Advanced Workshop on Earthquake Fault Mechanics: Theory, Simulation and Observations

ICTP, Trieste, Sept 2-14 2019

Lecture 10: earthquake nucleation and slow slip

Jean Paul Ampuero (IRD/UCA Geoazur)

How do earthquakes start?

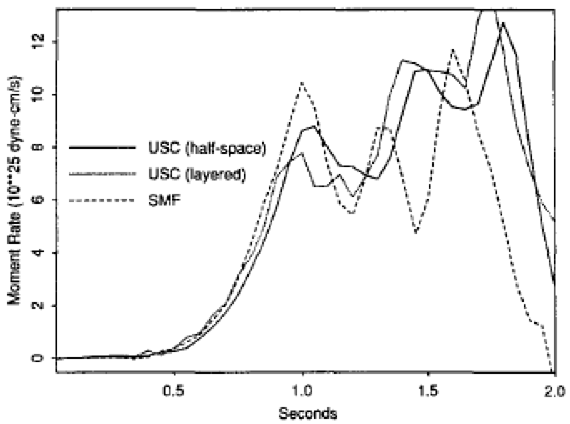
Do small and large earthquakes start the same?

Predictive value of earthquake onset and foreshock sequences?

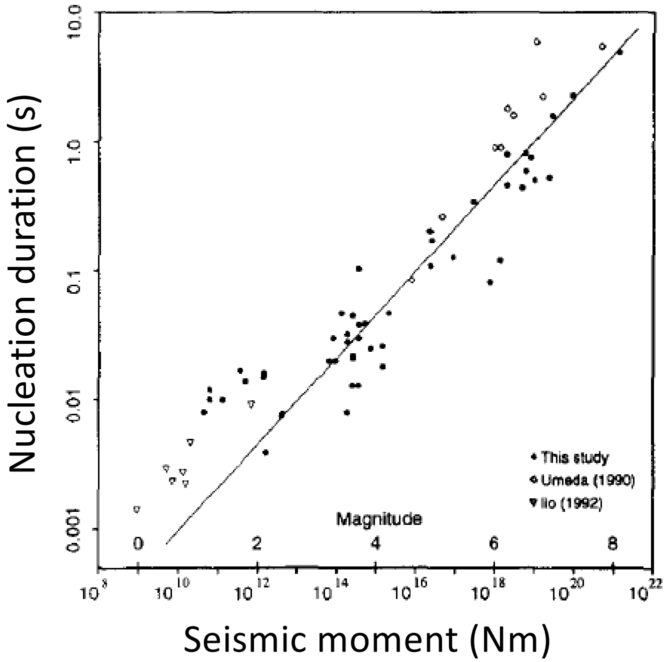
- Seismological observations
- Laboratory observations
- Earthquake nucleation models

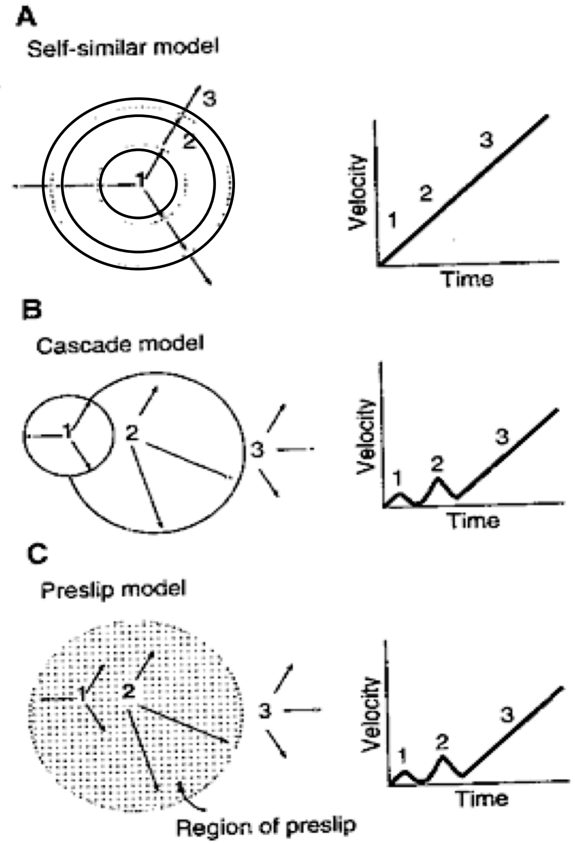
Seismological observations of earthquake nucleation

Seismological observations

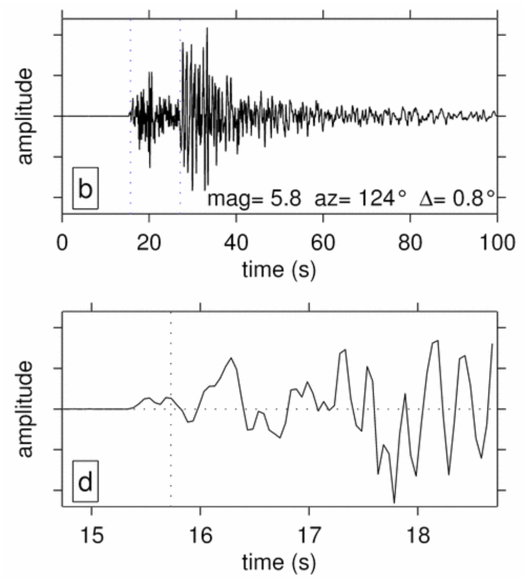


Ellsworth and Beroza (1995)
Beroza and Ellsworth (1996)





Seismological observations related to early warning research

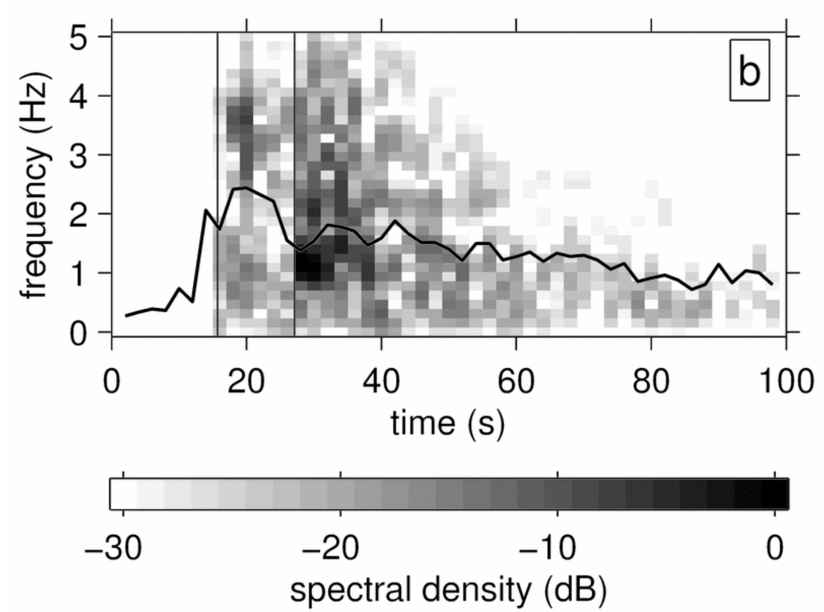


Simons et al (2006)

$$\tau_c^2 = 4\pi^2 \frac{\int_0^{\tau_0} u^2(t)\,dt}{\int_0^{\tau_0} \dot{u}^2(t)\,dt}$$

$1/\tau_c \sim$ instantaneous frequency

Nakamura (1988)

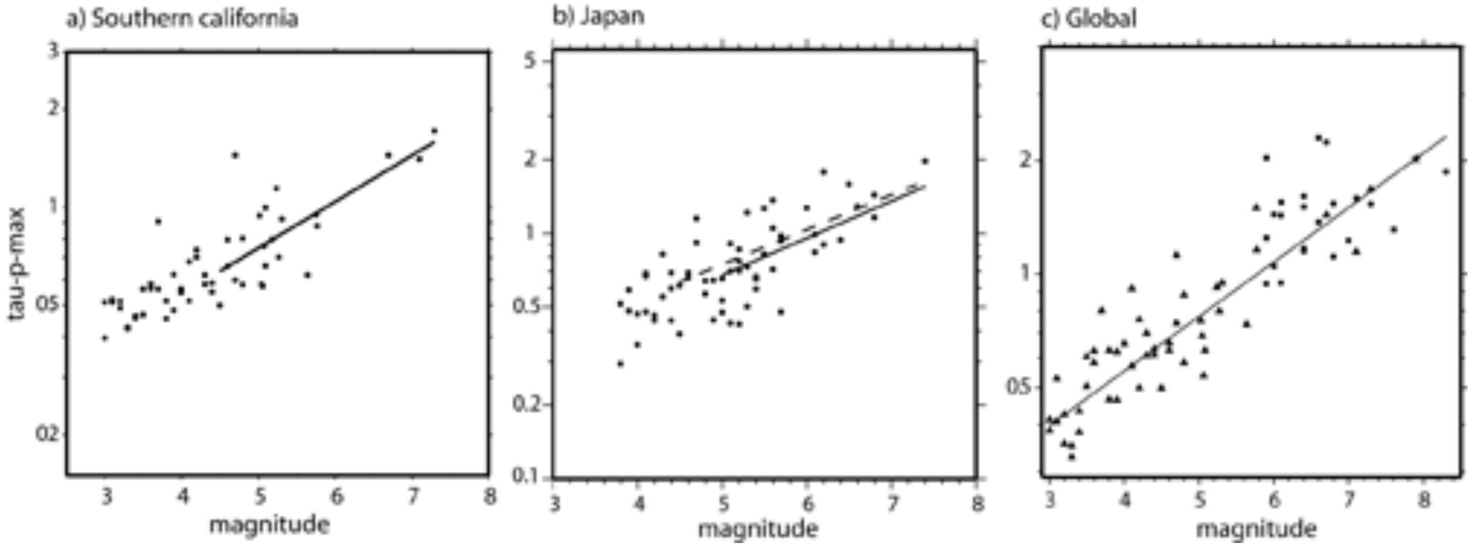


Seismological observations related to early warning research

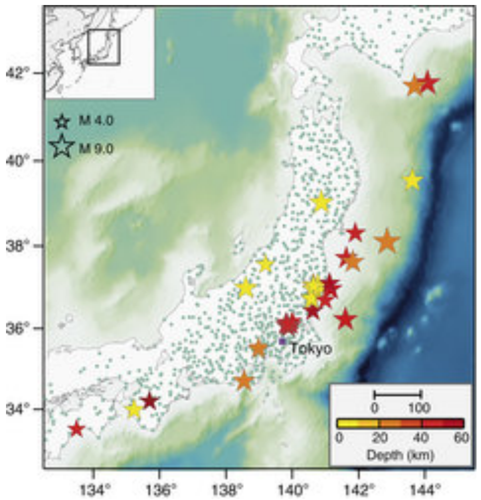
$$\tau_c^2 = 4\pi^2 \frac{\int_0^{\tau_0} u^2(t)\mathrm{d}t}{\int_0^{\tau_0} \dot{u}^2(t)\mathrm{d}t}$$

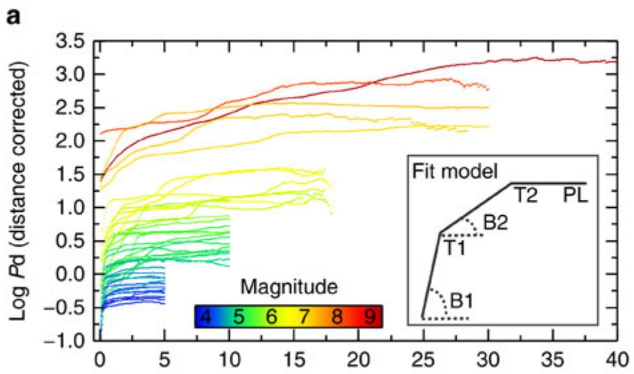
Magnitude dependence of early dominant period

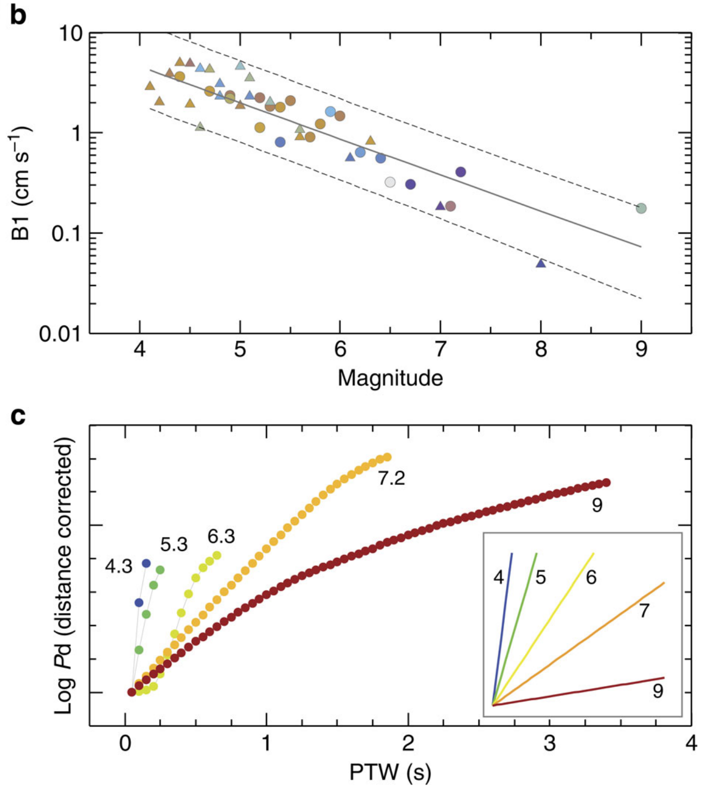
Allen and Kanamori (2003)



Seismological observations of earthquake initiation







Peak ground displacement (Pd) grows exponentially.

Growth rate depends on magnitude

Colombelli et al (2014)

Seismological observations of earthquake initiation

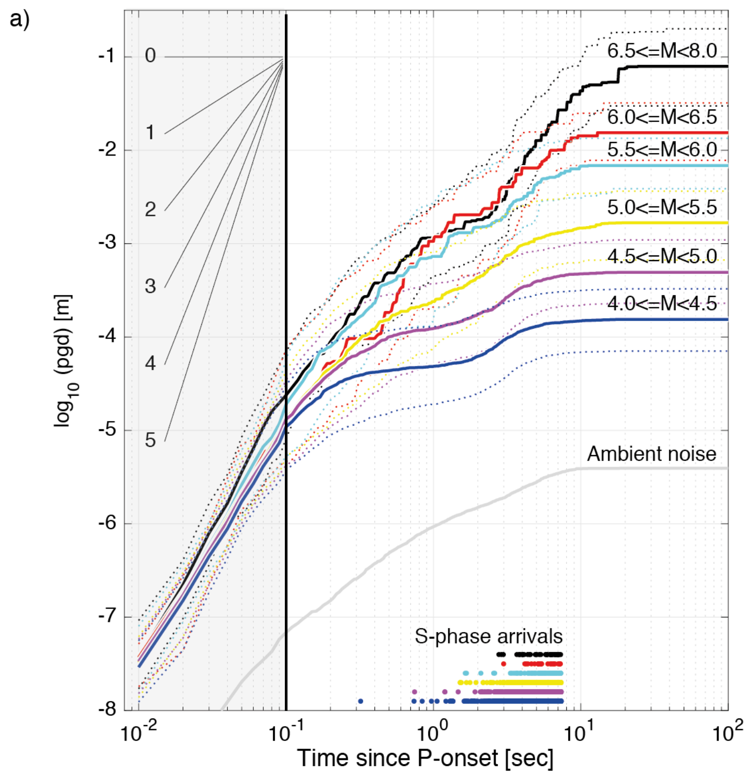
Evidence for universal earthquake rupture initiation behavior
Meier et al (GRL 2016)

Study based on short-distance recordings of shallow crustal earthquakes

Take ground displacement growth as proxy for STF

Growth initially compatible with self-similar pulse and crack models

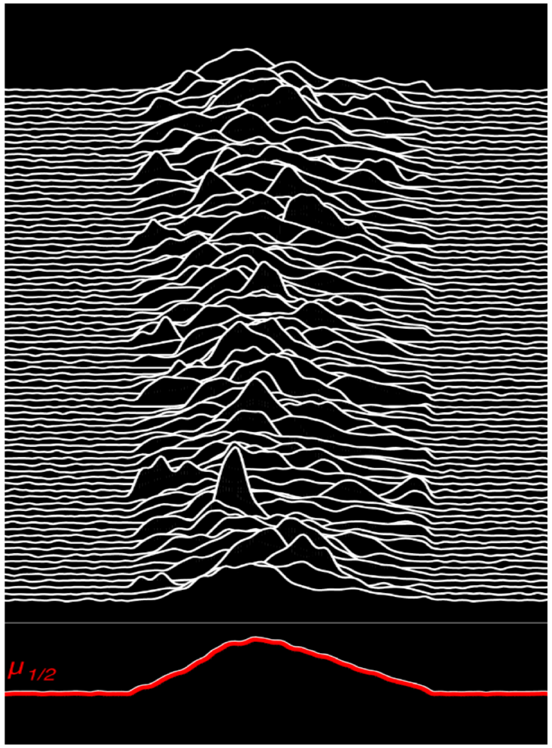
Slower growth after ~1s, M~5



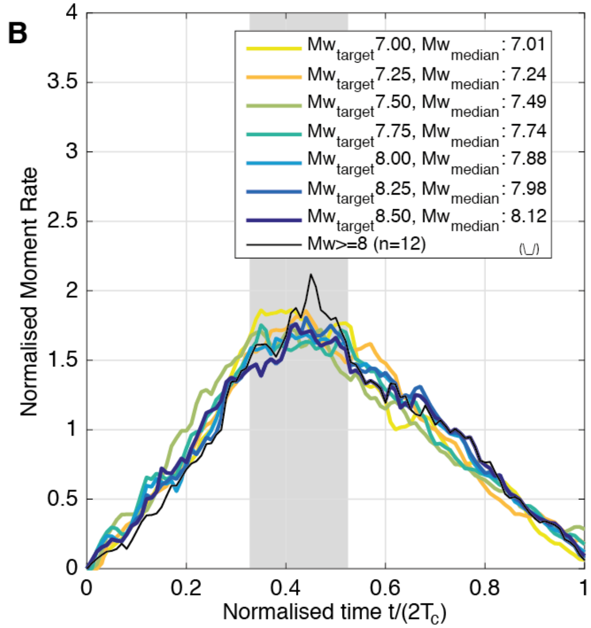
Meier et al., 2016, GRL

The Hidden Simplicity of Large Subduction Earthquakes

Meier, Ampuero and Heaton (*Science* 2017)



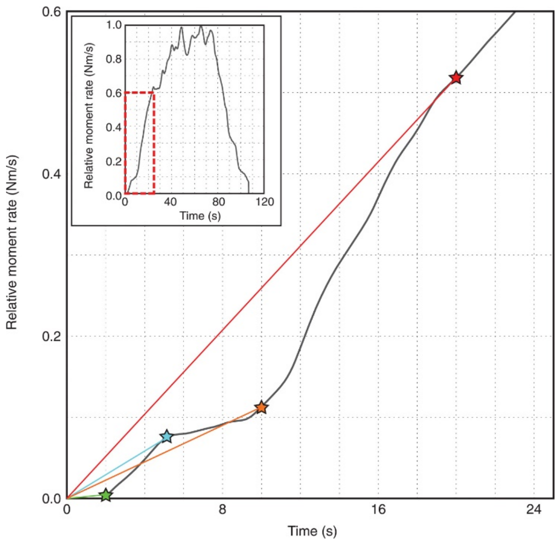
On average (median),
all STFs can be scaled to a very simple, quasi-triangular shape

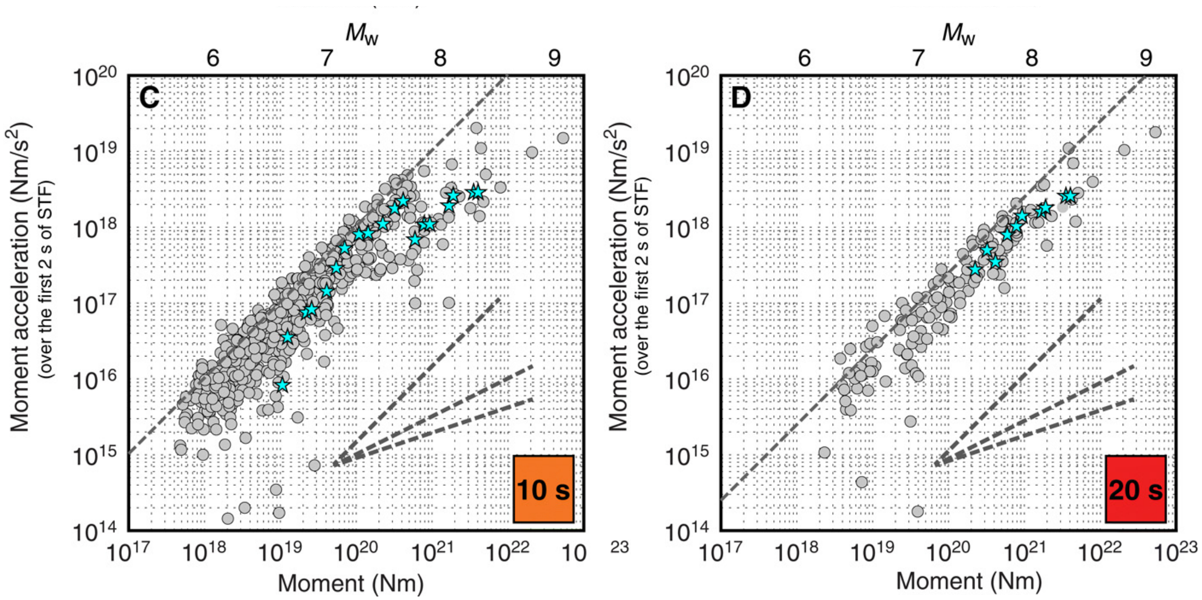


Characterizing large earthquakes before rupture is complete

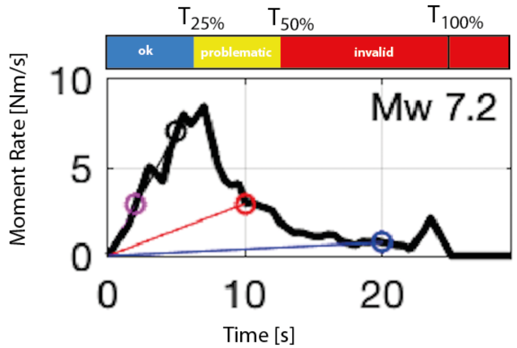
Melgar and Hayes (*Sci Adv* 2019)

“early in the rupture process—after about 10 s—large and very large earthquakes can be distinguished”

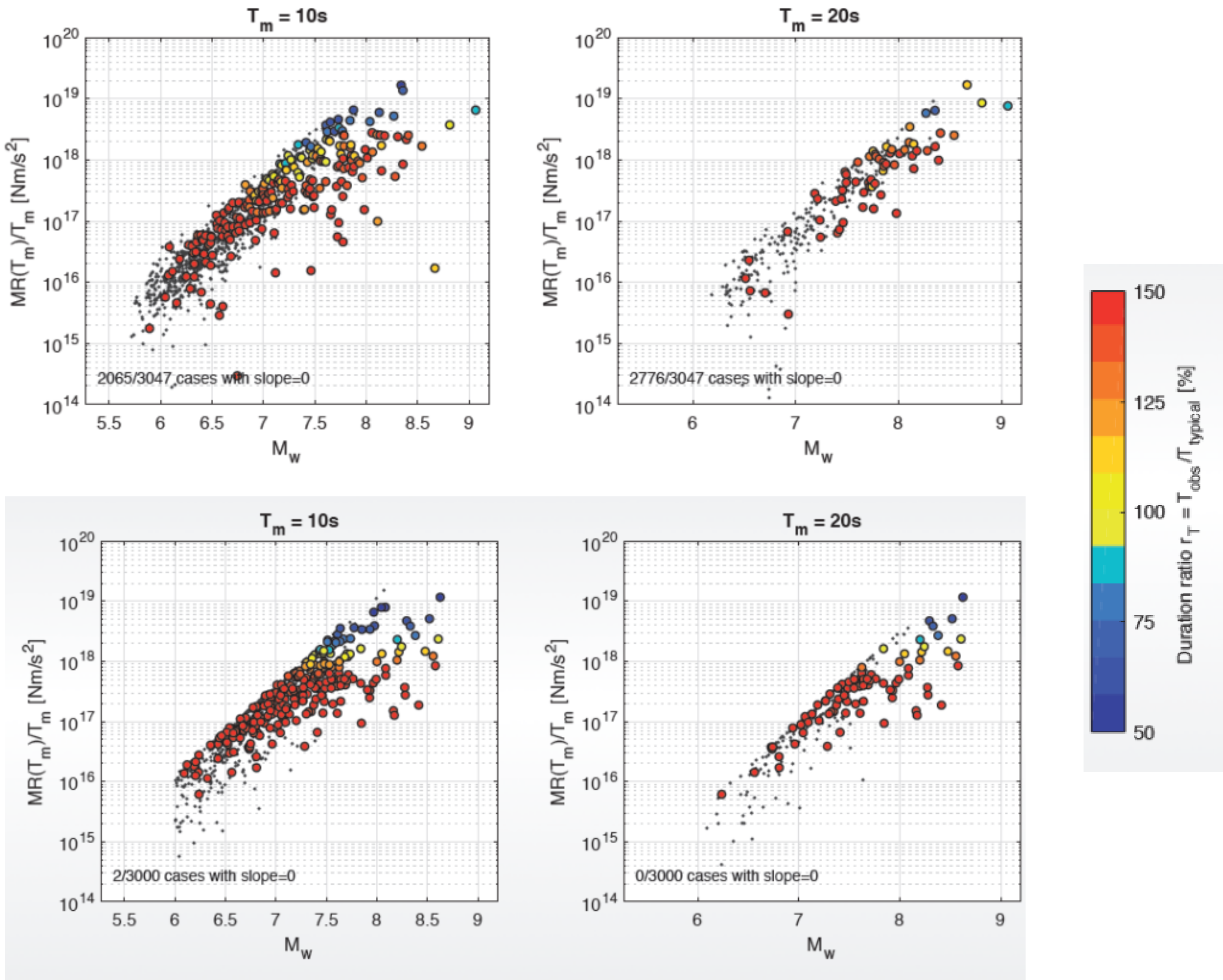




Data colored by ratio of event rupture duration and typical rupture duration for its magnitude

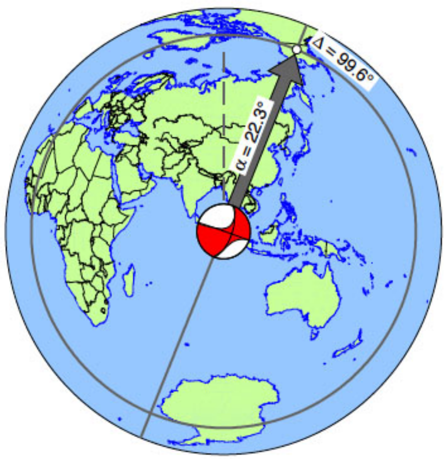


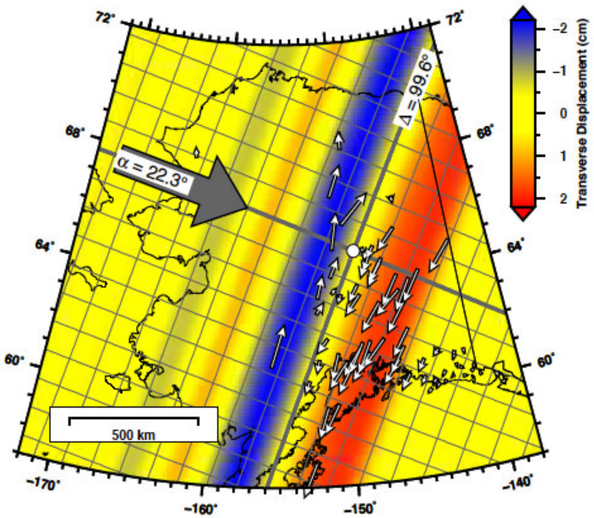
Same figure but for simulation data based on the scalable STF model of Meier et al (2017)

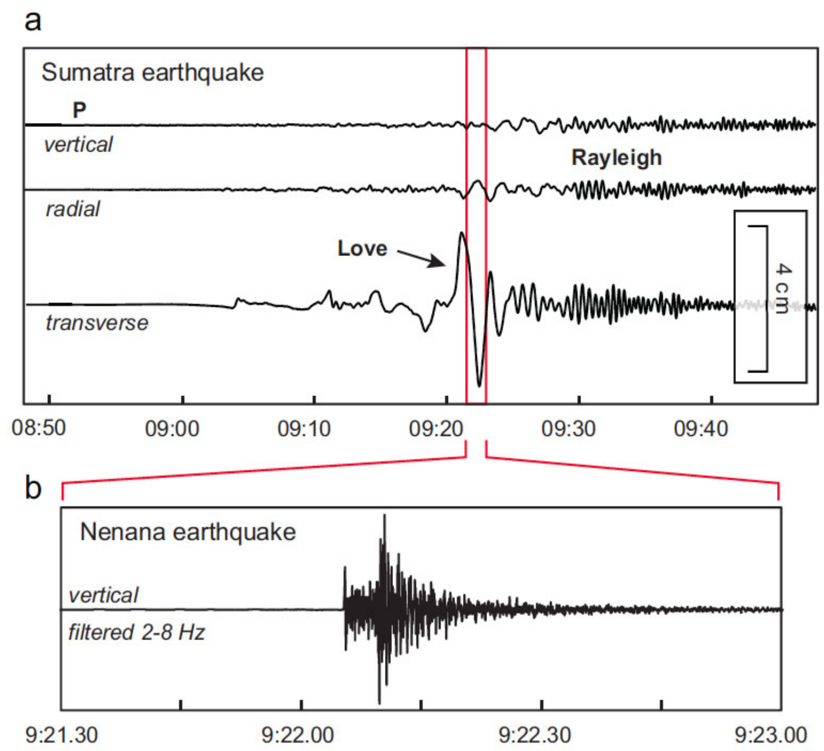


Meier et al (2019, in prep)

Seismological observations



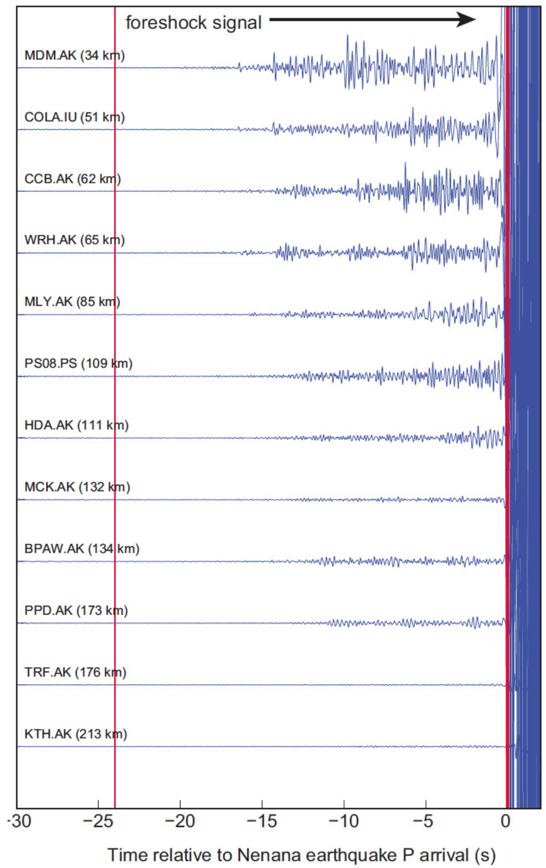


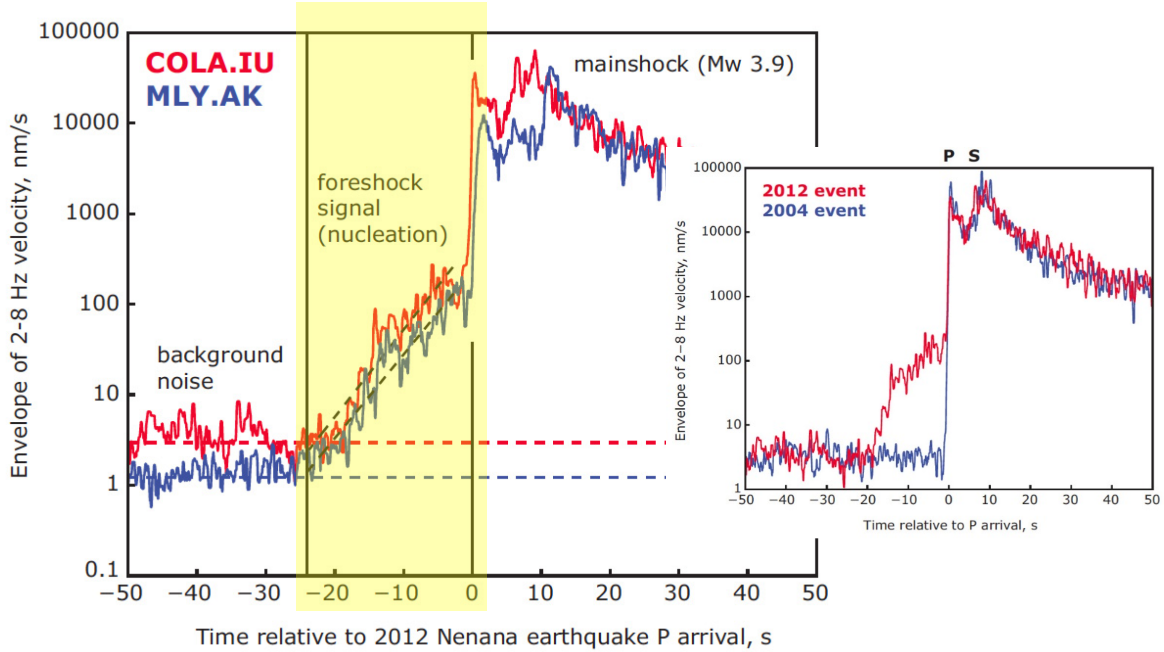


A Mw3.9 earthquake in Alaska triggered by Love waves from the April 11, 2012 Mw 8.6 Sumatra earthquake

Tape et al (2013)

Seismological observations





Nucleation phase of the Mw3.9 Alaska triggered earthquake
Tape et al (2013)

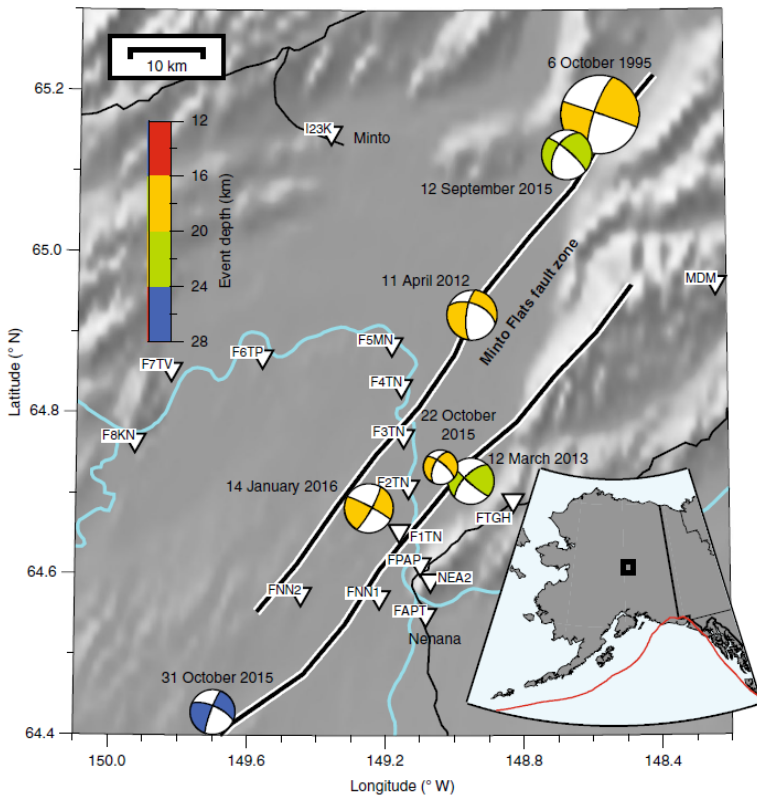
nature geoscience

June 2018

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

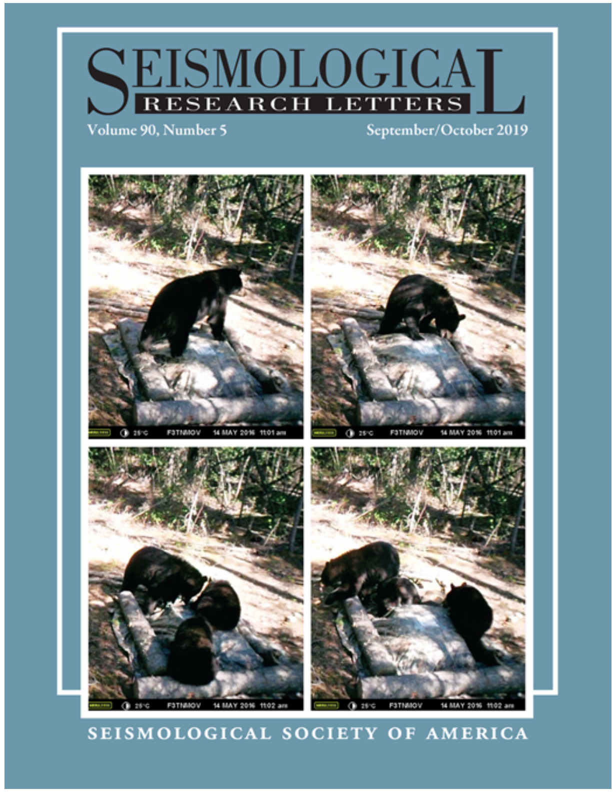
Carl Tape[1*], Stephen Holtkamp[1], Vipul Silwal[1], Jessica Hawthorne[2], Yoshihiro Kaneko[3], Jean Paul Ampuero[4,5], Chen Ji[6], Natalia Ruppert[1], Kyle Smith[1] and Michael E. West[1]

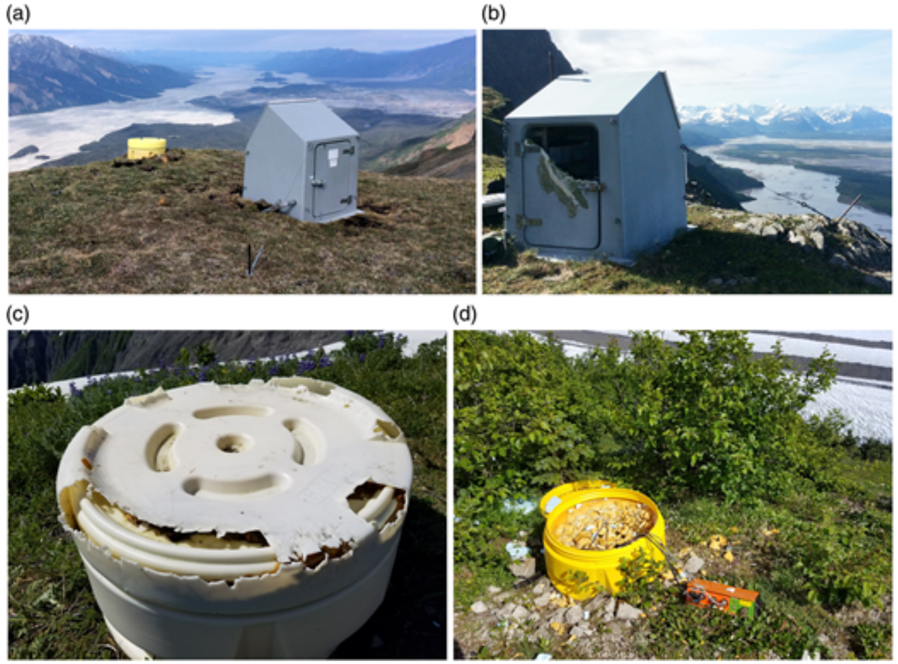
Slow and fast earthquakes (regular and low-frequency events) at the base of the seismogenic zone in the Minto Flats fault zone, central Alaska



Bear Encounters with Seismic Stations in Alaska and Northwestern Canada

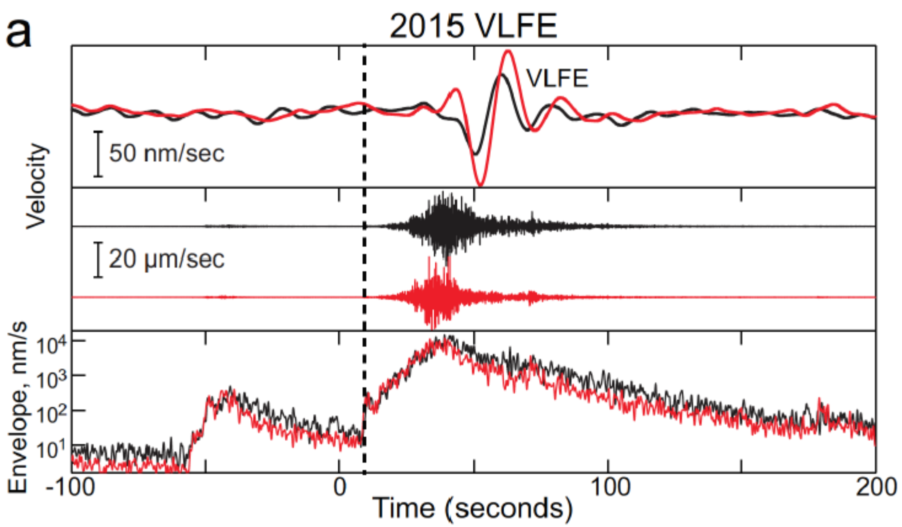
Tape et al (SRL 2019)



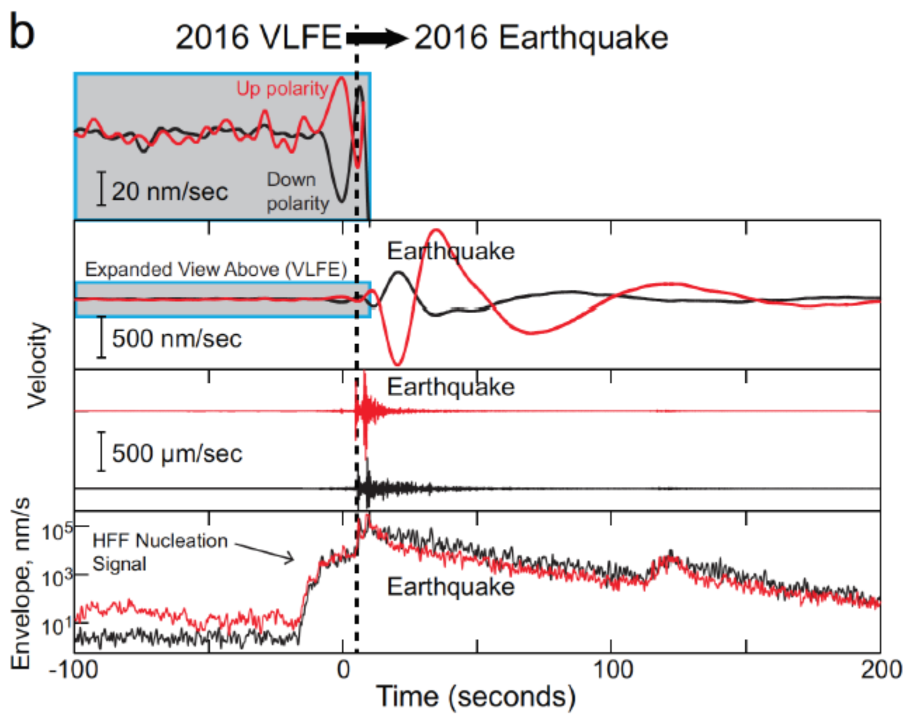


Seismic vaults and equipment enclosures in Alaska visited by curious bears

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



A VLFE transitioning to an earthquake on January 14, 2016

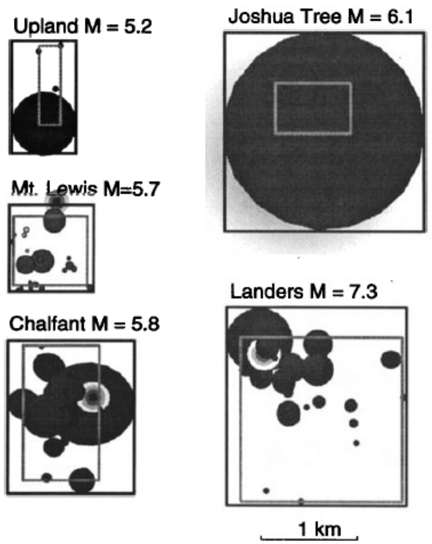


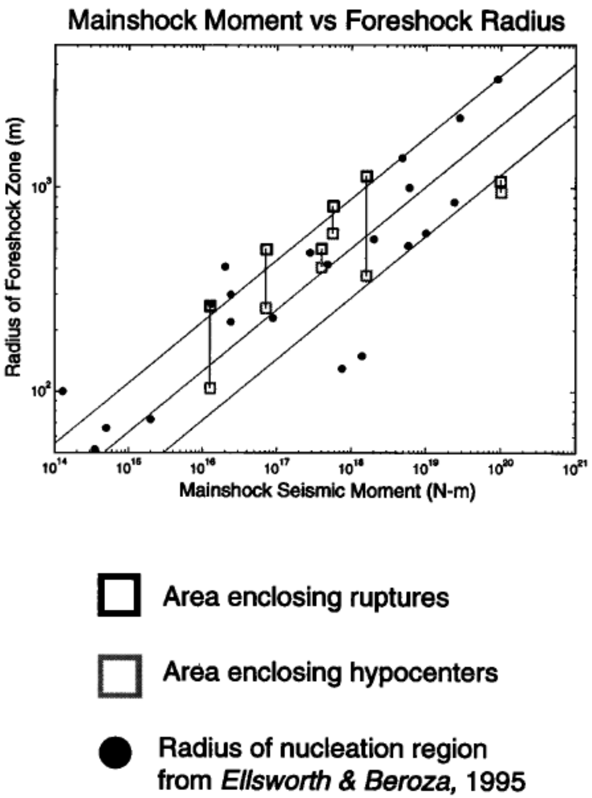
Tape et al (Nat Geo 2018)

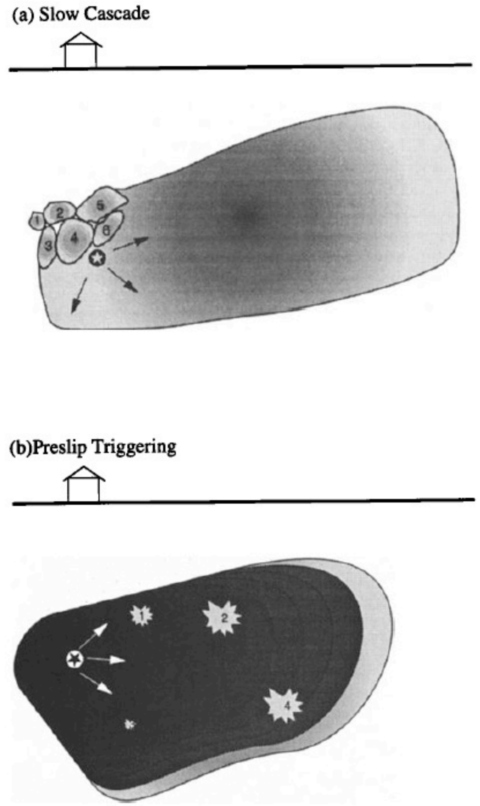
Seismological observations

Foreshock sequences

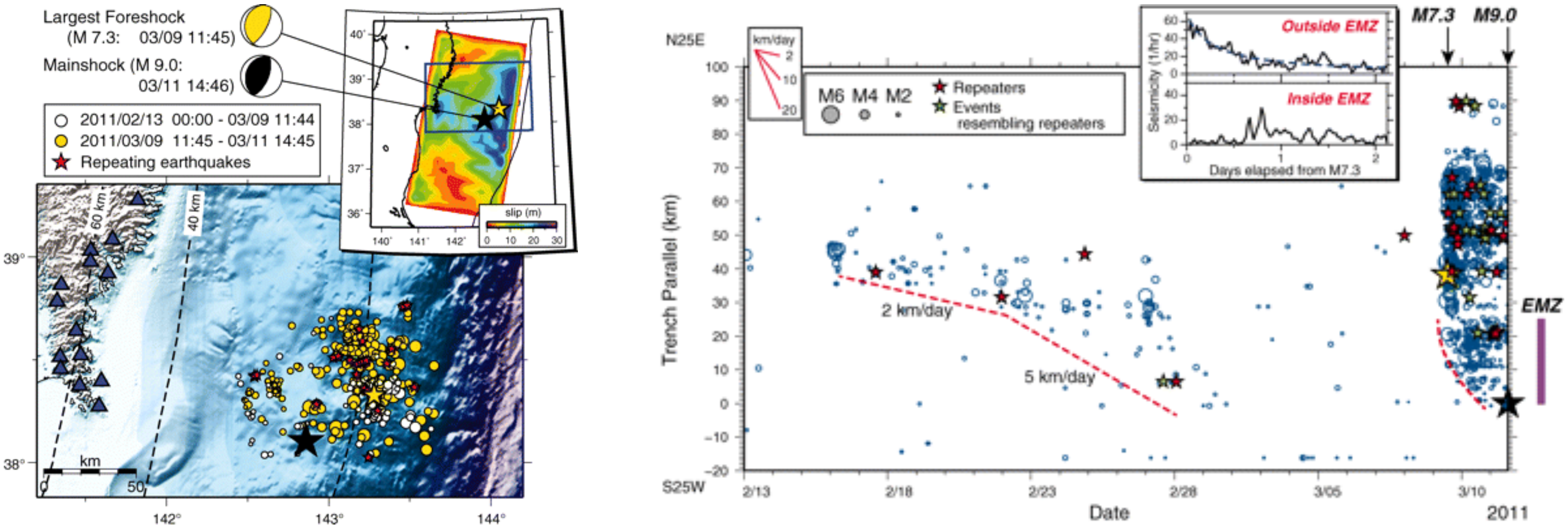
Dodge et al (1996)







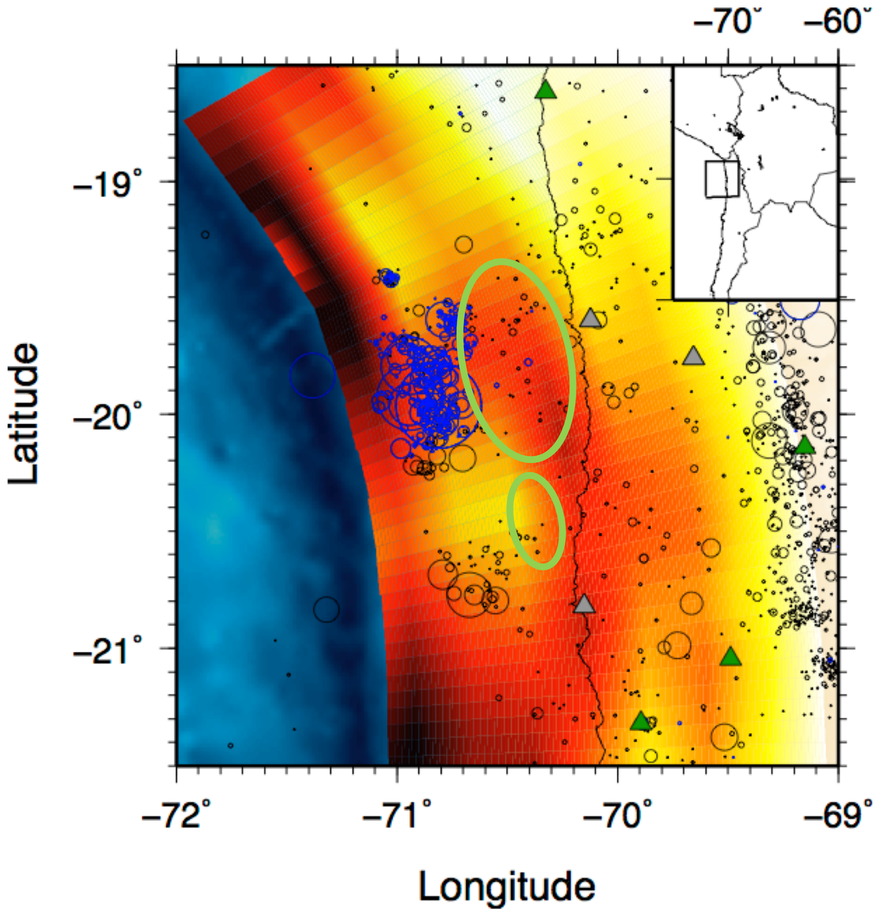
Seismological observations

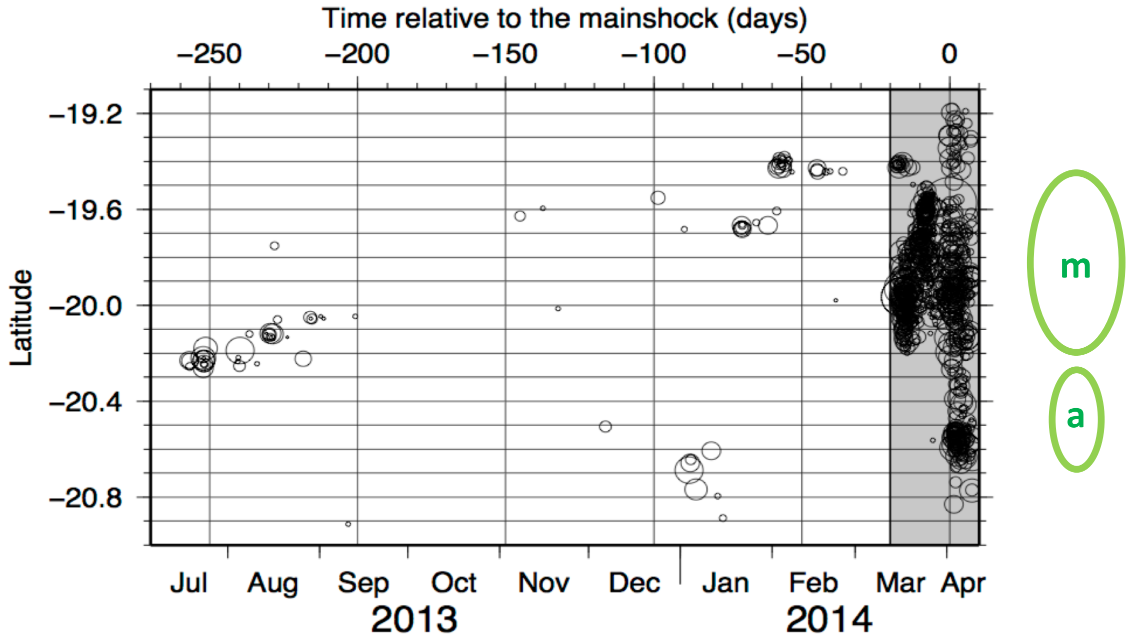


Foreshock sequence of the 2011 Tohoku earthquake

Kato et al (2012)

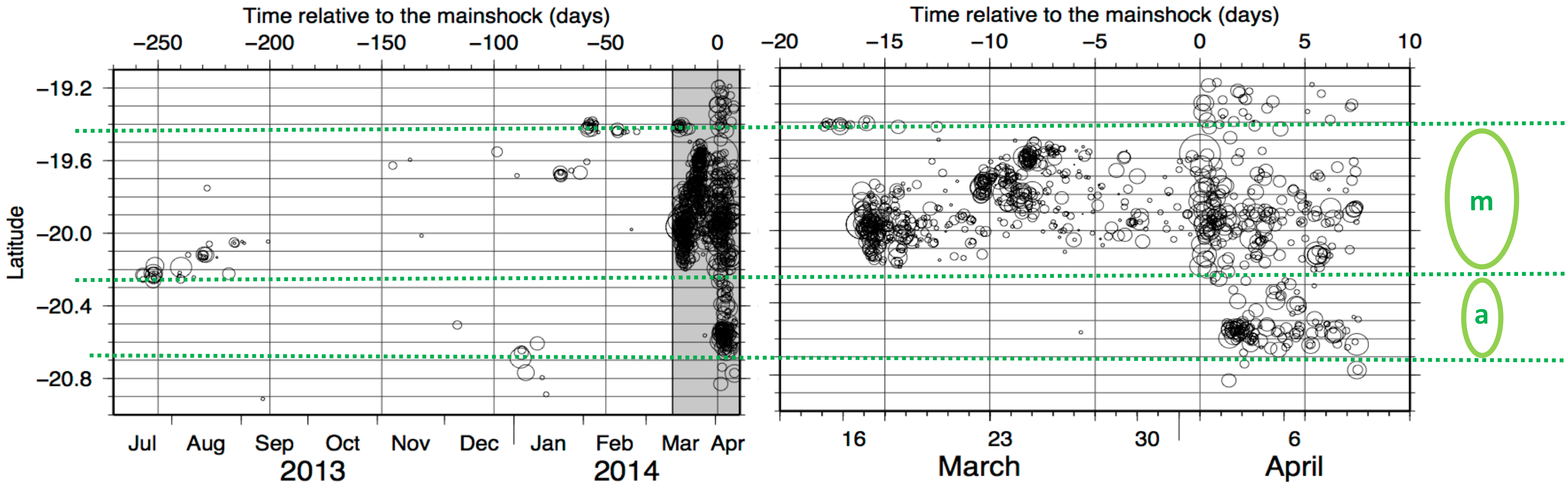
2014 Iquique earthquake + foreshock sequence





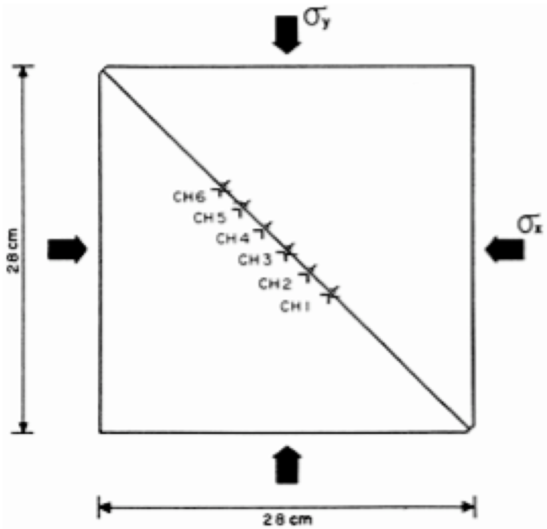
IPOC stations
Regional catalog by CSN Chile
Seismic coupling by Metois et al (2013)

2014 Iquique foreshock sequence

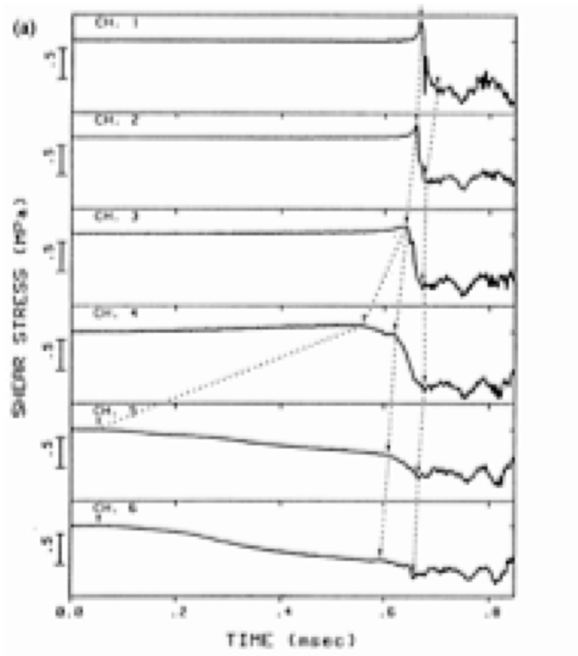


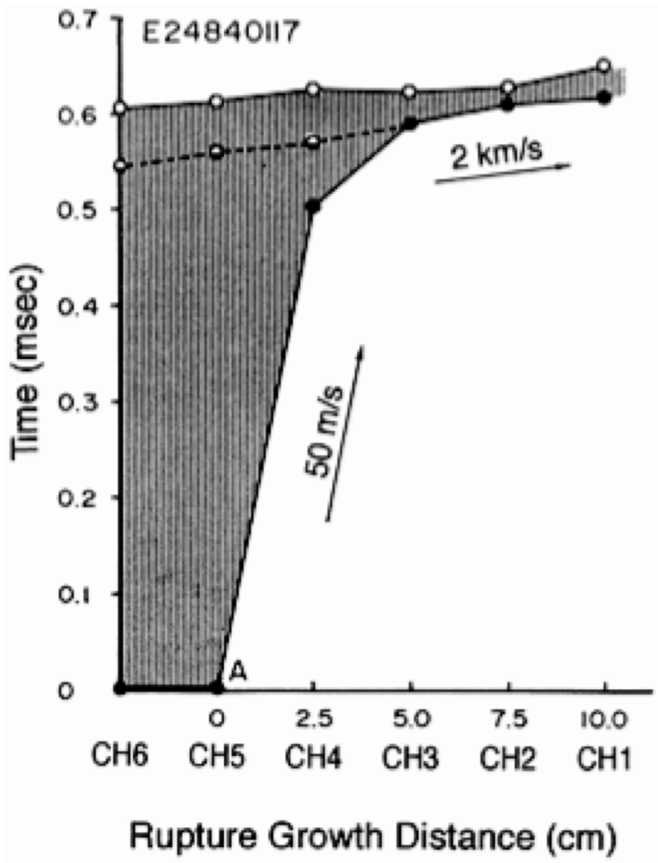
Laboratory observations of rupture nucleation

Laboratory experiments

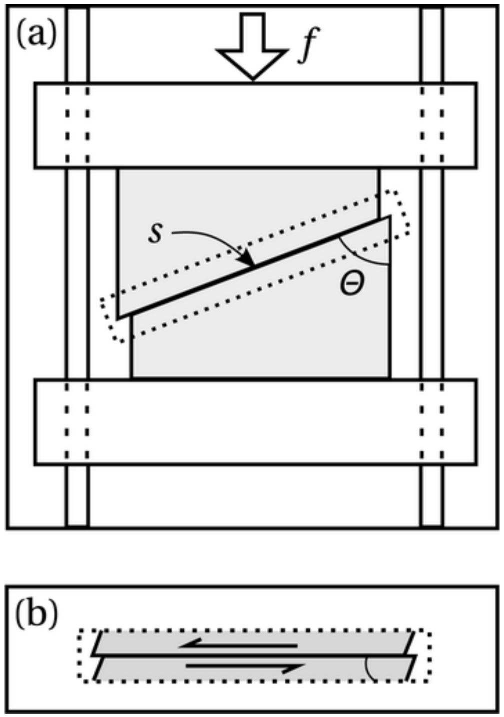


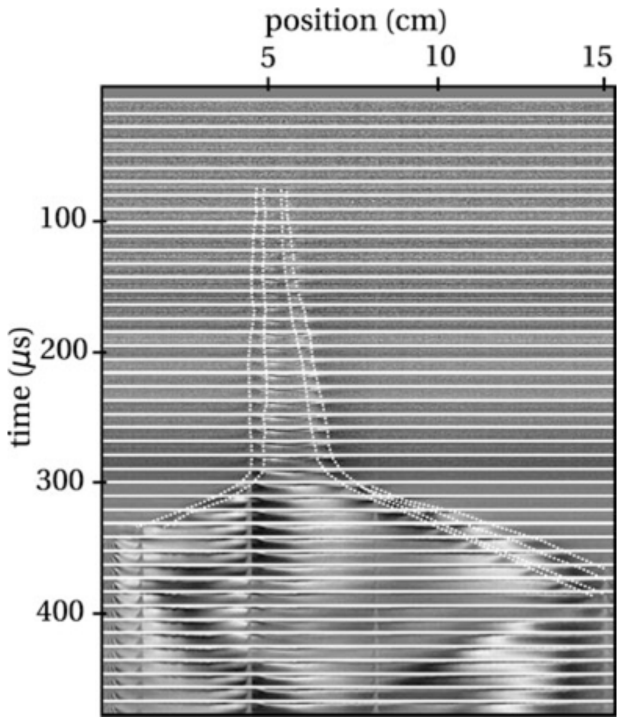
Ohnaka (1990)





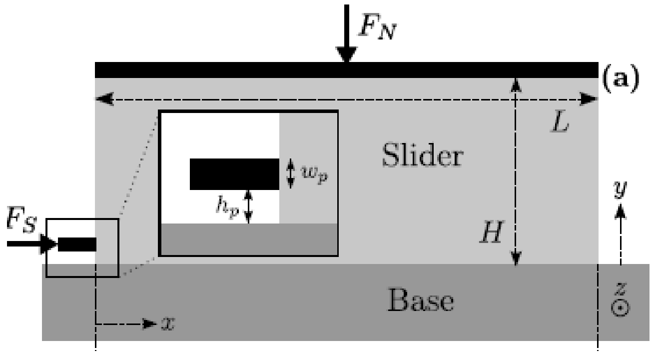
Laboratory experiments

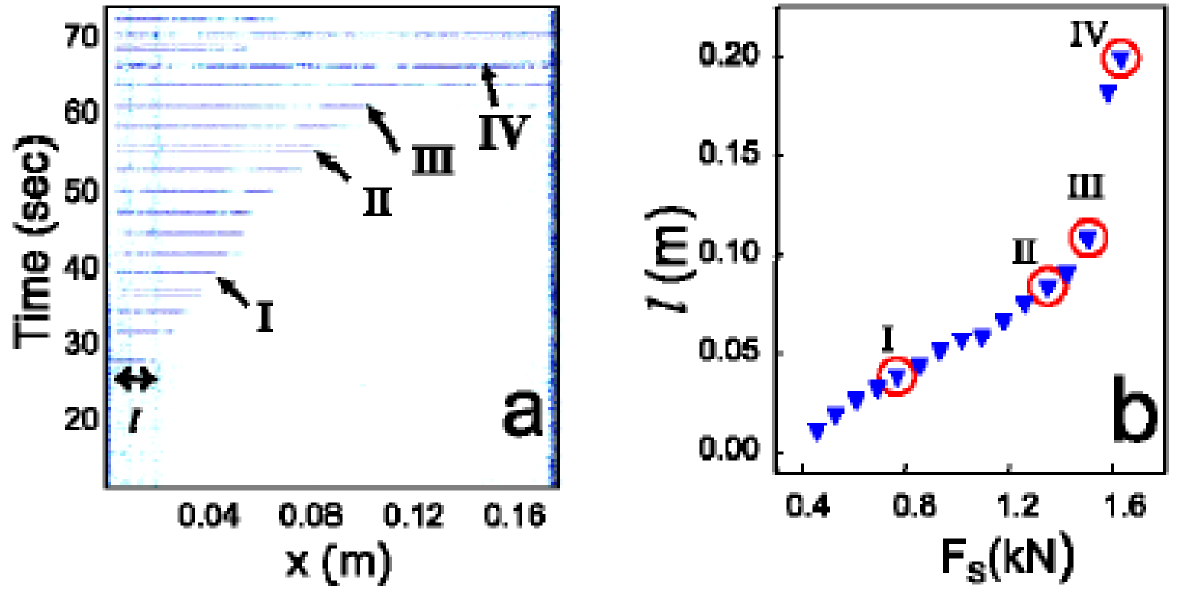




Nielsen et al (2010)

Laboratory experiments

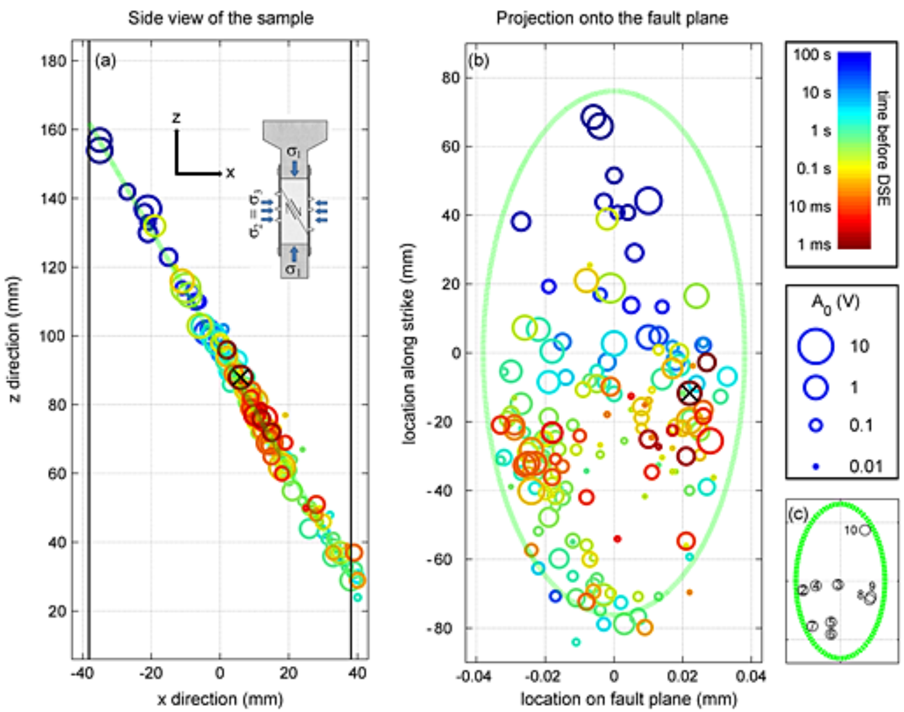




Laboratory foreshocks

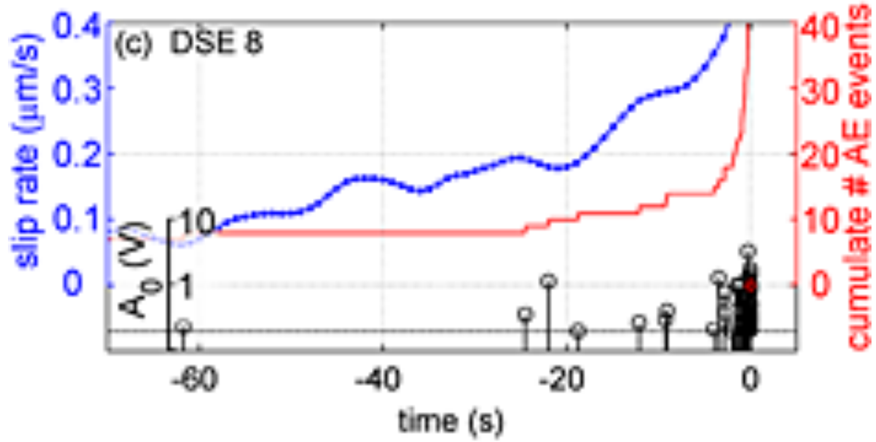
Rubinstein et al (2007)

Laboratory experiments



Foreshocks promoted by aseismic slip

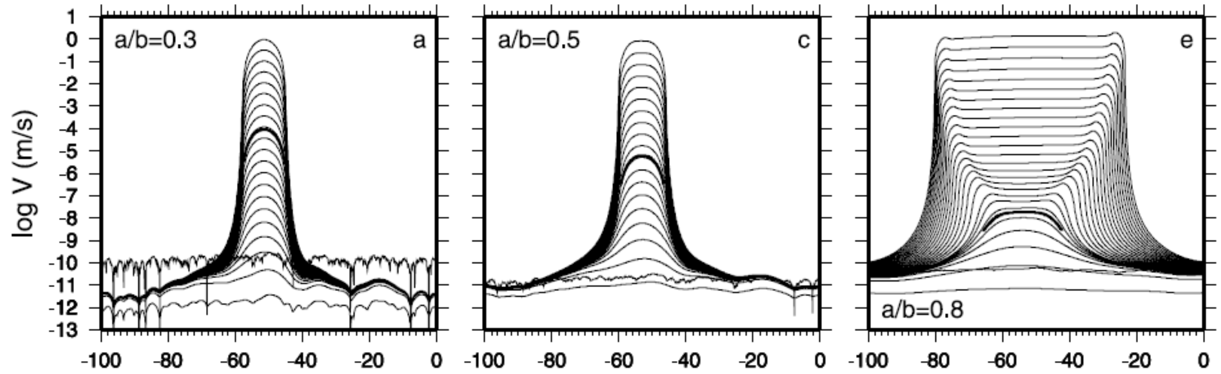
McLaskey and Kilgore (2014)



Rate-and-state models of earthquake nucleation

Nucleation sizes in rate-and-state friction

Different nucleation styles depending on a/b (ratio of viscous to weakening effects in rate-and-state friction)



Localized slip at low a/b

Expanding slip at high a/b

Minimum localization size:

$$L_b = \frac{\mu L}{b\sigma}$$

Maximum nucleation size:

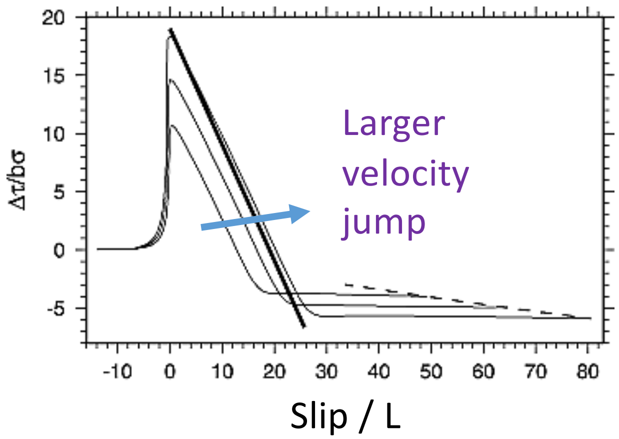
$$L_\infty = \mu L \frac{b}{(b-a)^2\sigma}$$

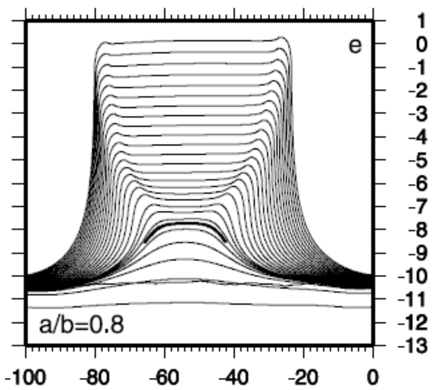
$$= \left(\frac{b}{b-a}\right)^2 L_b$$

$$L_c = \frac{\mu L}{(b-a)\sigma} = \frac{b}{b-a} L_b$$

Rubin and Ampuero (2005)

Nucleation size in rate-and-state friction





From lecture 2: crack in static equilibrium of size a

$$G_0 = \frac{\Delta\tau^2 a}{2\mu} = G_c \quad \rightarrow \quad a = 2\mu G_c/\Delta\tau^2$$

Rate-and-state behaves as slip-weakening near the rupture front, with equivalent properties:

$$G_c \approx \frac{1}{2} b\sigma L \ln\left(\frac{V}{V^*}\right)^2$$

Stress drop $\Delta\tau \approx (b-a)\sigma \ln\left(\frac{V}{V^*}\right)$

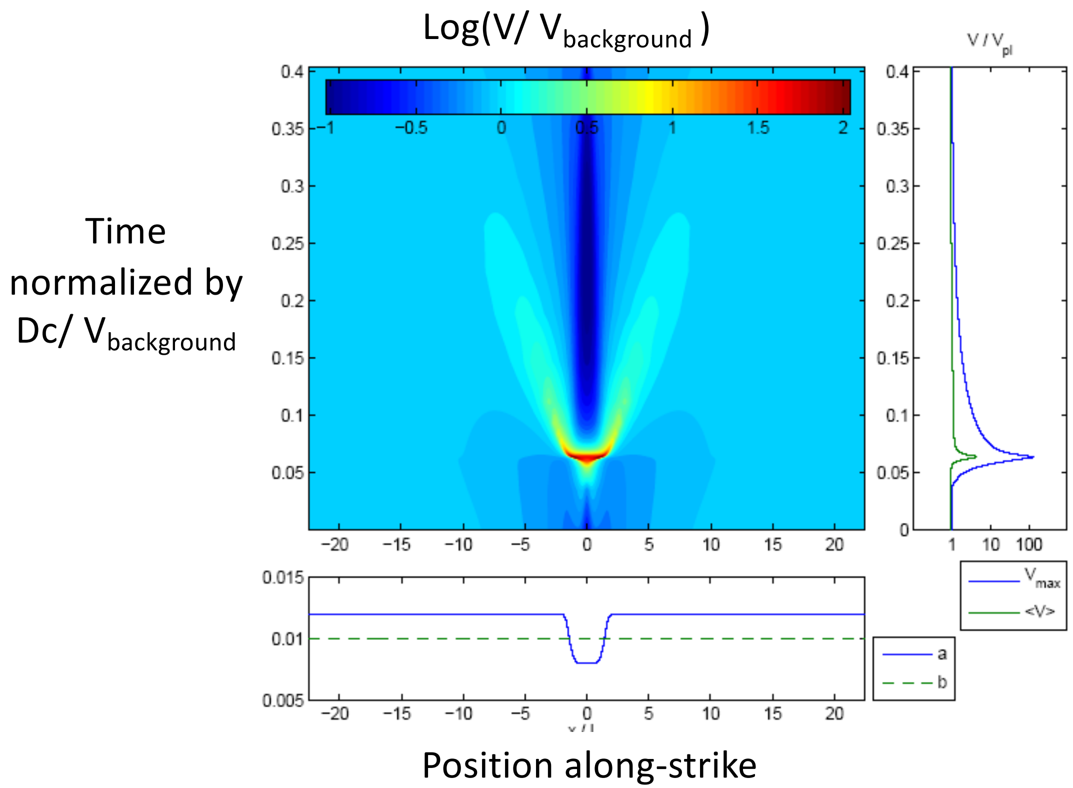
→ Crack size:

$$a \approx \frac{\mu L}{b\sigma} \frac{b^2}{(b-a)^2} = L_\infty$$

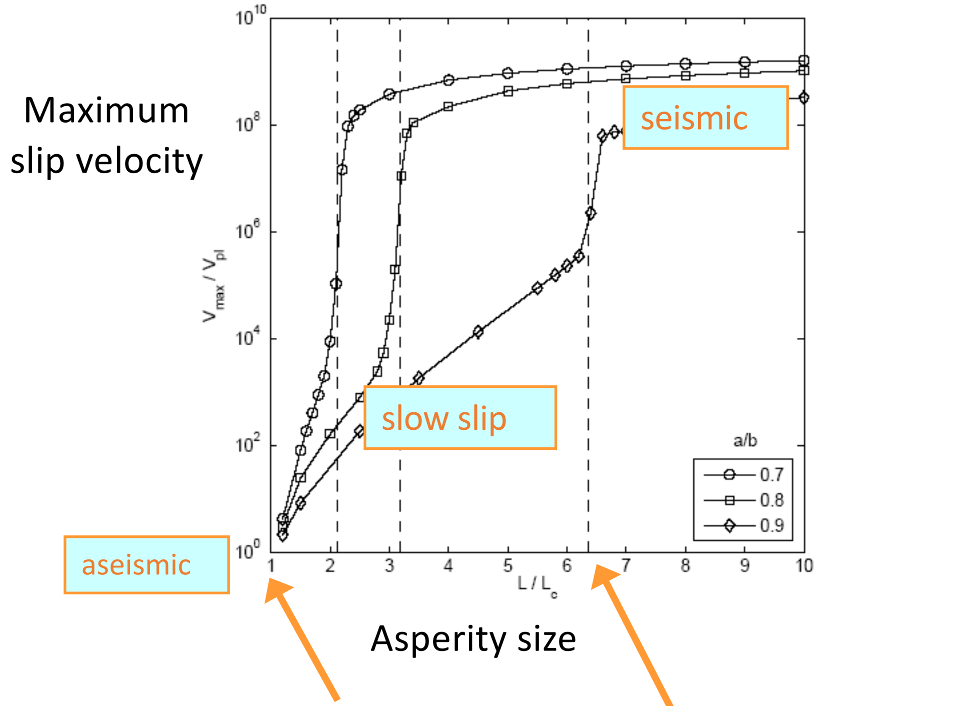
Rubin and Ampuero (2005)

Example: brittle asperity isolated in a creeping fault zone

An isolated brittle asperity (v-weakening) within a creeping fault (v-strengthening).
Constant slip velocity $V_{background}$ imposed far from the asperity.



Example: brittle asperity isolated in a creeping fault zone

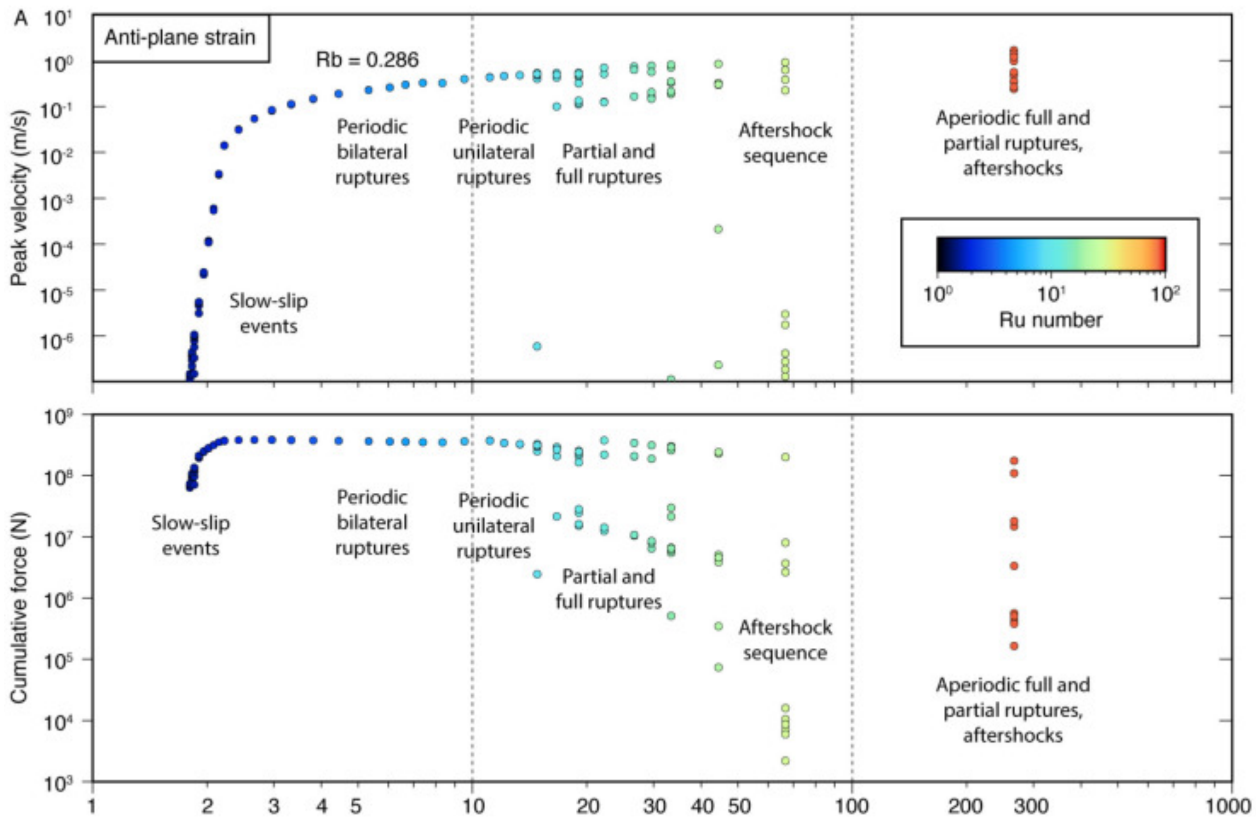


$$L_b \doteq \frac{\mu D_c}{b\sigma}$$

$$L_c \doteq \frac{\mu D_c}{(b-a)\sigma}$$

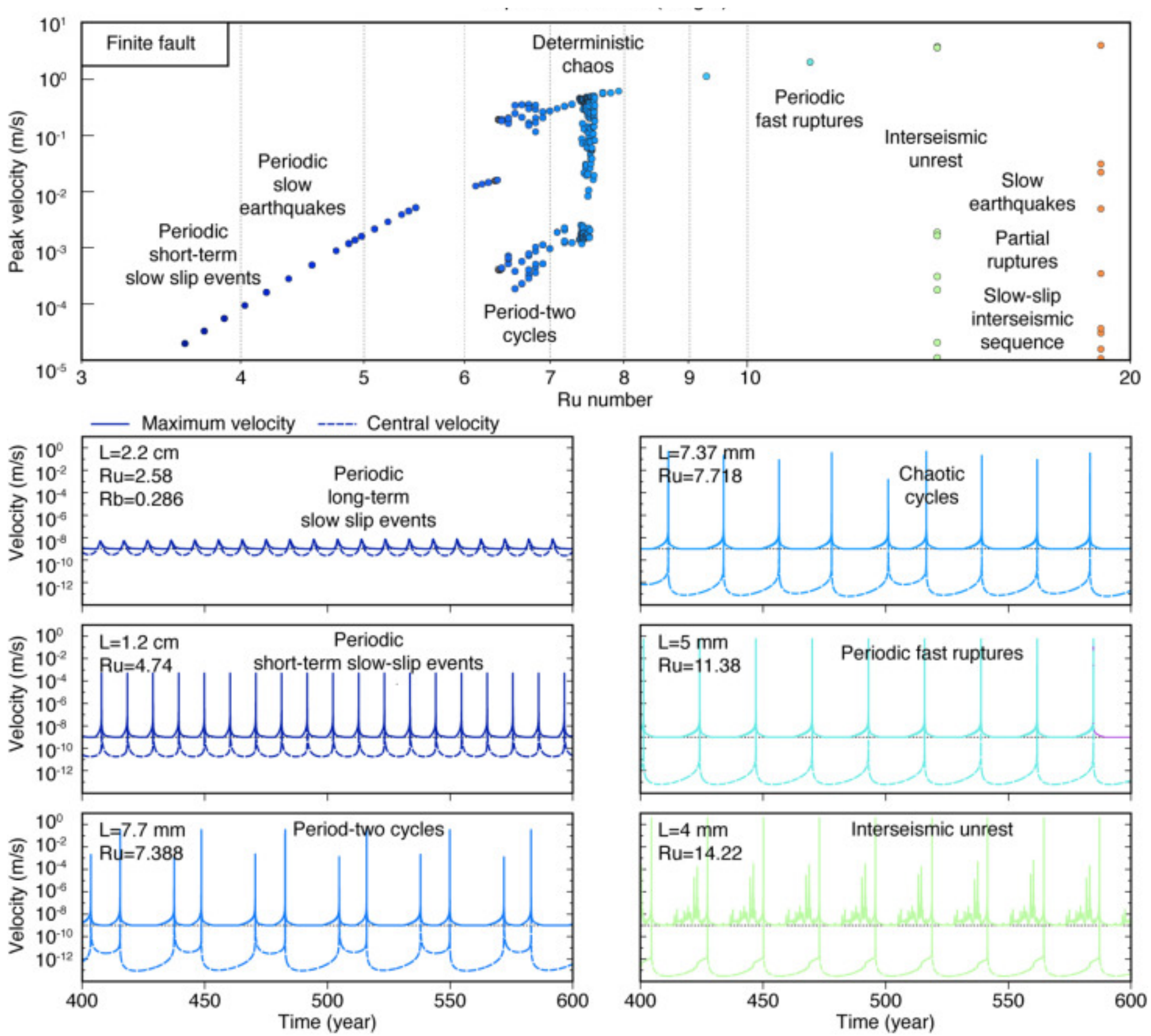
$$L_\infty = \frac{1}{\pi}\left(\frac{b}{b-a}\right)^2 L_b$$

Barbot (2019)



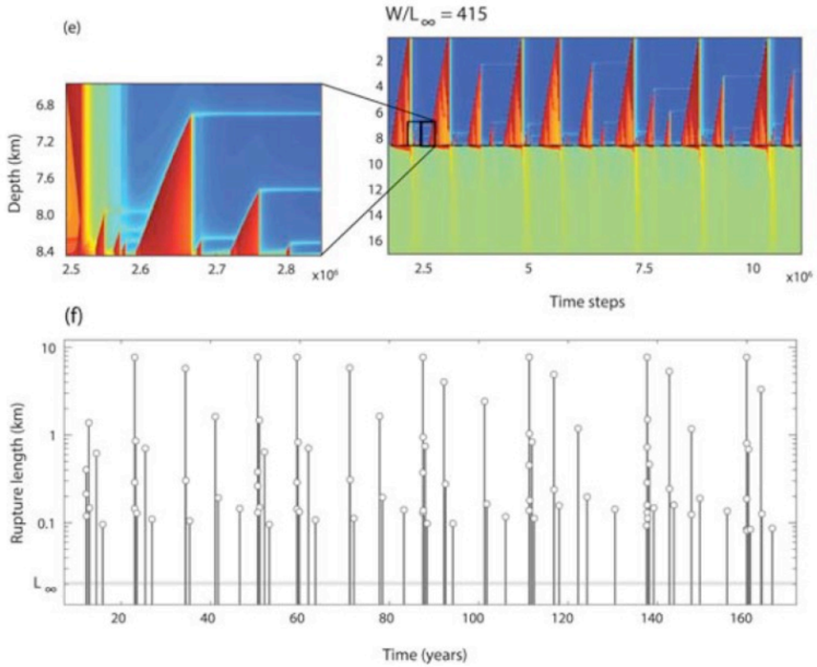
Fault size / nucleation size

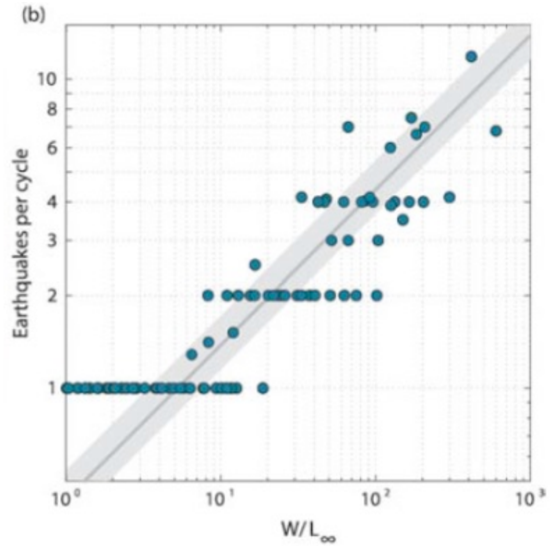
Barbot (2019)



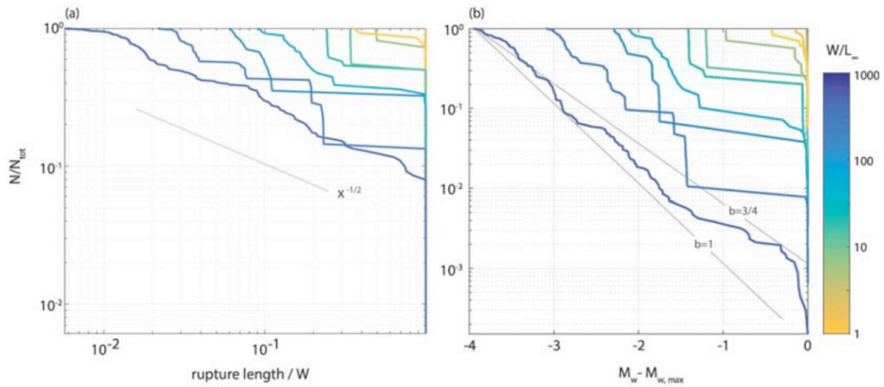
Fault size / nucleation size

Cattania (2019)

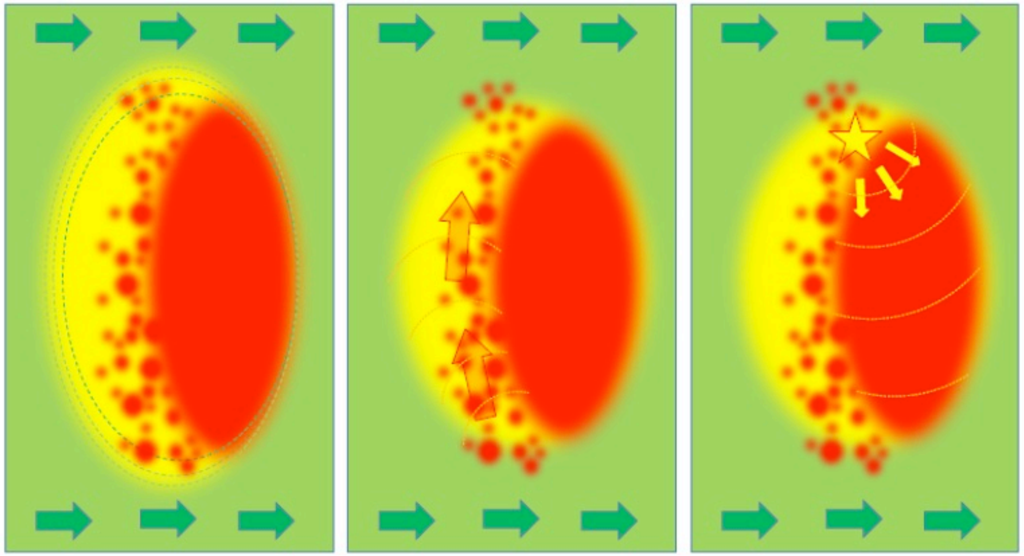




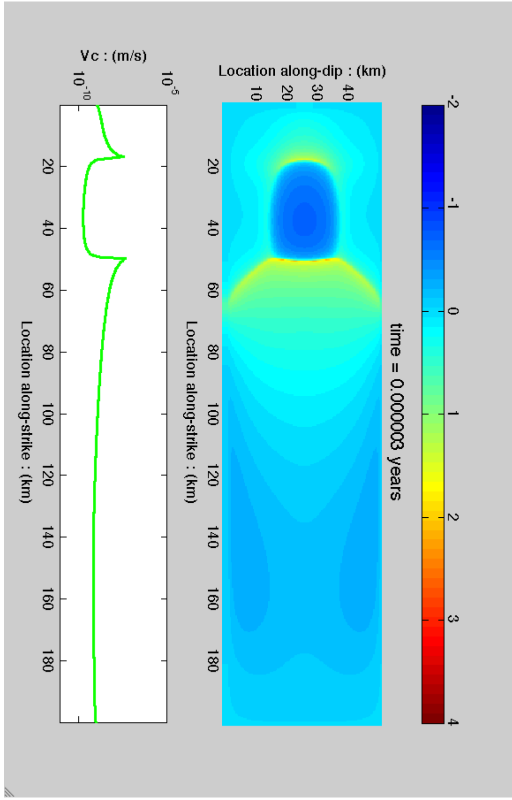
Fault size / nucleation size



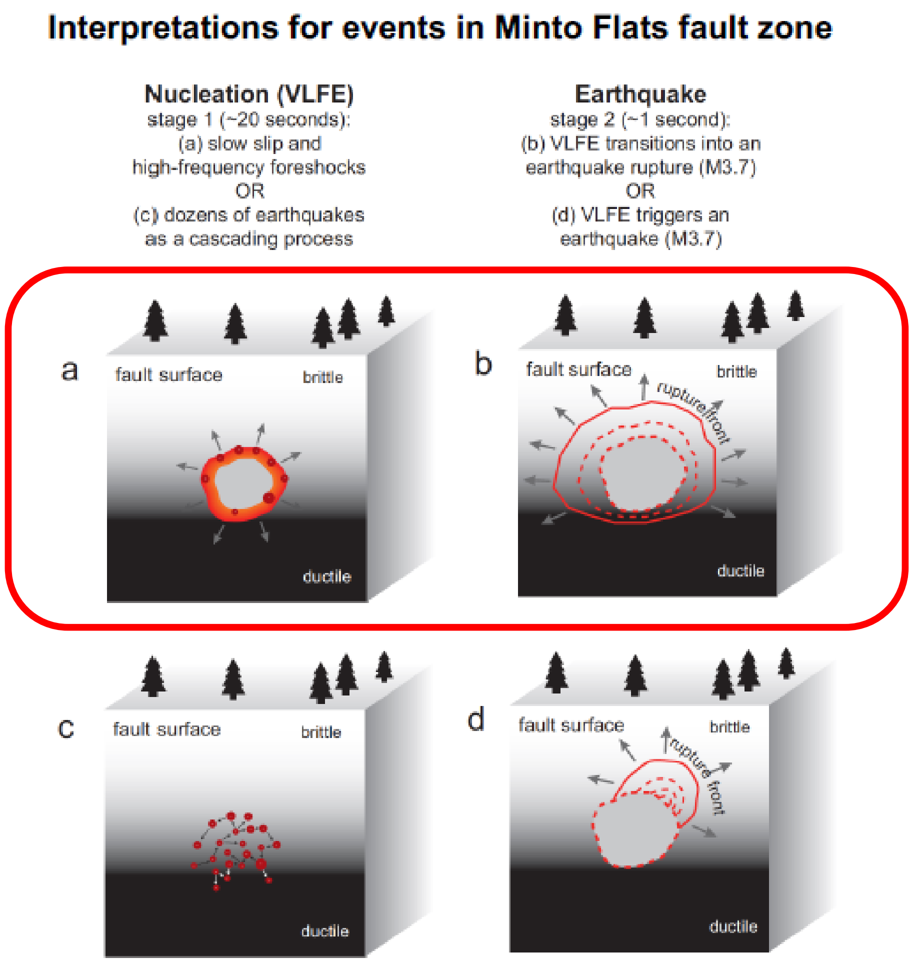
Rate-and-state models of slow slip and foreshock swarms

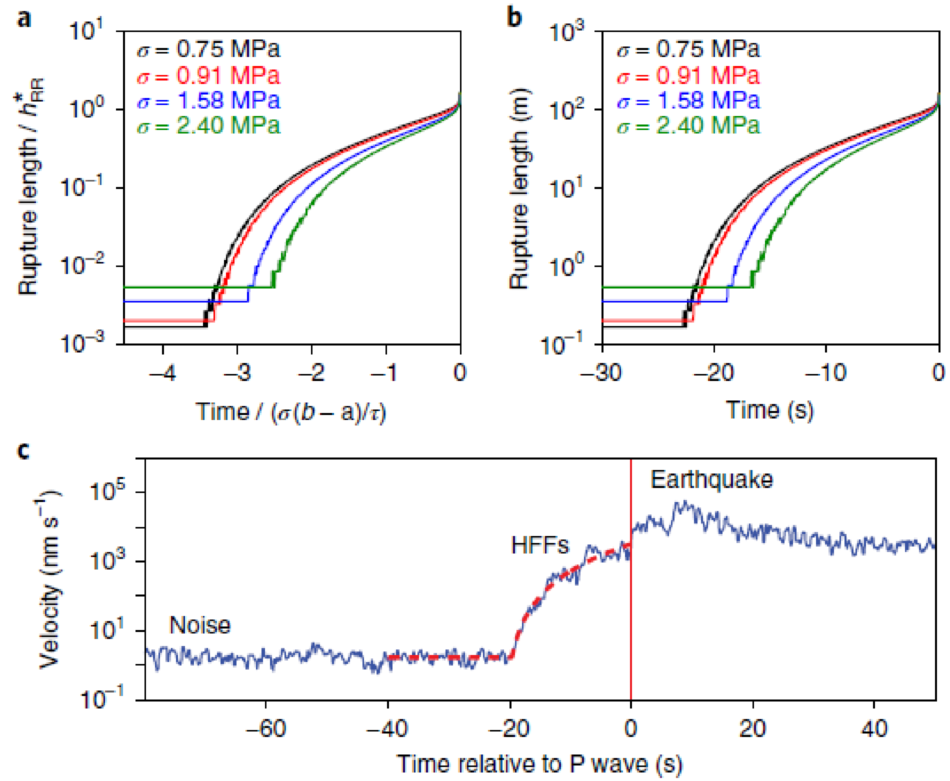


Conceptual model of slow slip event + foreshocks leading to a large earthquake



Numerical model (QDYN)
of slow slip event + small earthquakes/tremors





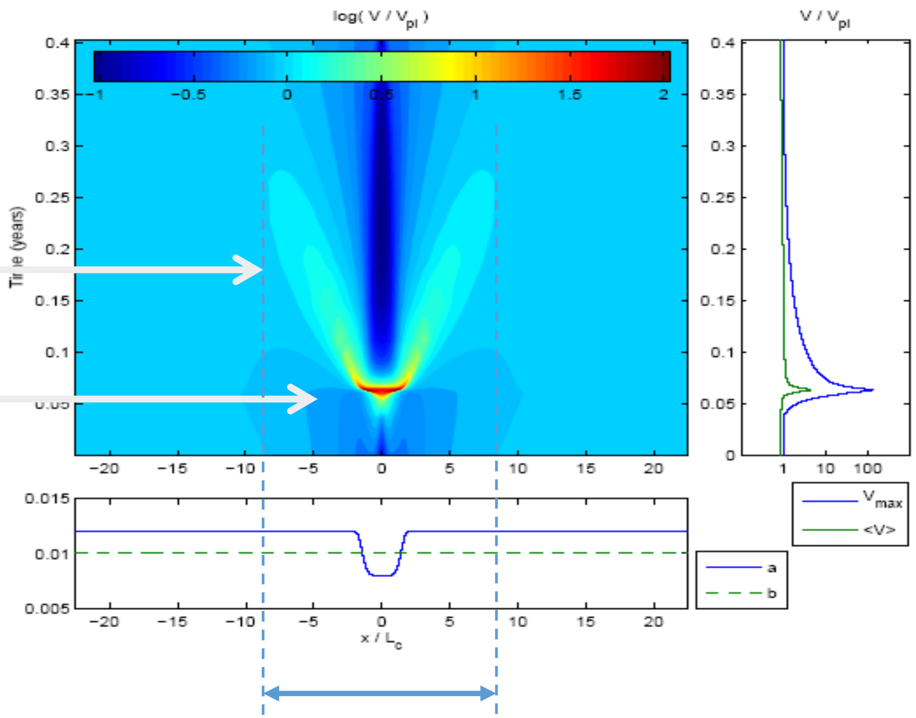
Tape et al (Nat Geo 2018)

Rate-and-state models of slow slip and tremor

Migrating swarms: asperity interactions mediated by creep transients

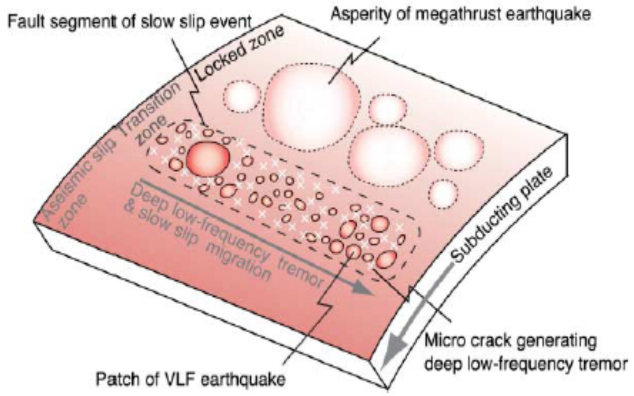
It triggers a migrating aseismic transient

The asperity breaks



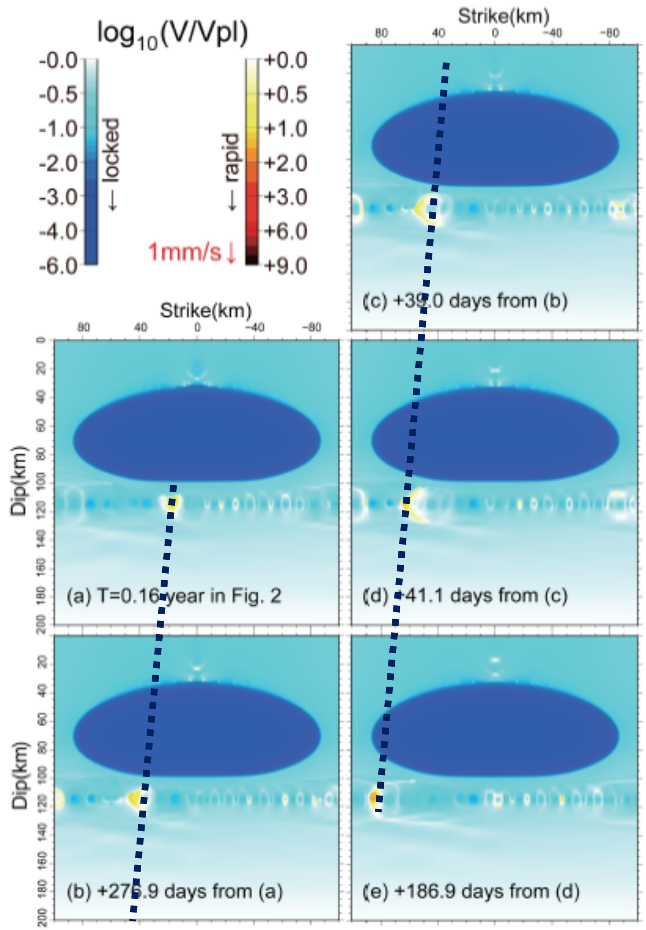
Influence radius

Migrating swarms:
asperity interactions
mediated by creep transients



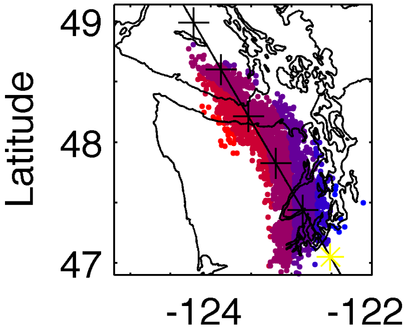
Cascading failure of a population of brittle asperities

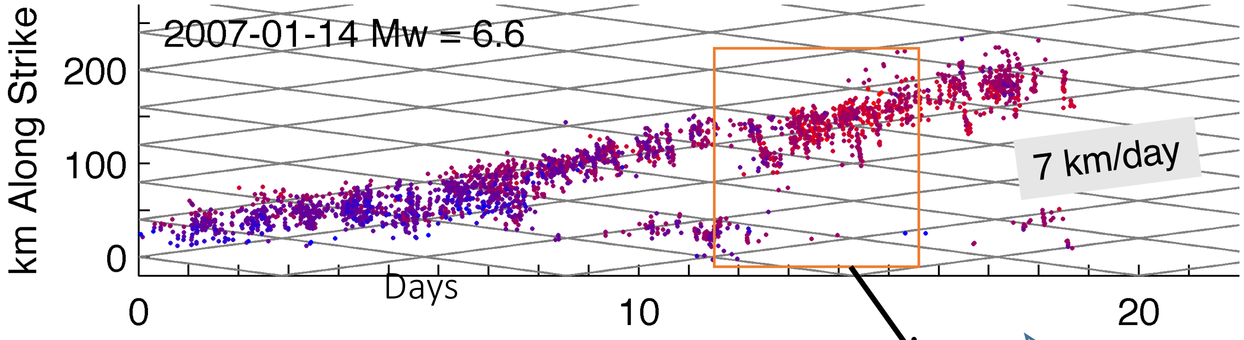
→ Tremor swarm

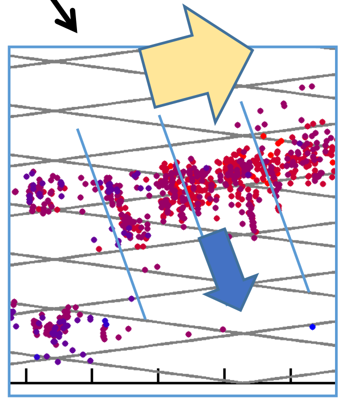


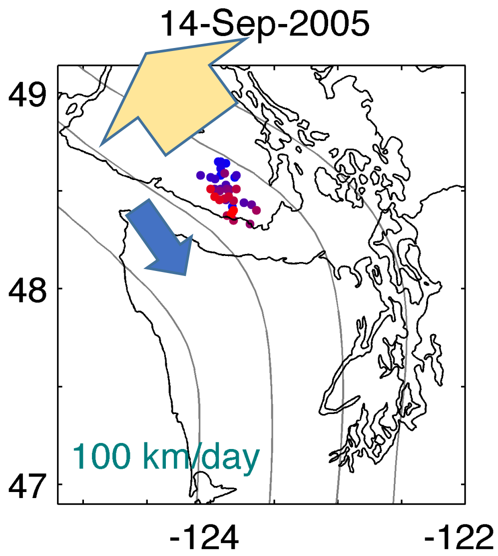
Quasi-dynamic 3D simulations with
K. Ariyoshi (JAMSTEC)

Slow slip and tremor migration patterns









Non-volcanic tremor migration patterns in Cascadia, USA

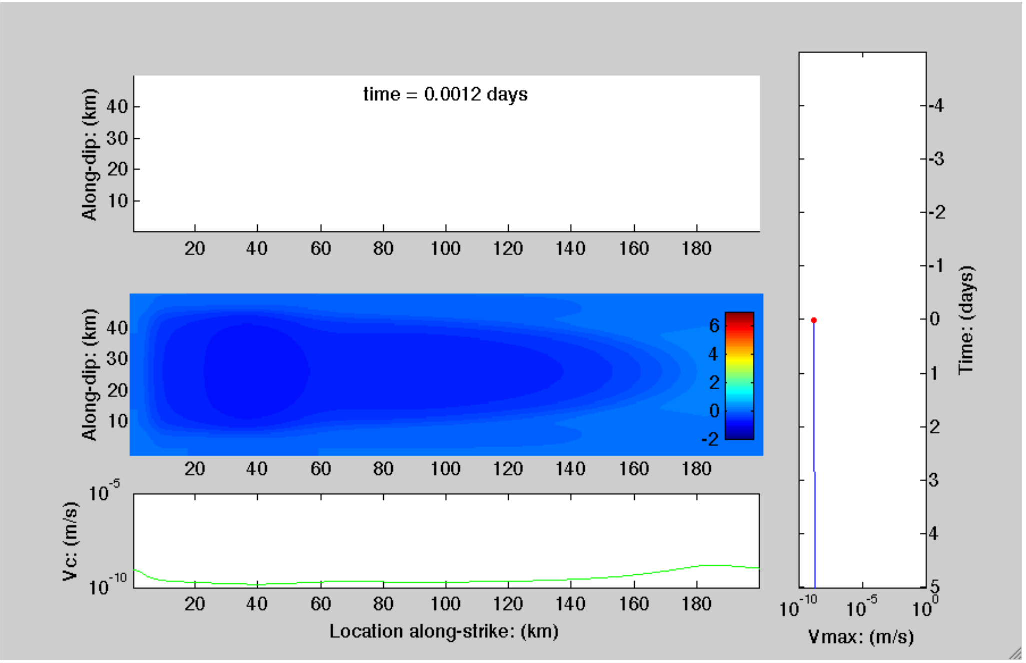
Tremor migrates slowly along strike (~10 km/day) tracking the front of the slow slip event

Episodic tremor swarms propagate backwards, faster (~ 100 km/day)

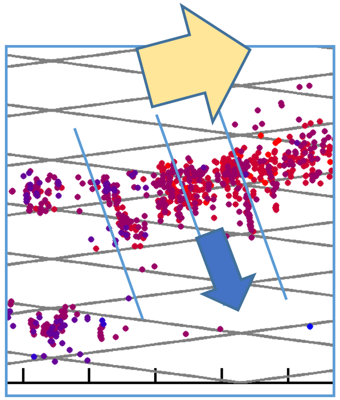
Houston et al (2010)

Simulations of slow slip and tremor

QDYN model of slow slip and tremor

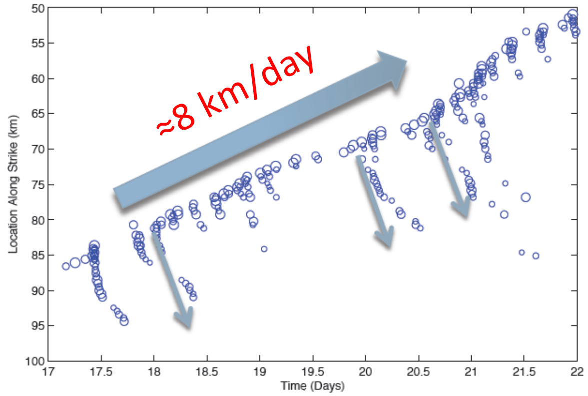


Luo and Ampuero



Rapidal Tremor Reversals observed in Cascadia

Houston et al (2010)



Model