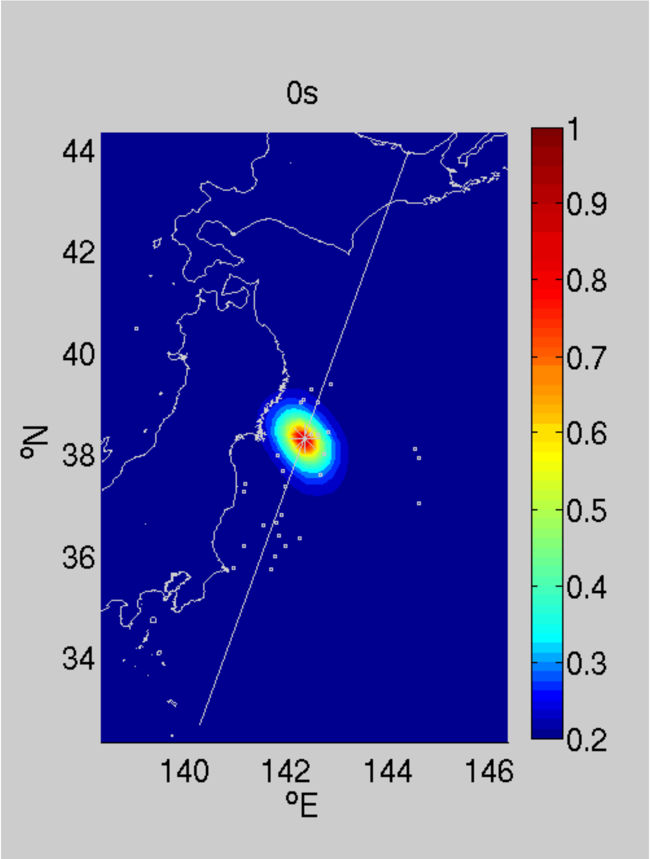
# The spectrum of slip behaviors emerging from interactions between seismic and aseismic slip

Jean-Paul Ampuero (IRD / UCA, Géoazur)

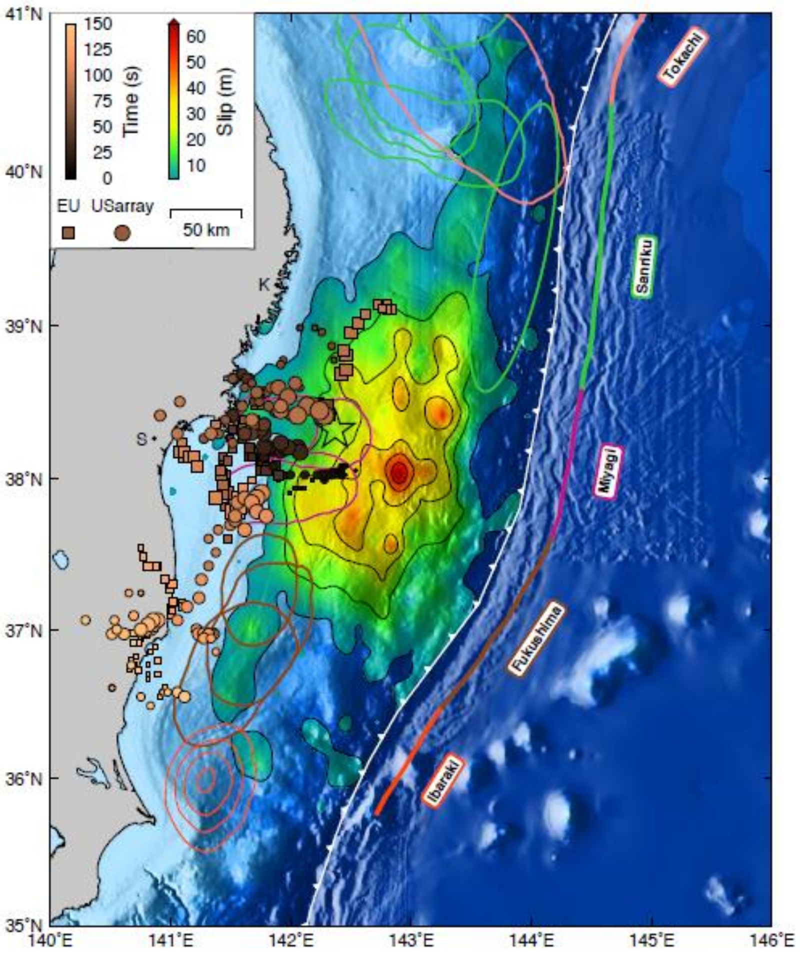
# Spectrum of slip behavior

Natural phenomena involving intermingled slow and fast slip:

- Heterogeneous fault coupling
- Slow slip and tremor
- Foreshocks and aseismic pre-slip
- High and low frequency slip during large earthquakes




The 2011 M9 Tohoku (Japan) earthquake imaged by back-projection of USArray data (Meng, Inbal and Ampuero, 2011)




Simons et al (2011), Meng et al (2011)

Brownish symbols: 1Hz radiators extracted from back-projection movies

Colored contours: static slip from GPS & tsunami data

Spatial complementarity of high- and low-frequency slip:

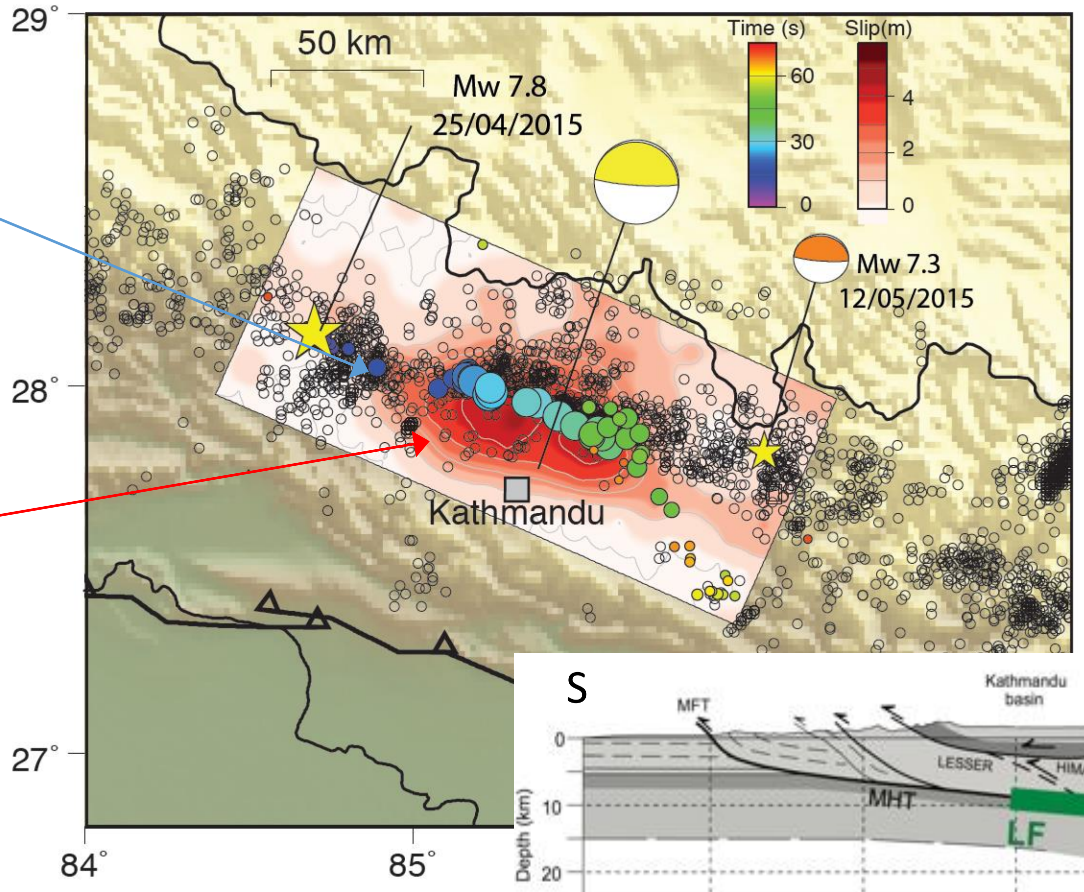
HF radiation is deeper than static slip

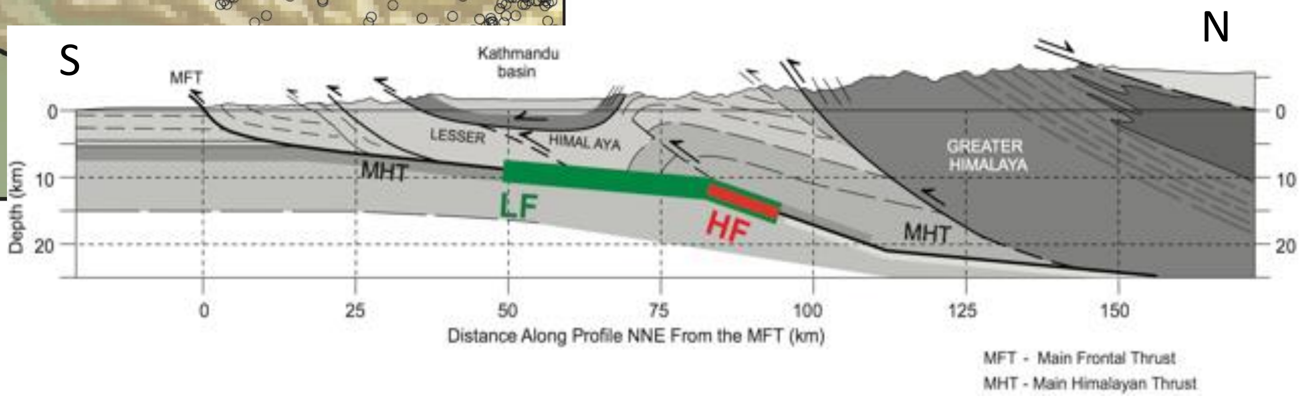
HF radiation occurs even where the rupture is overall slow

# 2015 Mw7.8 Nepal earthquake

Colored circles: High-frequency radiation (1 Hz back-projection)

Reddish contours: Low-frequency slip (finite source inversion)




Avouac et al (2015), Ampuero et al (2016)

# Combining seismic and aseismic data

Dual megathrust slip behaviors of the 2014 Iquique earthquake sequence

Lingsen Meng[a,*], Hui Huang[b], Roland Bürgmann[c], Jean Paul Ampuero[d], Anne Strader[a]

EPSL 2015

Locally and remotely triggered aseismic slip on the central San Jacinto Fault near Anza, CA, from joint inversion of seismicity and strainmeter data

A. Inbal[1], J.-P. Ampuero[2], and J.-P. Avouac[2]

JGR 2017

Estimates of aseismic slip associated with small earthquakes near San Juan Bautista, CA

J. C. Hawthorne[1], M. Simons[2], and J.-P. Ampuero[2]

JGR 2016

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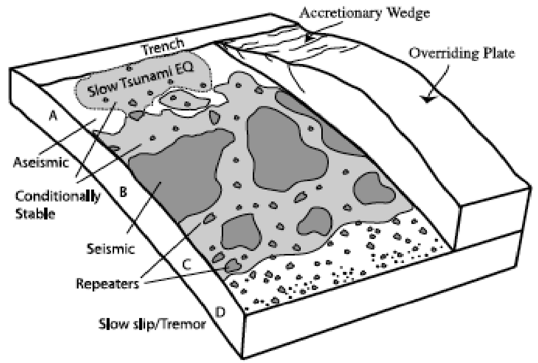
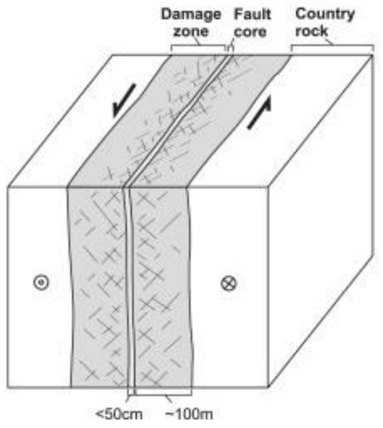
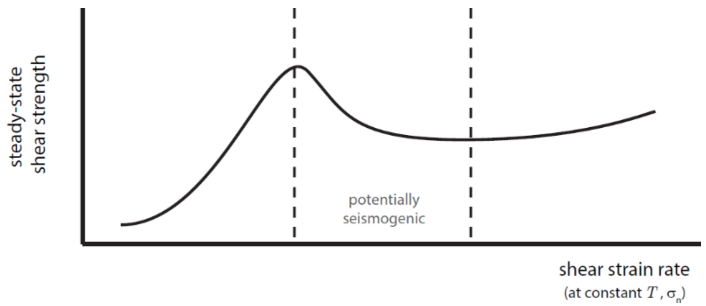
Numerical models show important effects of:

- Heterogeneous fault friction properties
- Low rigidity fault zones
- Rate-dependent rheological transitions



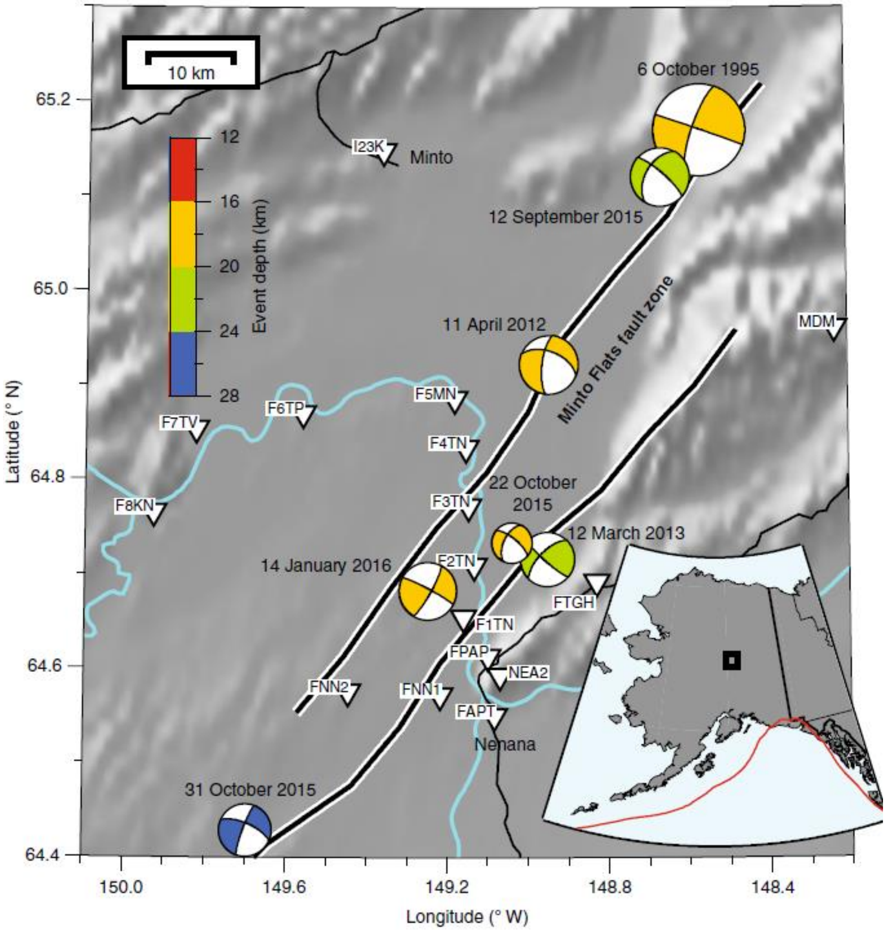
nature geoscience

June 2018

# Earthquake nucleation and fault slip complexity in the lower crust of central Alaska

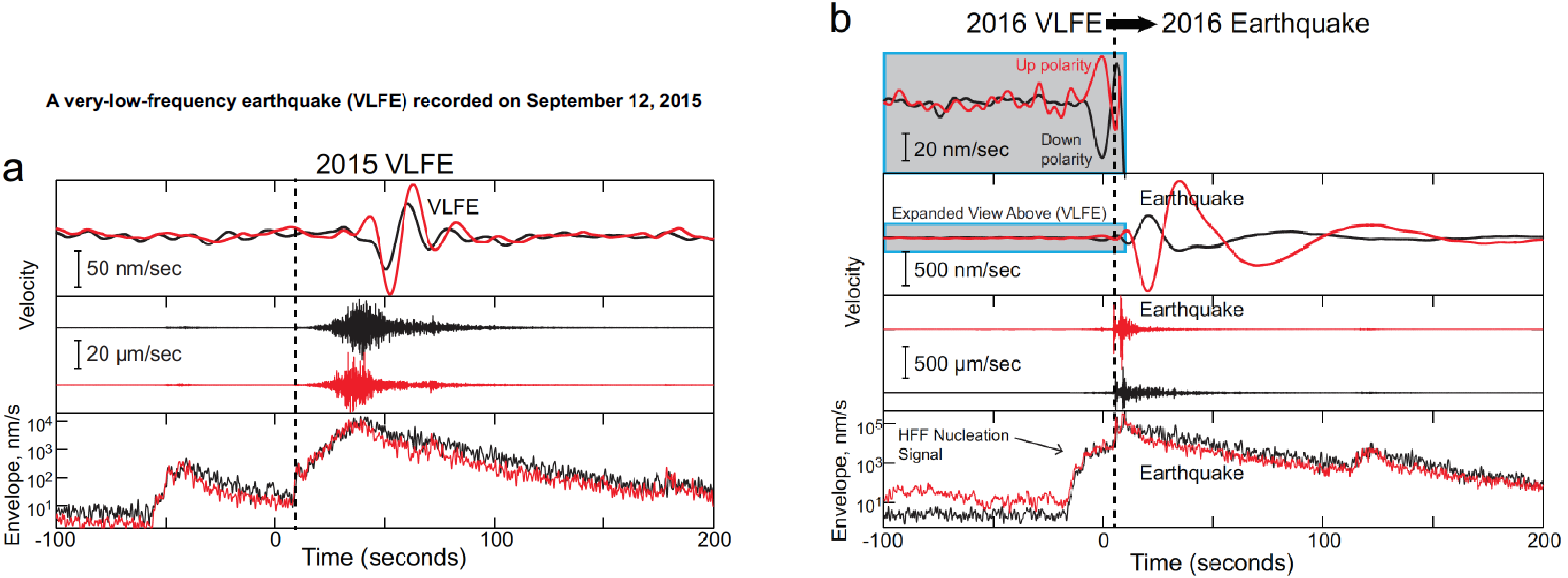
Carl Tape[1*], Stephen Holtkamp[1], Vipul Silwal[1], Jessica Hawthorne[2], Yoshihiro Kaneko[3], Jean Paul Ampuero[4,5], Chen Ji[6], Natalia Ruppert[1], Kyle Smith[1] and Michael E. West[1]

Slow and fast earthquakes (regular and low-frequency events) at the base of the seismogenic zone in the Minto Flats fault zone, central Alaska



**A very-low-frequency earthquake (VLFE) recorded on September 12, 2015**

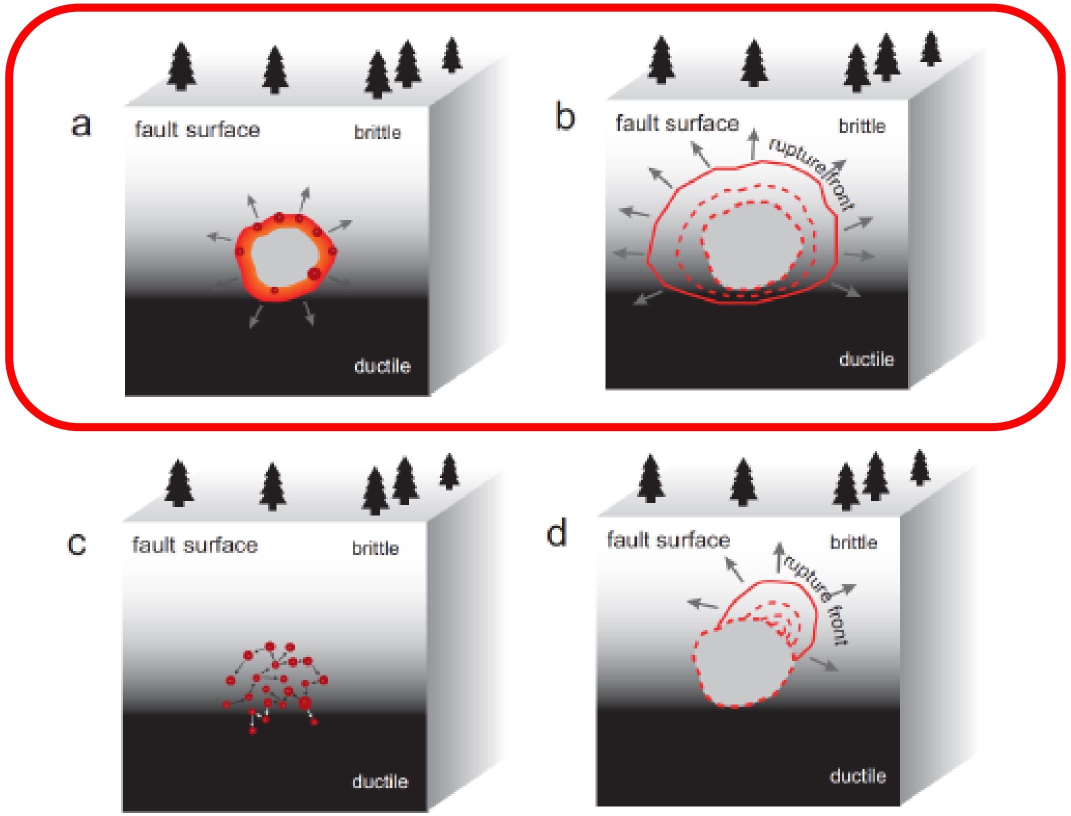
**A VLFE transitioning to an earthquake on January 14, 2016**

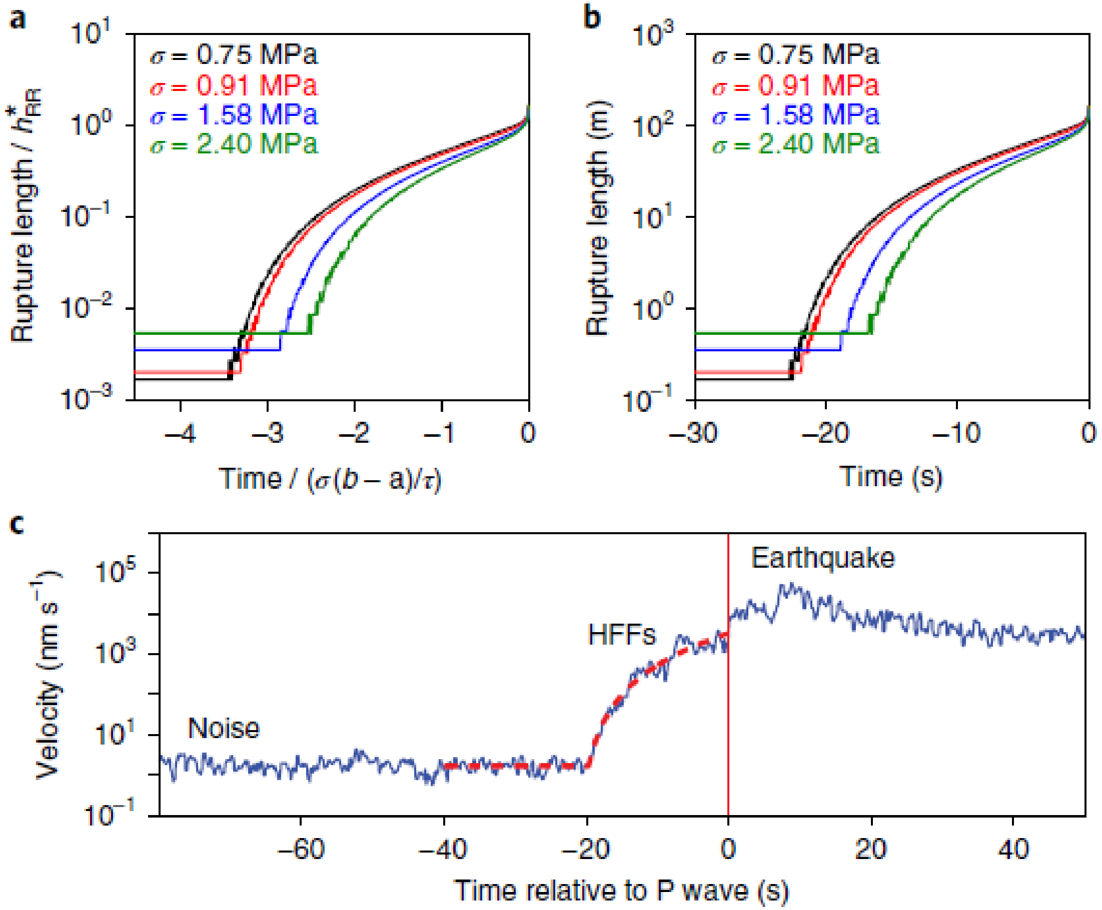


## Interpretations for events in Minto Flats fault zone

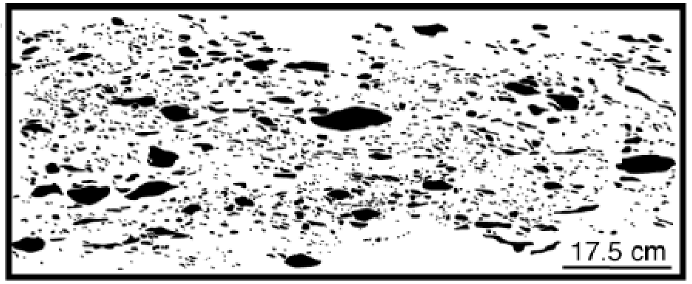
**Nucleation (VLFE)**
stage 1 (~20 seconds):
(a) slow slip and
high-frequency foreshocks
OR
(c) dozens of earthquakes
as a cascading process

**Earthquake**
stage 2 (~1 second):
(b) VLFE transitions into an
earthquake rupture (M3.7)
OR
(d) VLFE triggers an
earthquake (M3.7)



# Faults are heterogeneous

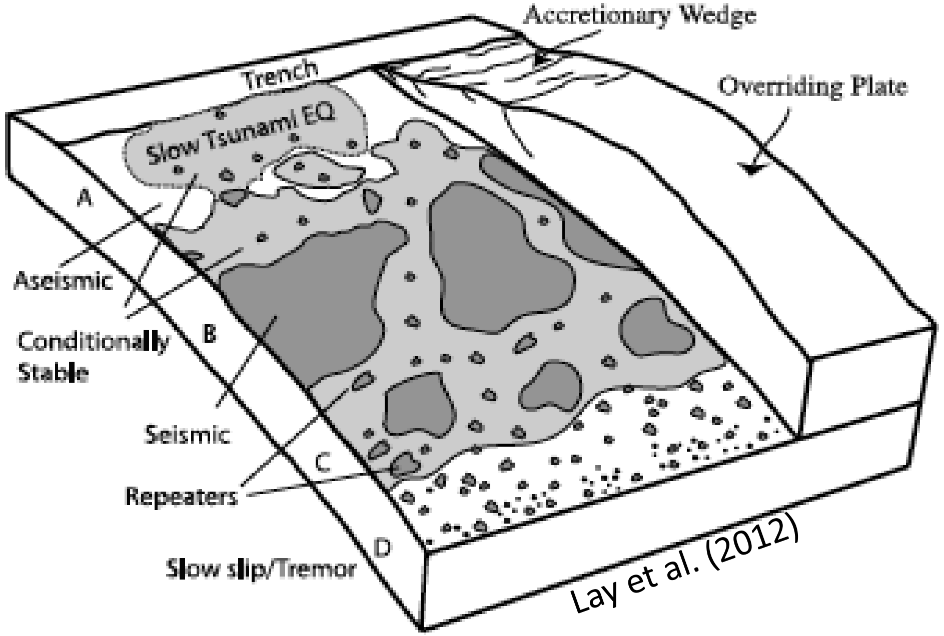




Fault zone melanges: competent lenses (phacoids) embedded in a ductile matrix (Fagereng, 2011)

How does heterogeneity affect slip behavior?

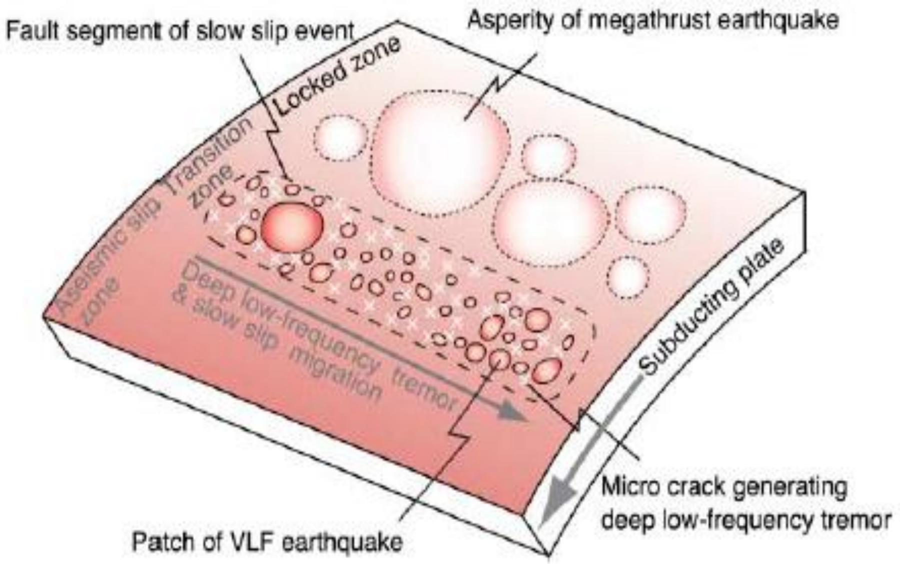
(fast vs slow, loud vs silent, high- vs low-frequency)

What are the effective properties of a composite fault zone?

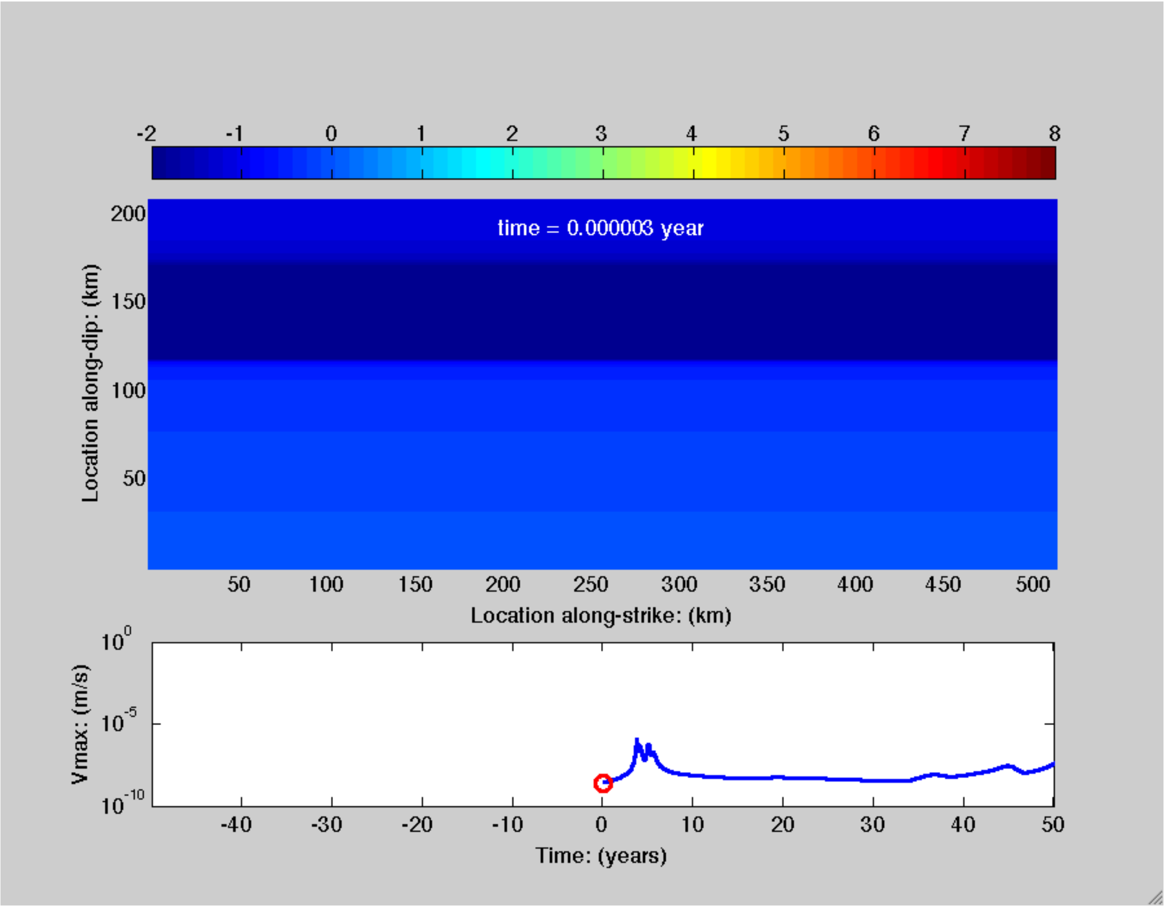



Lay et al. (2012)

# Heterogeneous fault models




Earthquake cycle simulations



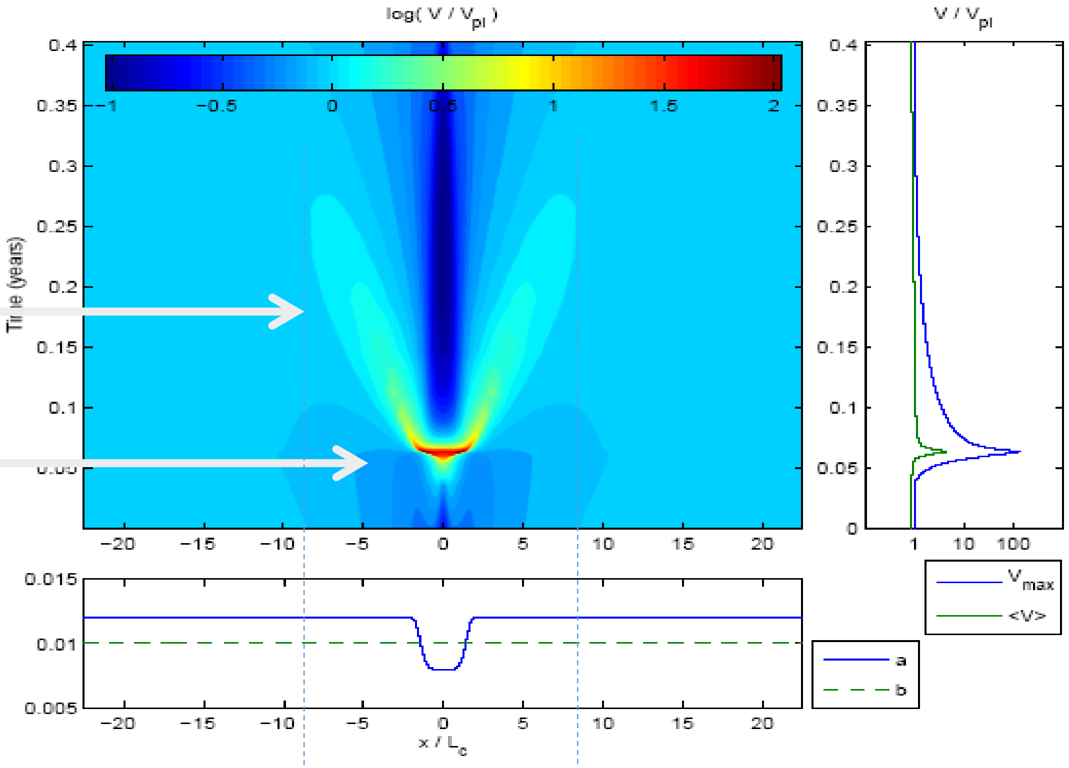

Luo and Ampuero

github.com/ydluo/qdyn

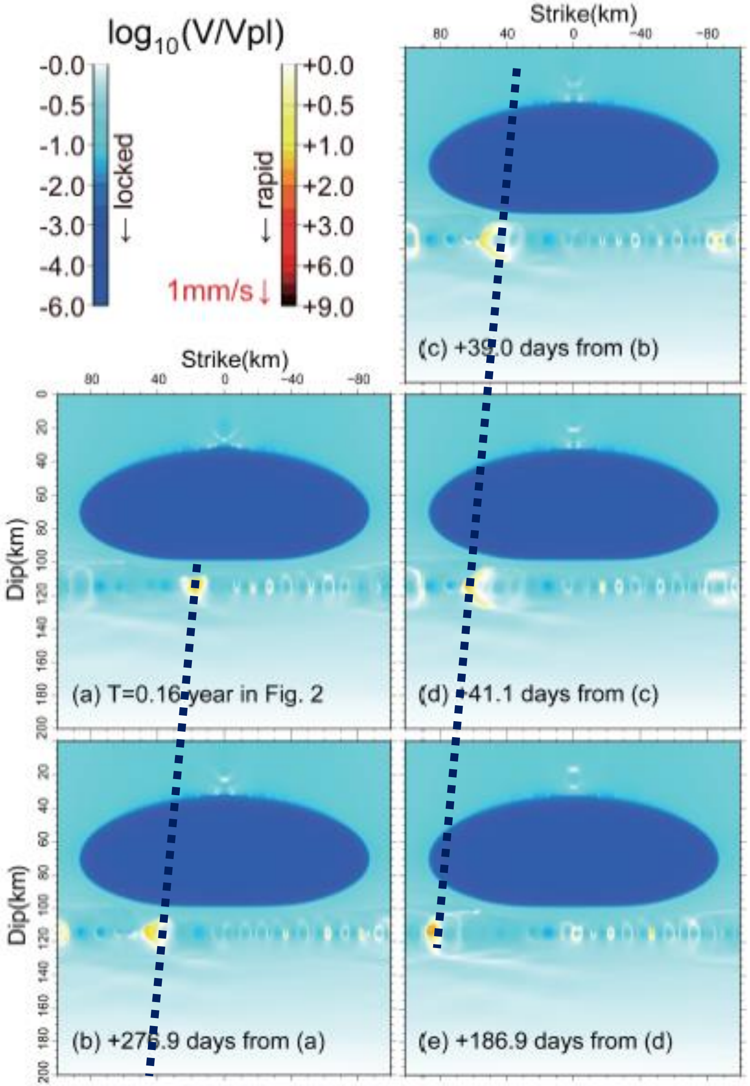
# Migrating swarms: asperity interactions mediated by creep transients

It triggers a migrating aseismic transient

The asperity breaks

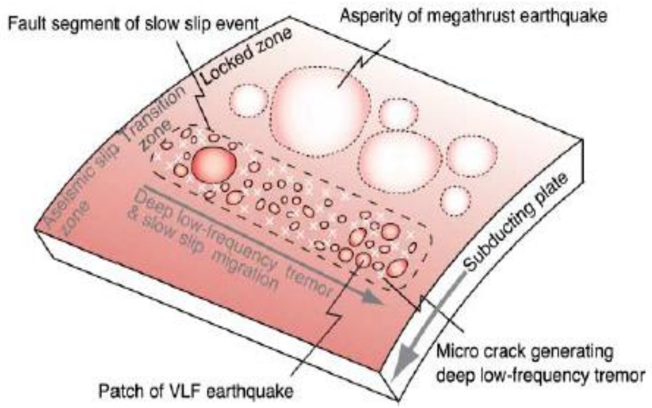



Influence radius

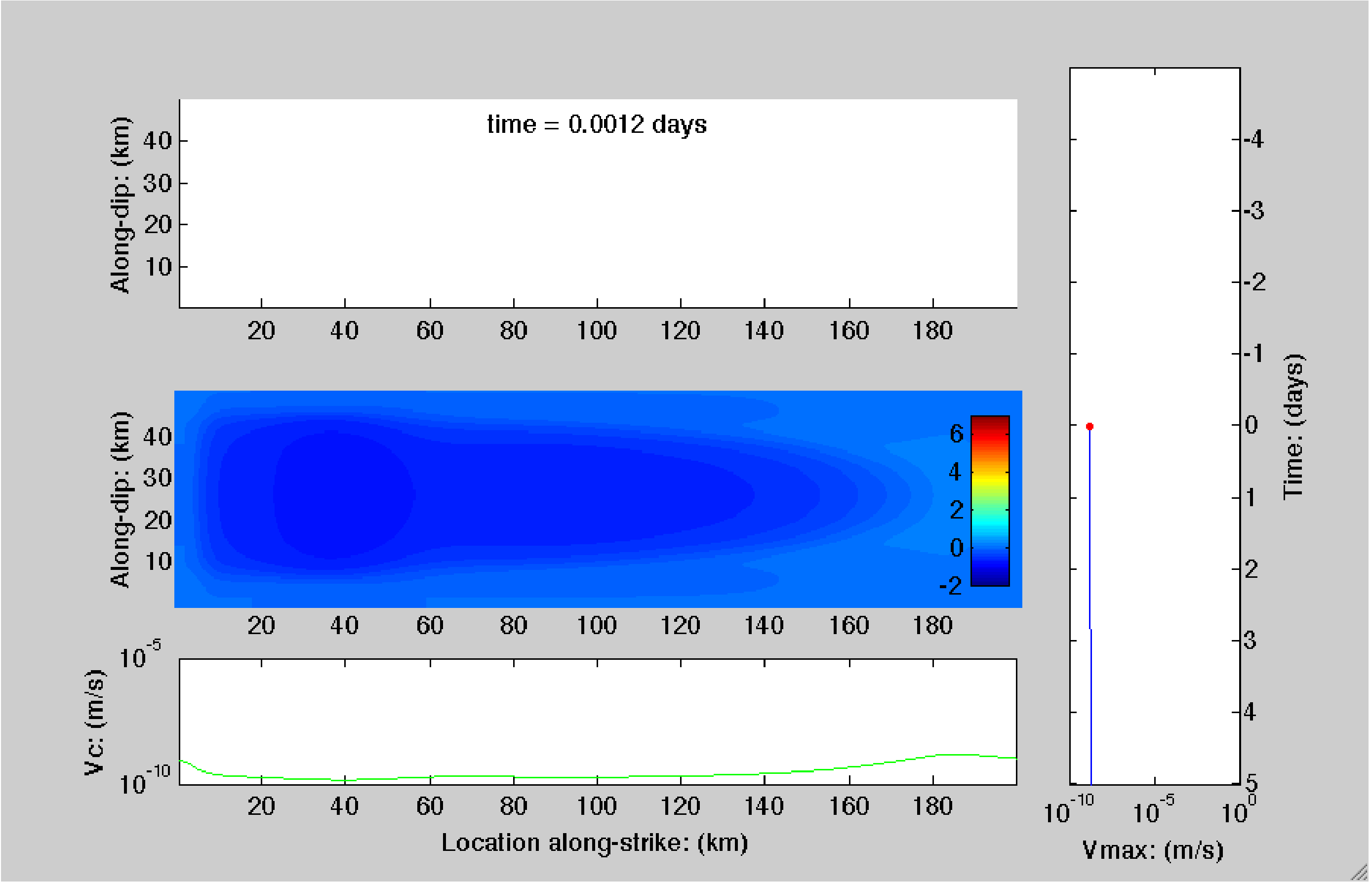



Quasi-dynamic 3D simulations with K. Ariyoshi (JAMSTEC)

# Simulations of slow slip and tremor




Quasi-dynamic rate-and-state friction models with heterogeneous properties



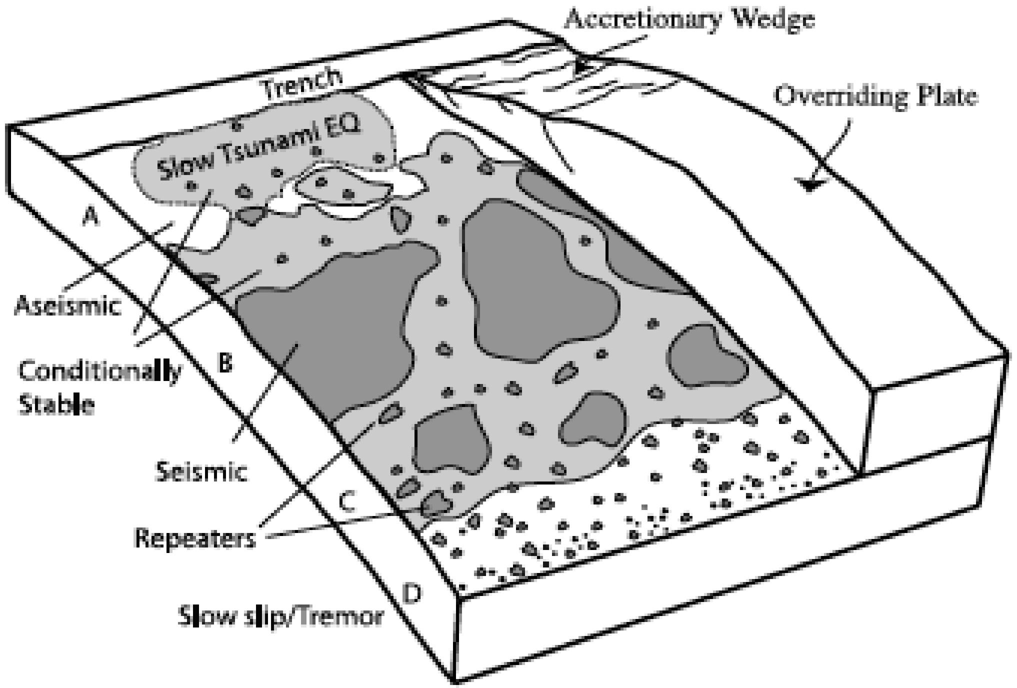

Two end member models, depending on asperity density $\rho$:

1. Slow slip drives tremor (low $\rho$)
2. Tremor drives slow slip (high $\rho$)

Luo and Ampuero

github.com/ydluo/qdyn

# “Asperities” in conceptual models

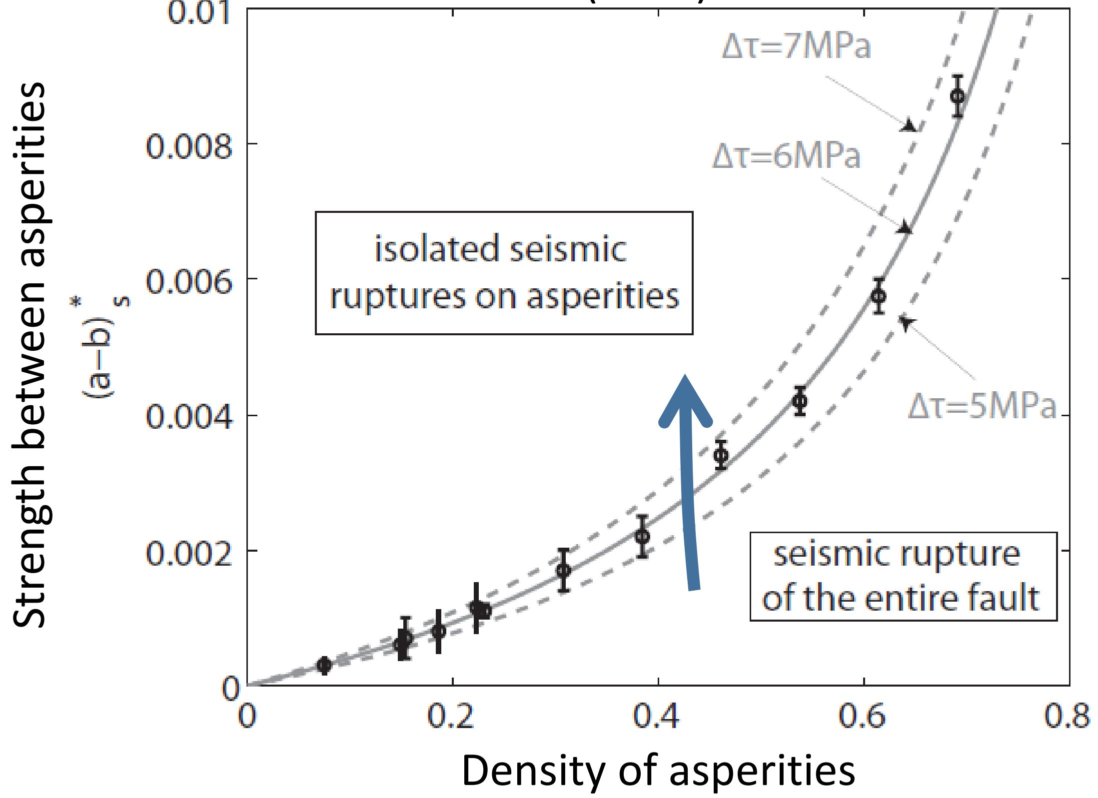



Asperity real size may not depend strongly on depth but their “radius of influence” may be affected by depth-dependent resistance of creeping matrix

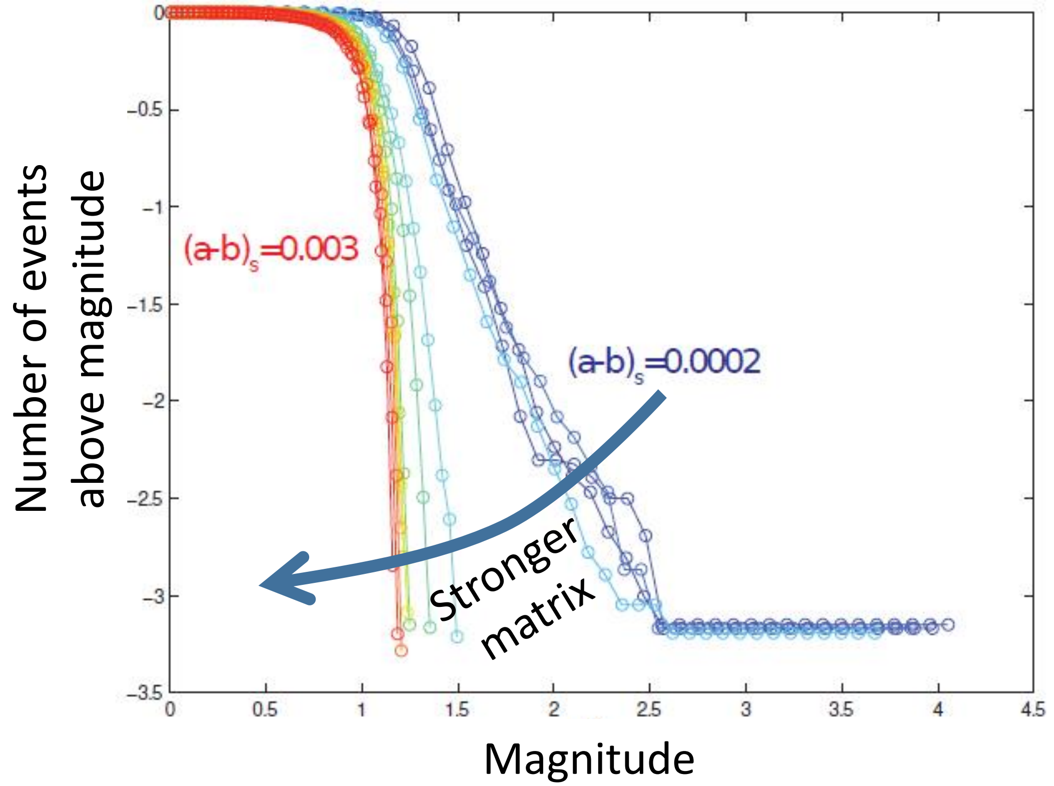
→ Size of “connected” asperity clusters changes with depth

# Critical asperity density

Dublanchet et al (2012)

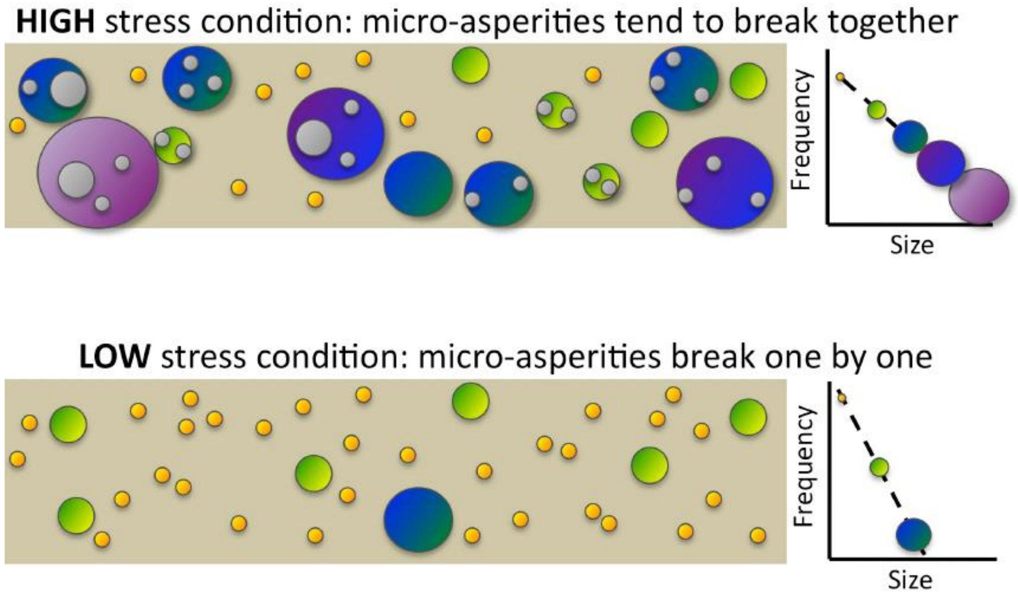


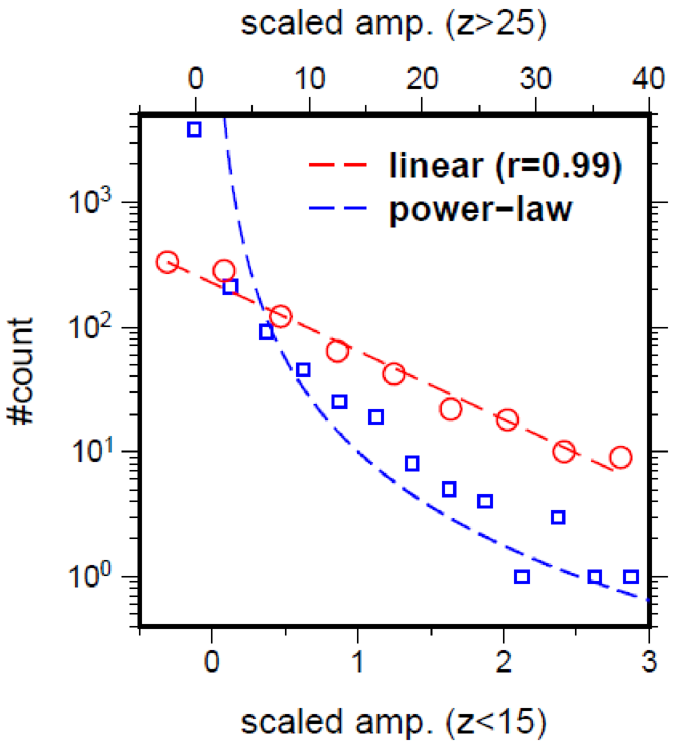

Multi-asperity simulations (Dublanchet and Ampuero)




Transition from **Gutenberg-Richter** to **exponential** behavior as the fault strengthens

# Deep events in Long Beach are scale-bounded




**Localized seismic deformation in the upper mantle revealed by dense seismic arrays**

Asaf Inbal,* Jean Paul Ampuero, Robert W. Clayton

Science, 2016

Earthquake size distribution:

Shallow events: power-law

Deep events: exponential

# Complexity without heterogeneities

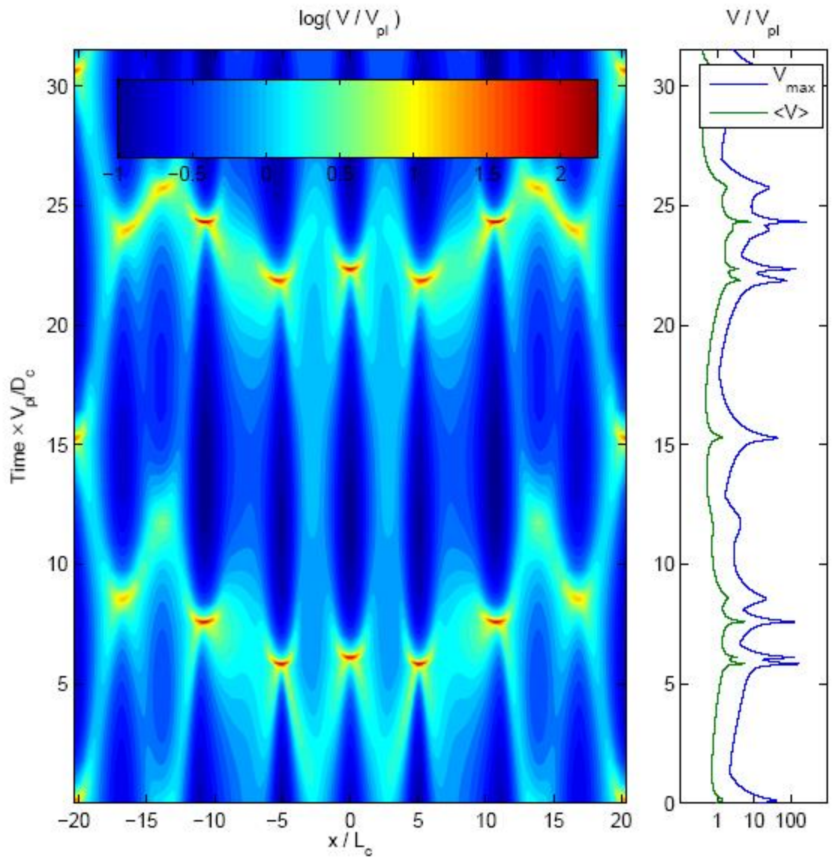


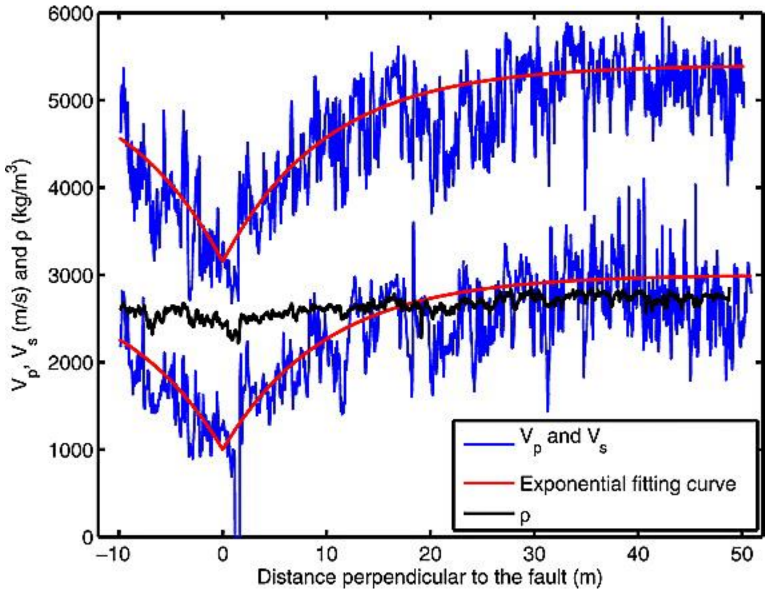

Figure 14: Slow earthquake cycles on a velocity-weakening fault strip, with $W/\pi L_c = 1.3$, $L/W = 10$ and $a/b = 0.8$.

Complex slip patterns can emerge spontaneously in an elongated velocity weakening fault strip, even if frictional properties are uniform.

(Analogous to instabilities in fluid dynamics, en route to turbulence)

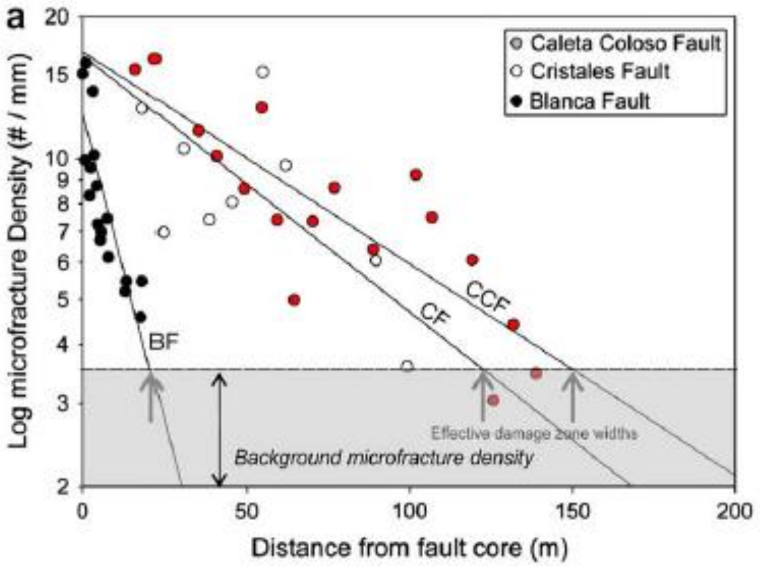
Possible at the very top of the transition zone, but not deeper

# Faults are thick:
# surrounded by damaged (low rigidity) zones



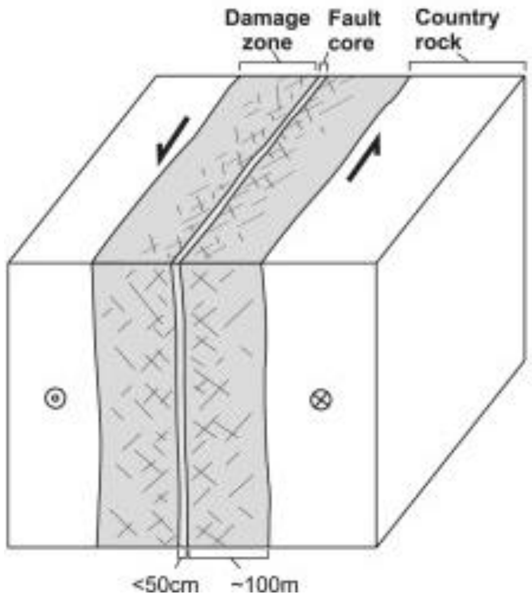

Nojima fault downhole log
(Huang & Ampuero 2011)

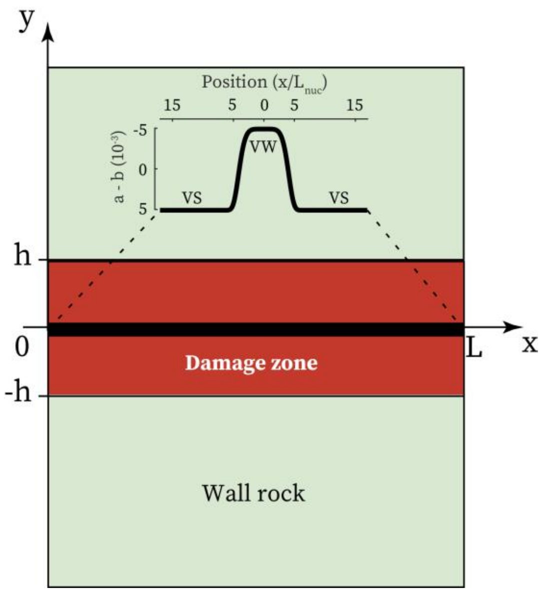

Punchbowl fault, CA
(Chester and Chester, 1998)

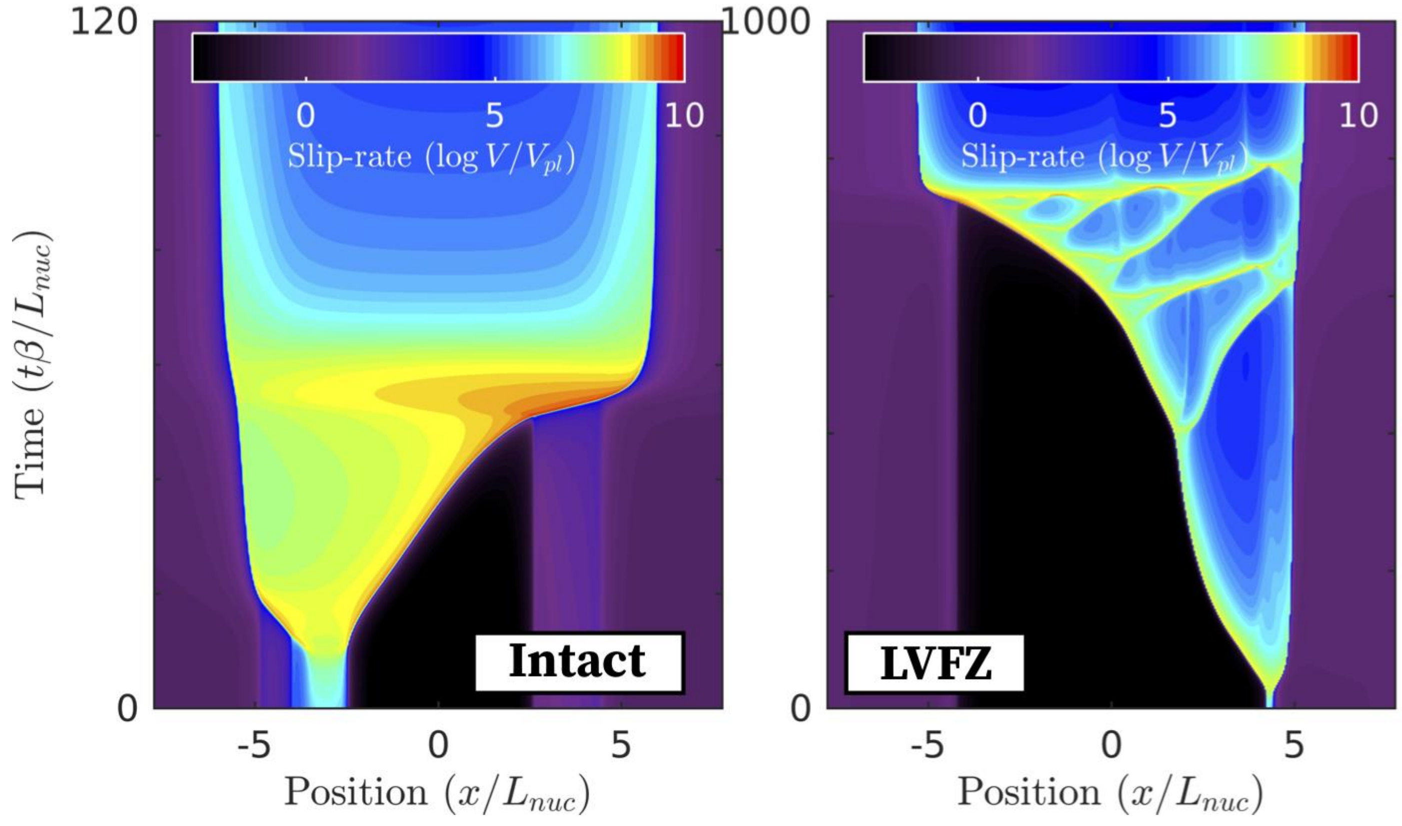



Microcrack density
(Mitchell & Faulkner 2009)

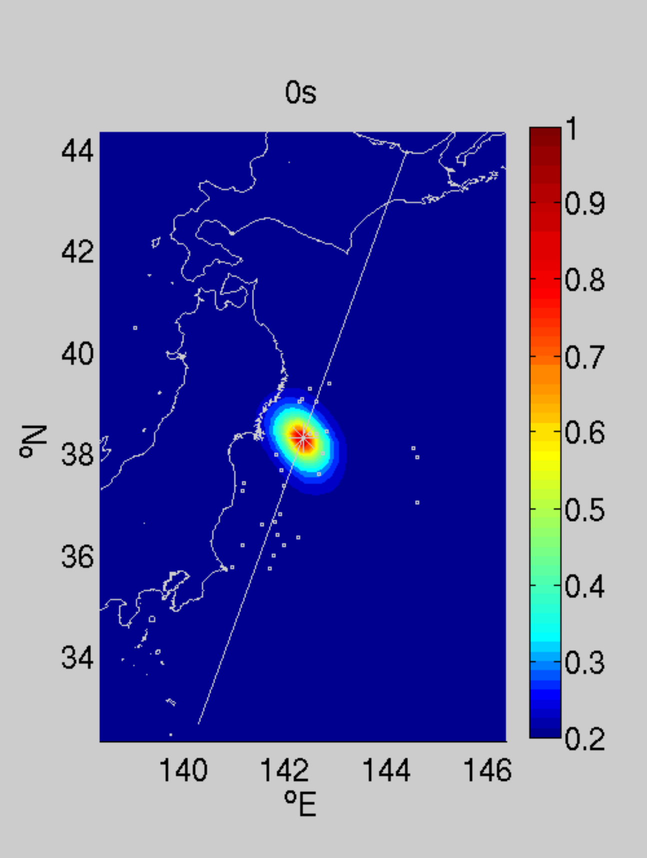
# Fault zone damage induces slip complexity



# High resolution rupture imaging enabled by large and dense seismic arrays

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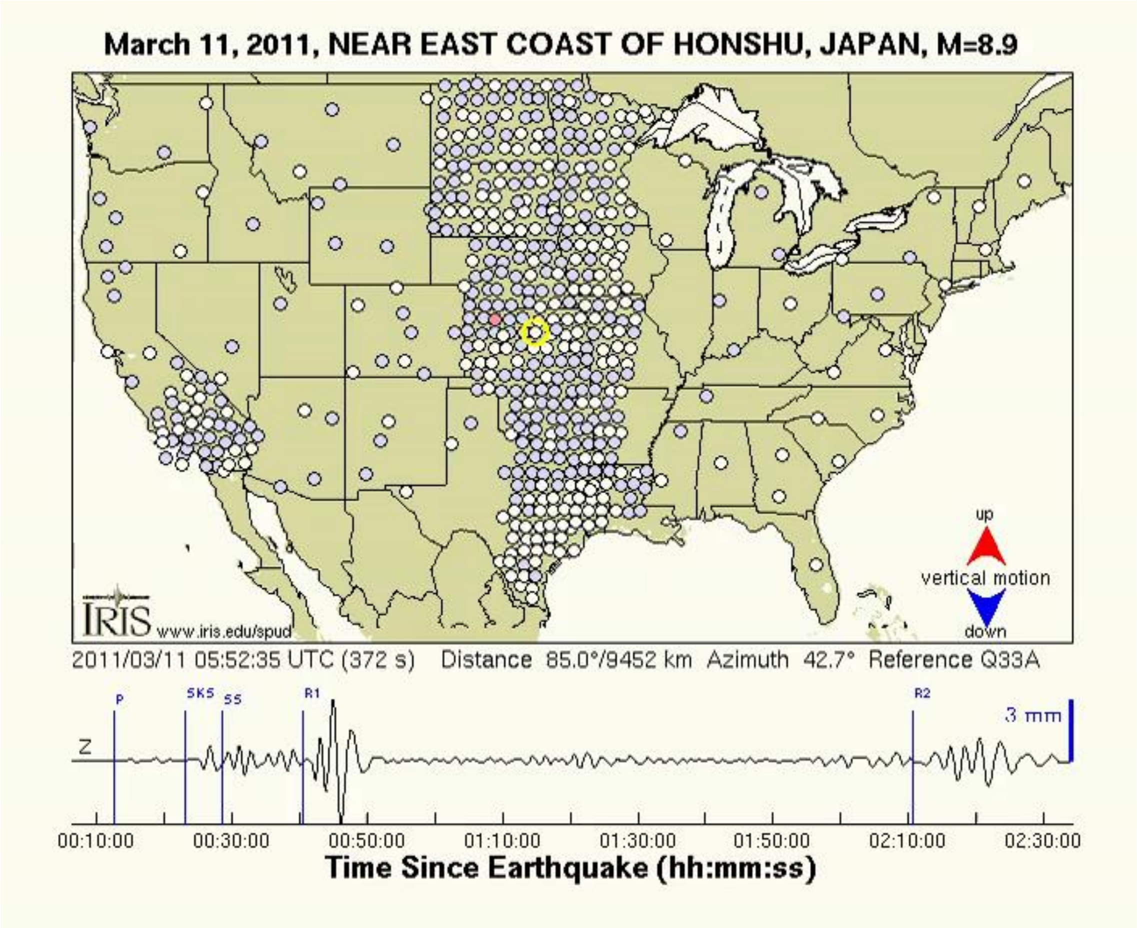
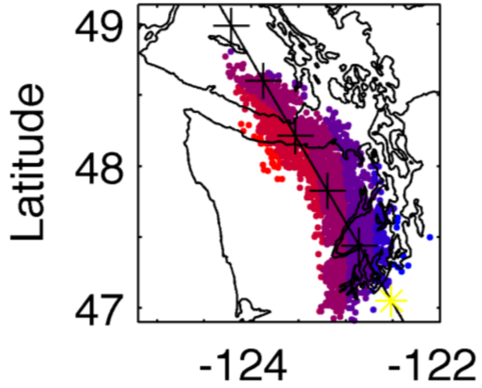
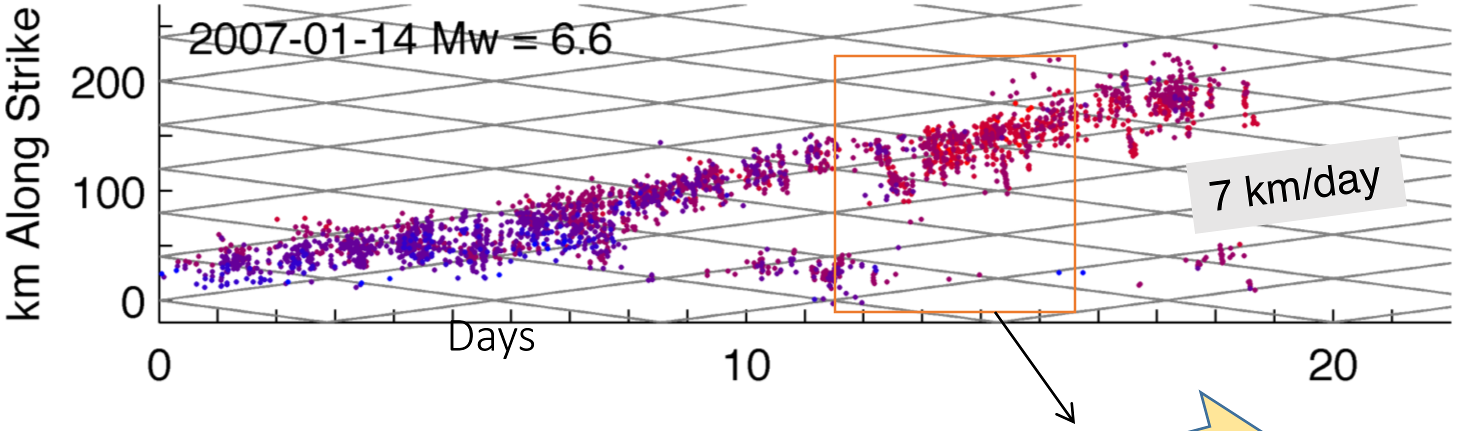
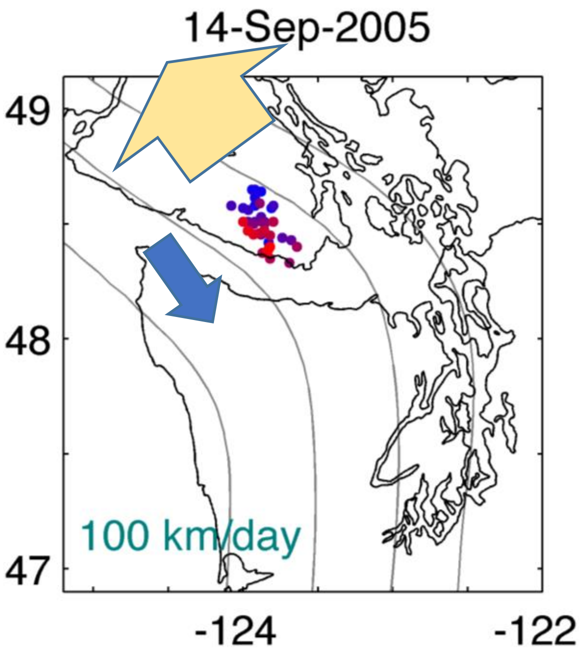



→ Rapid imaging of high-frequency wave sources

# Rapid tremor reversals

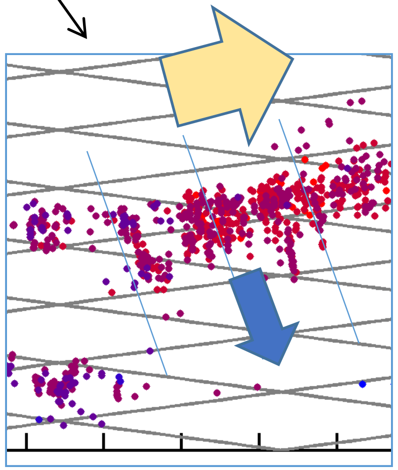


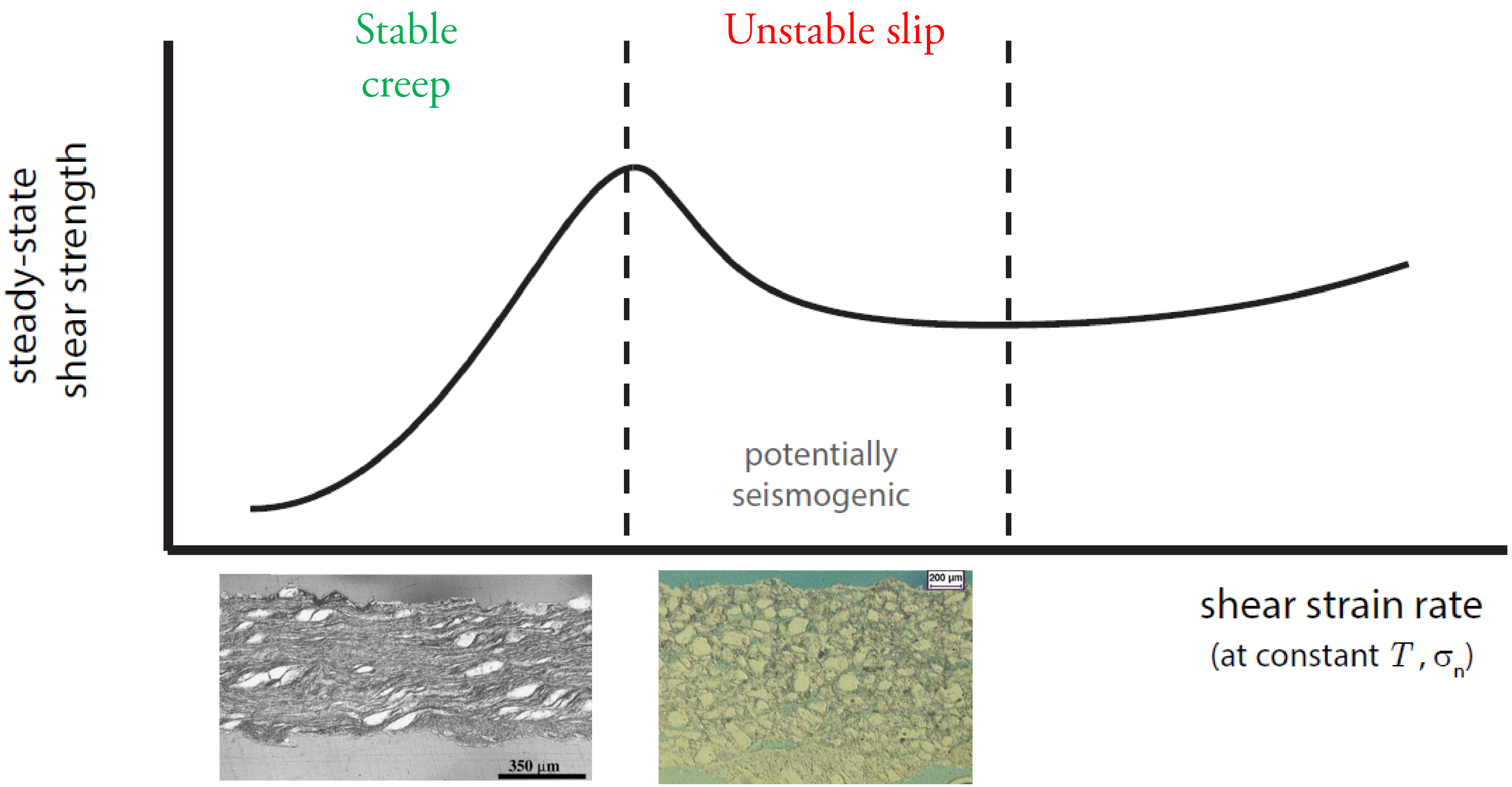

Non-volcanic tremor migration patterns in Cascadia, USA

Tremor migrates slowly along strike ( ~10 km/day) tracking the front of the slow slip event



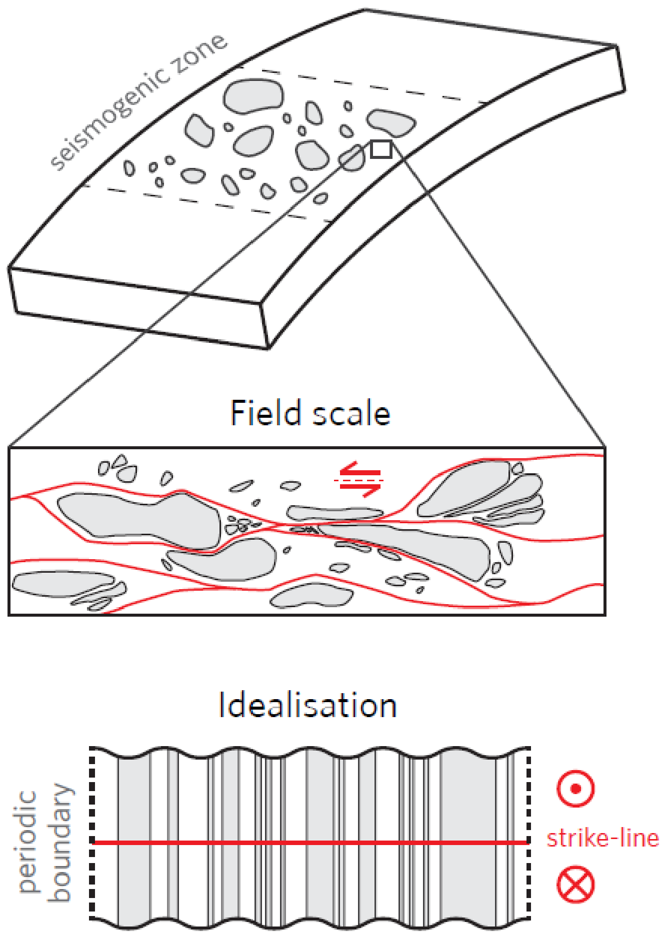
Houston et al (2010)

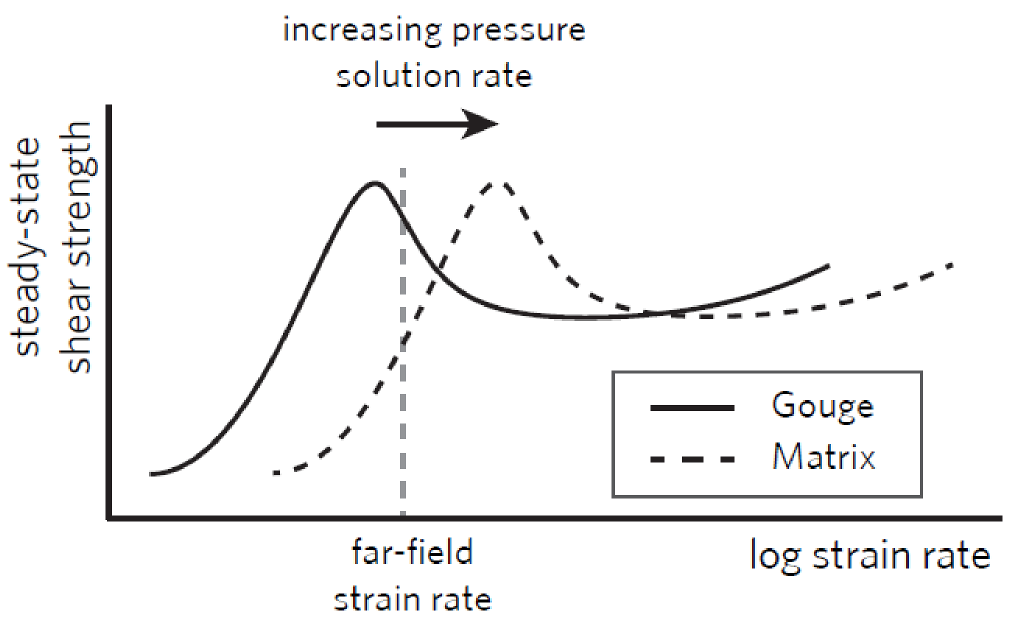
# Rheological transitions




van den Ende, Chen, Ampuero and Niemeijer (subm. 2018)
*Giant earthquakes on quiet faults governed by rheological transitions*

# Rheological transitions and behavioral changes




van den Ende et al (2018)

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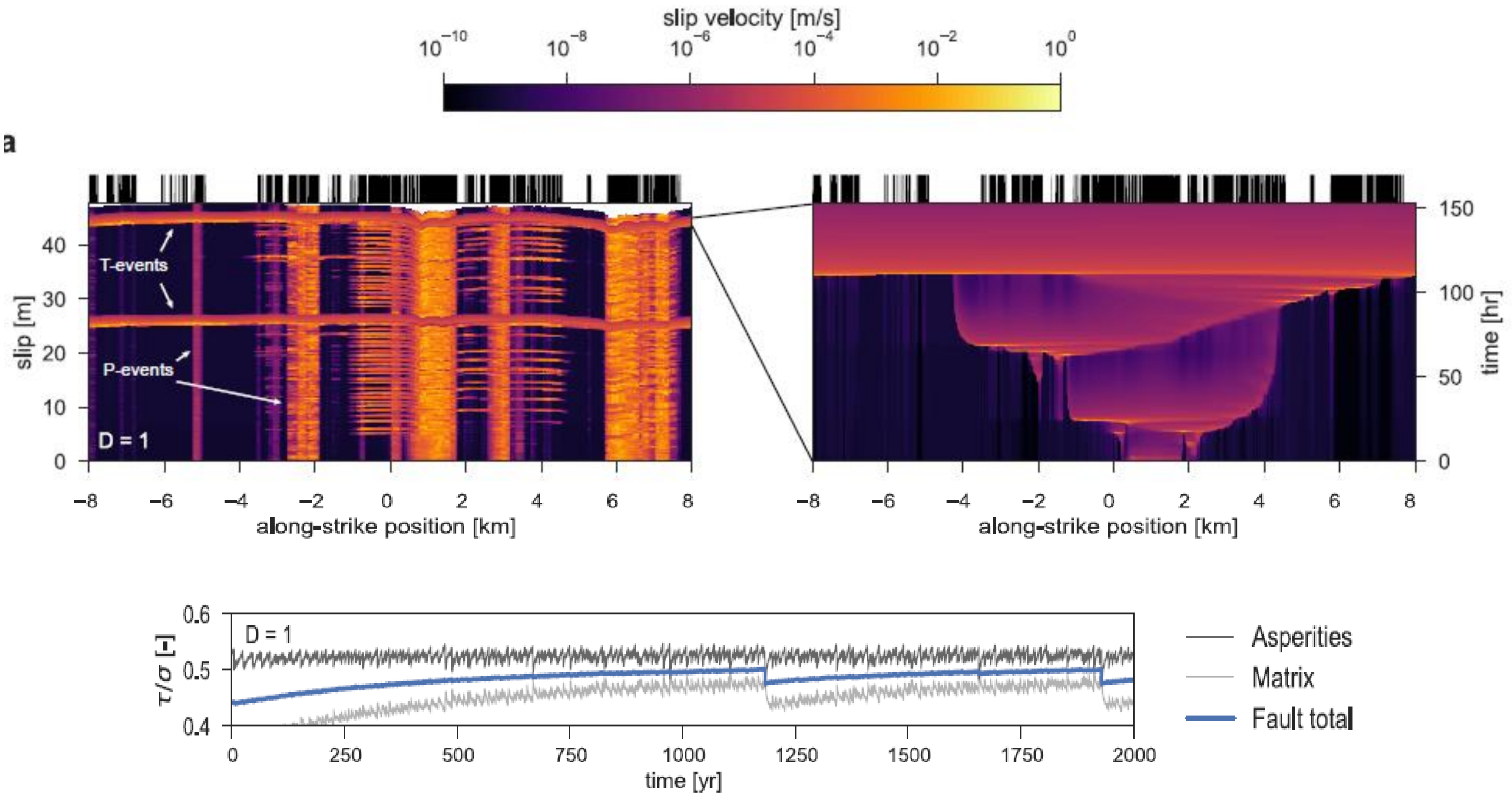


van den Ende et al (2018)

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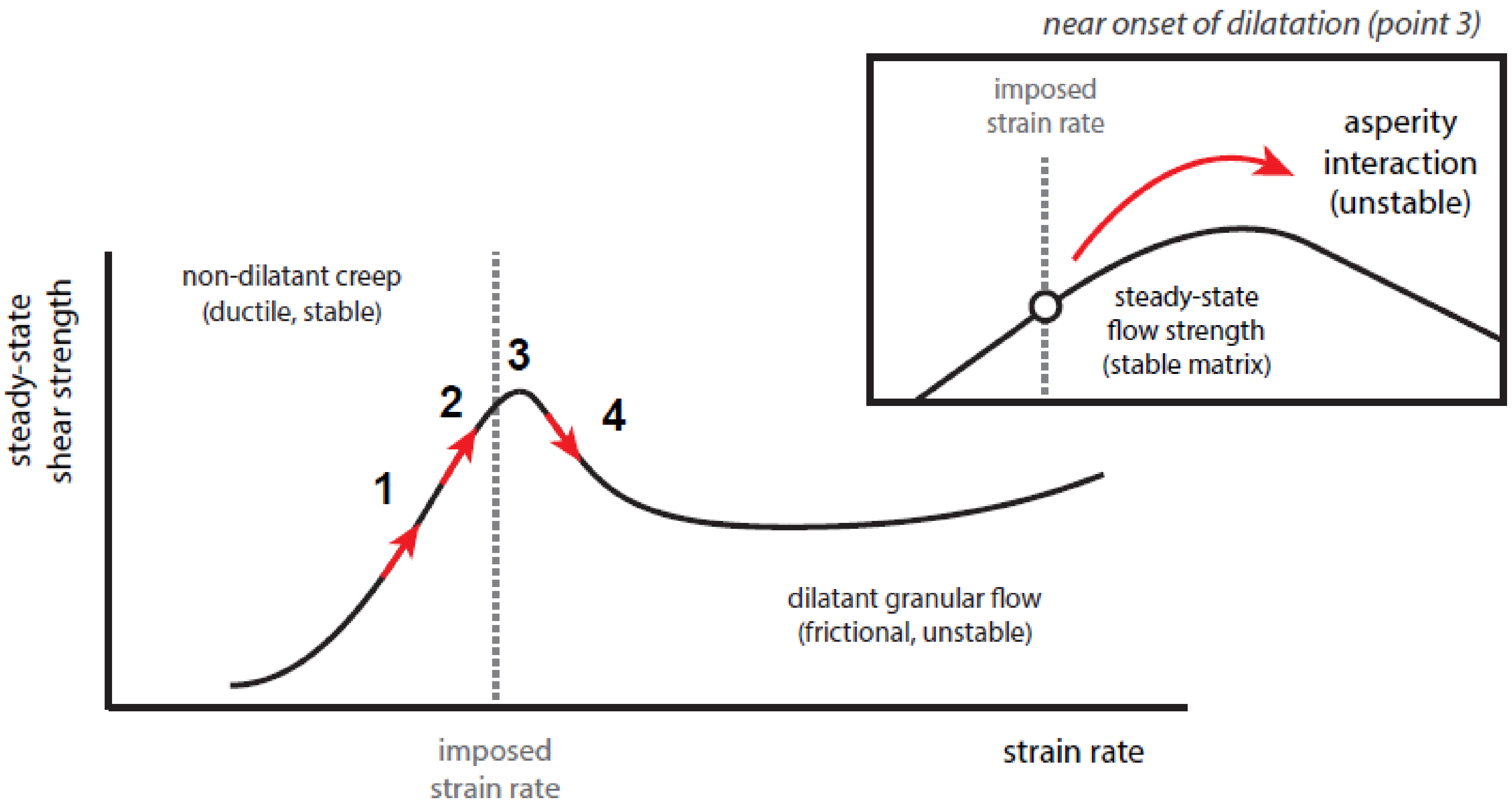


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