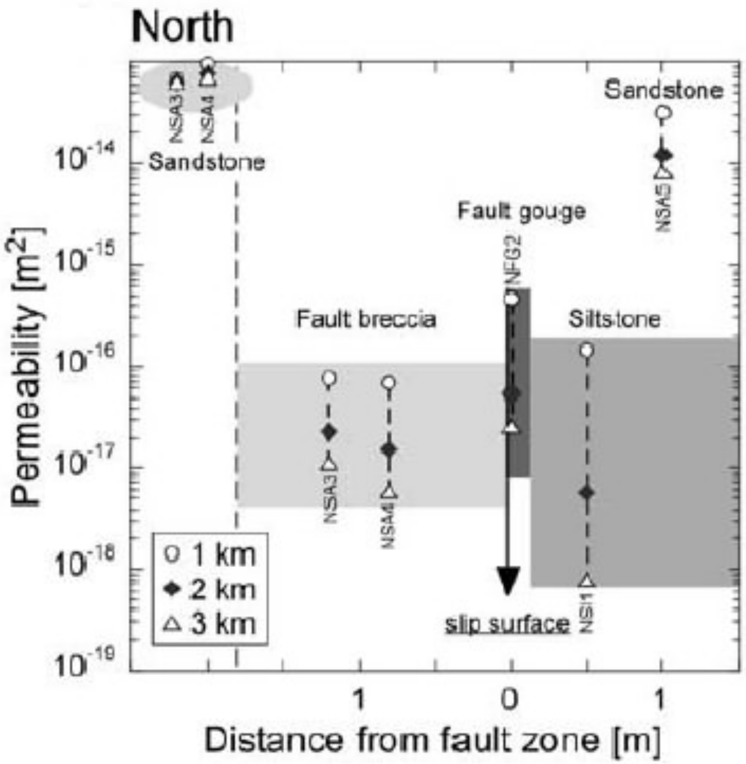
“Old” coupling model:
Loveless & Meade, JGR, 2010

“New” coupling model:
Loveless & Meade, GRL, 2011

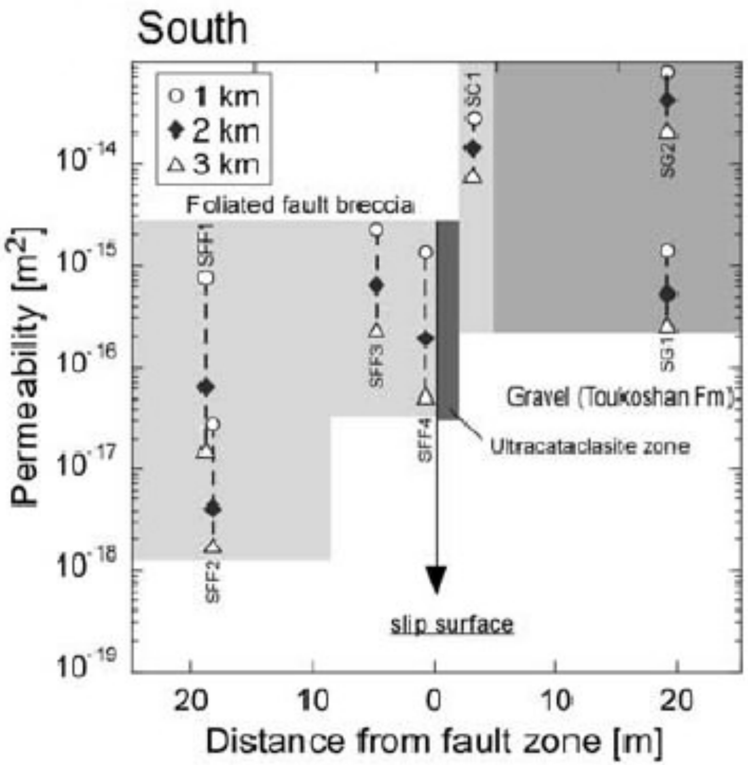
Back projection results:
Meng et al., GRL, 2011

Lab-measured permeability for the Chi-Chi earthquake fault

North: Less permeable



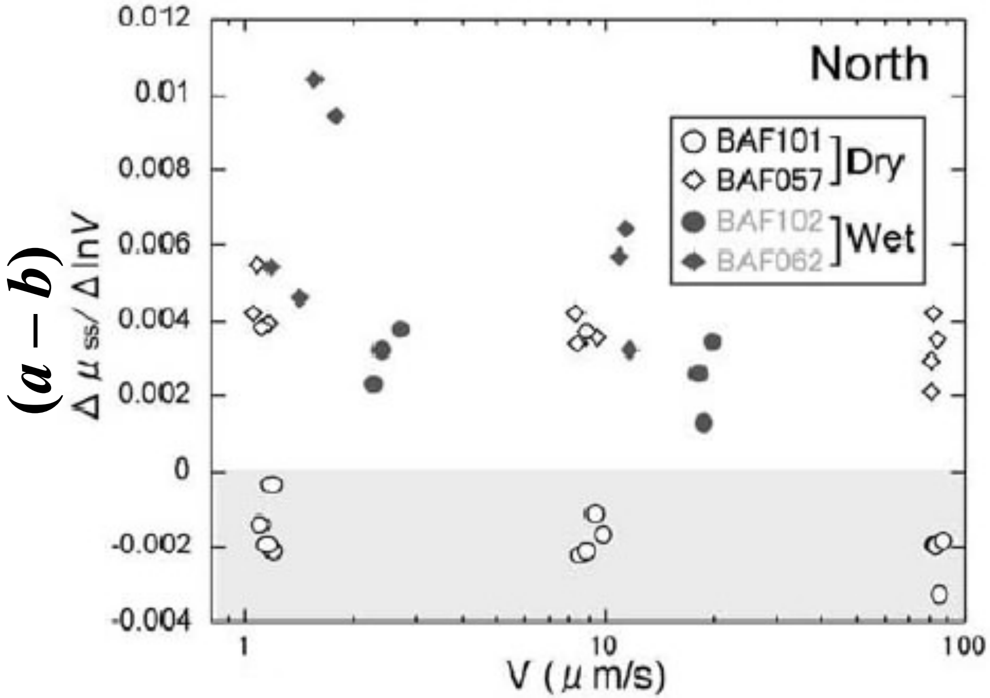
South: More permeable



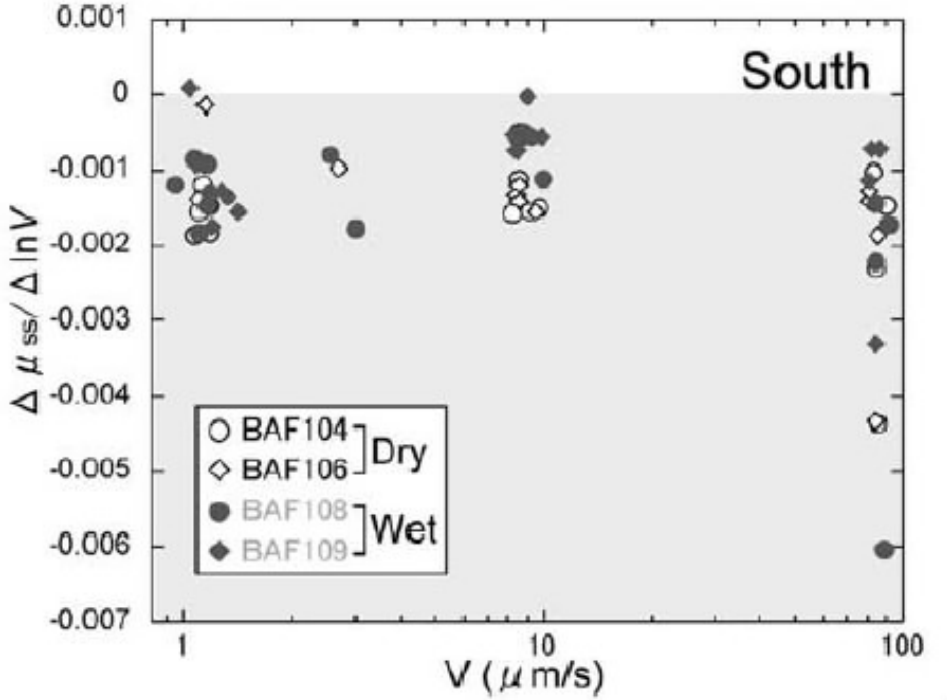
Tanikawa and Shimamoto, 2009

Lab-measured rate-and-state parameters for the Chi-Chi earthquake fault

North: **Velocity strengthening**
(despite having much larger slip!)



South: **Velocity weakening**



Samples are collected from bore holes at 200-300 m depth
in the Northern and Southern regions.

Tanikawa and Shimamoto, 2009