Societa Italiana di Fisica, Enrico Fermi school, Varenna, July 2018

The long (!) nucleation phase of laboratory earthquakes

Alexandre SCHUBNEL
Laboratoire de Géologie, ENS PARIS

Thanks to:
@ ENS: Samson Marty, Blandine Gardonio, Harsha Bhat, Raul Madariaga
@ IGN, Paris VII: Kristel Chanard
@ IRAP Toulouse: Soumaya Latour
@ EPFL: François Passelègue
@ Durham U.: Stefan Nielsen
....

European Research Council
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Observer & comprendre

AGENCE NATIONALE DE LA RECHERCHE

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Integrating 30 years of experimental rock fracture mechanics: Ohnaka's view

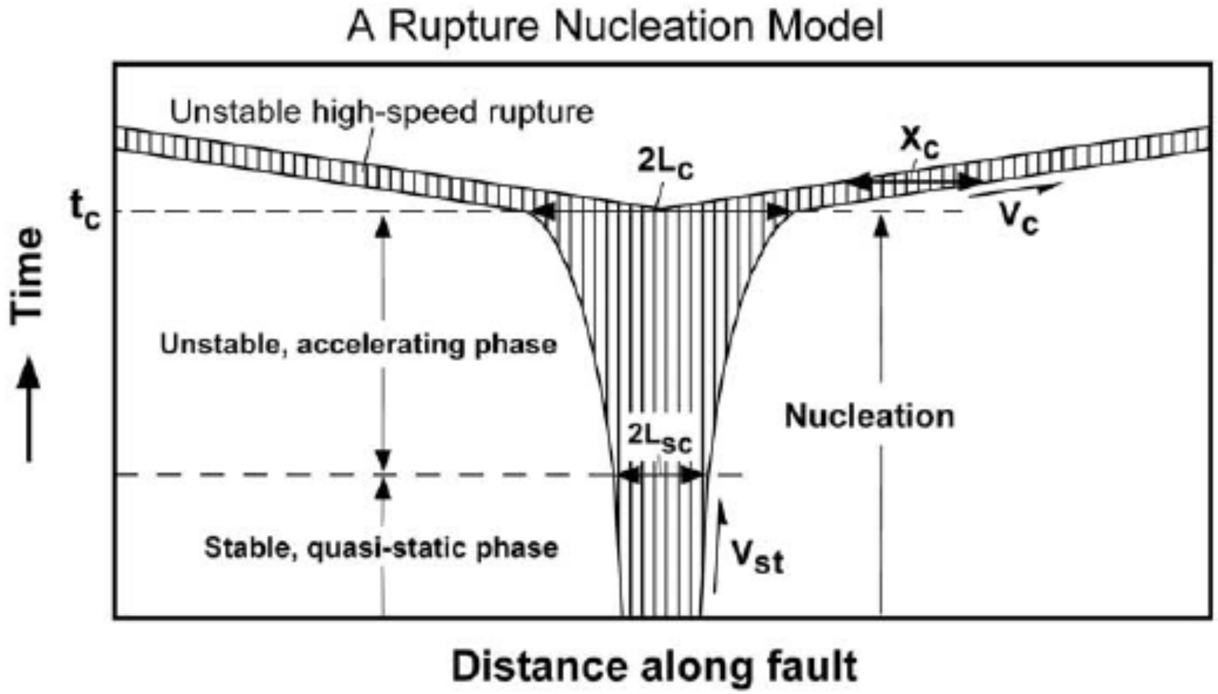


Figure 15. A physical model of rupture nucleation. Hatched portion indicates the zone in which the breakdown (or slip-weakening) proceeds with time.

Ohnaka 2003

Integrating 30 years of experimental rock fracture mechanics: Ohnaka's view

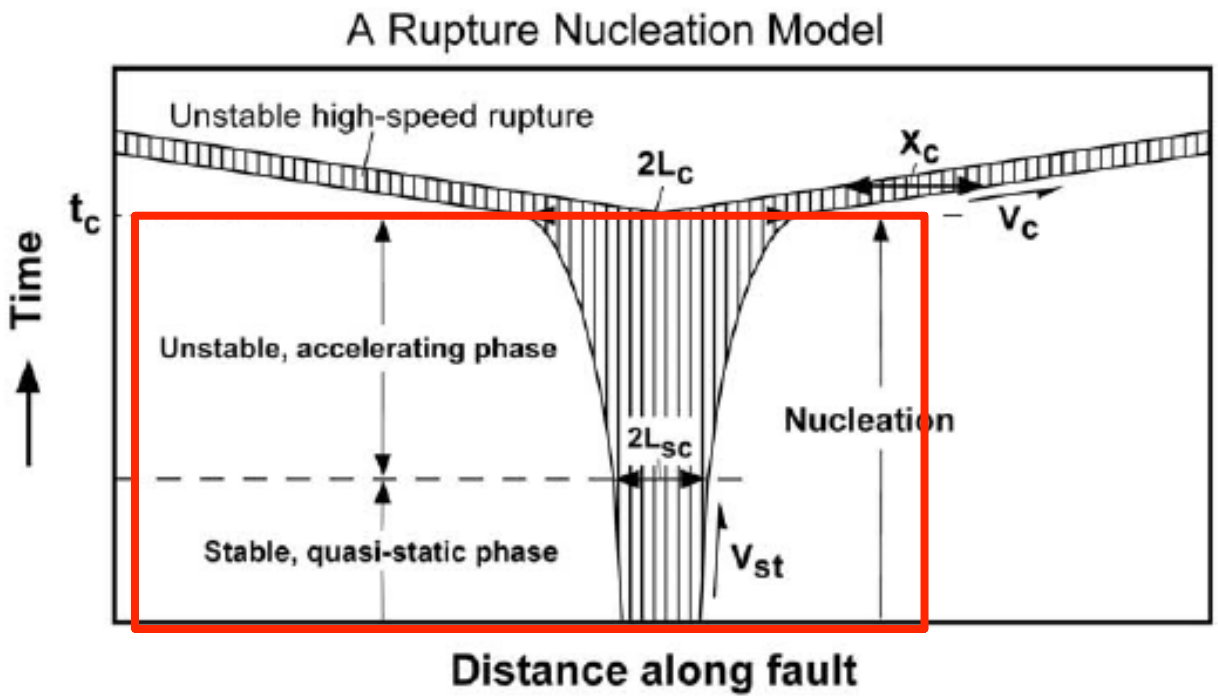
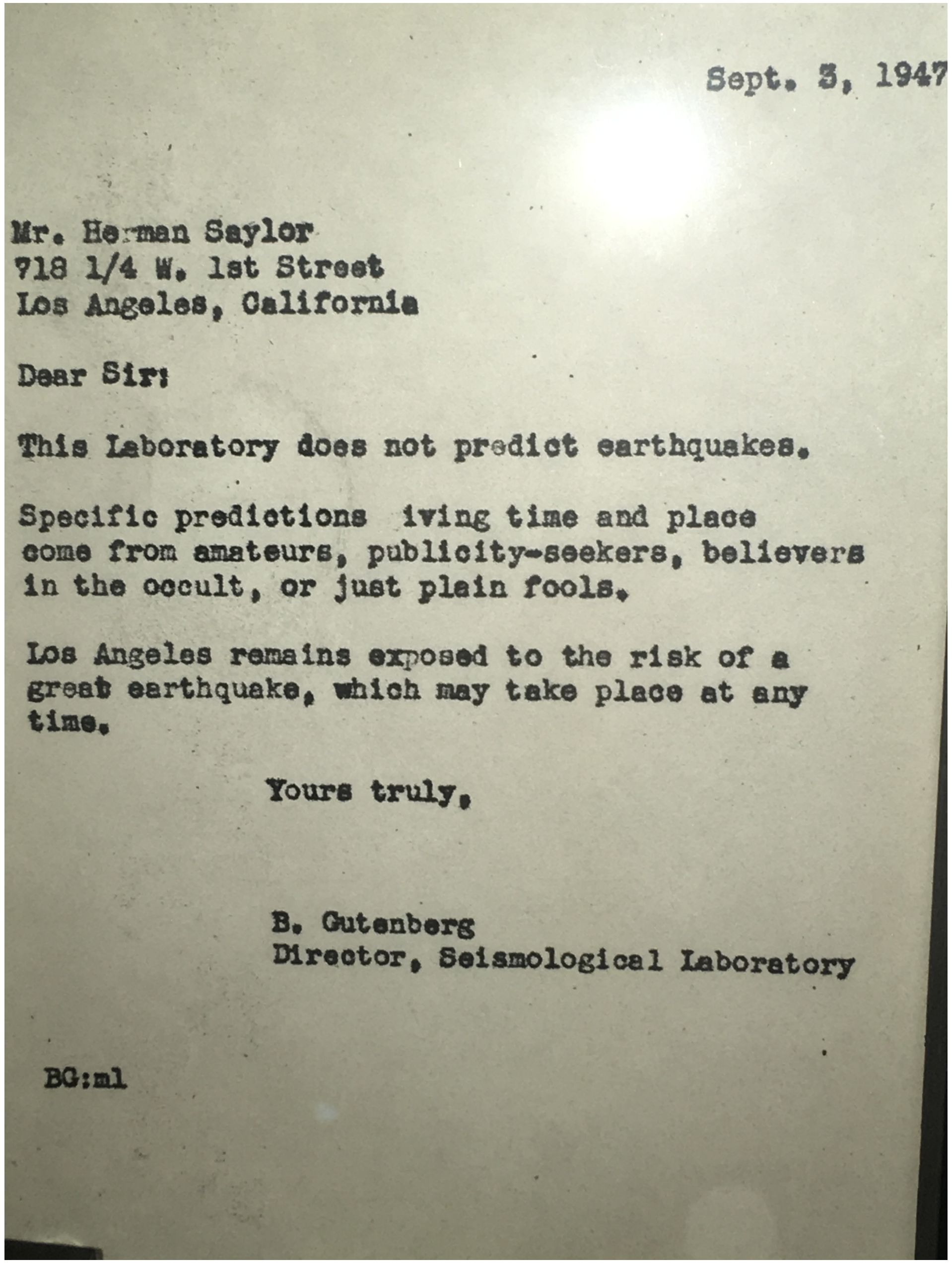


Figure 15. A physical model of rupture nucleation. Hatched portion indicates the zone in which the breakdown (or slip-weakening) proceeds with time.

Ohnaka 2003

MOTIVATION



Sept. 3, 1947

Mr. Herman Saylor
718 1/4 W. 1st Street
Los Angeles, California

Dear Sir:

This Laboratory does not predict earthquakes.

Specific predictions iving time and place
come from amateurs, publicity-seekers, believers
in the occult, or just plain fools.

Los Angeles remains exposed to the risk of a
great earthquake, which may take place at any
time.

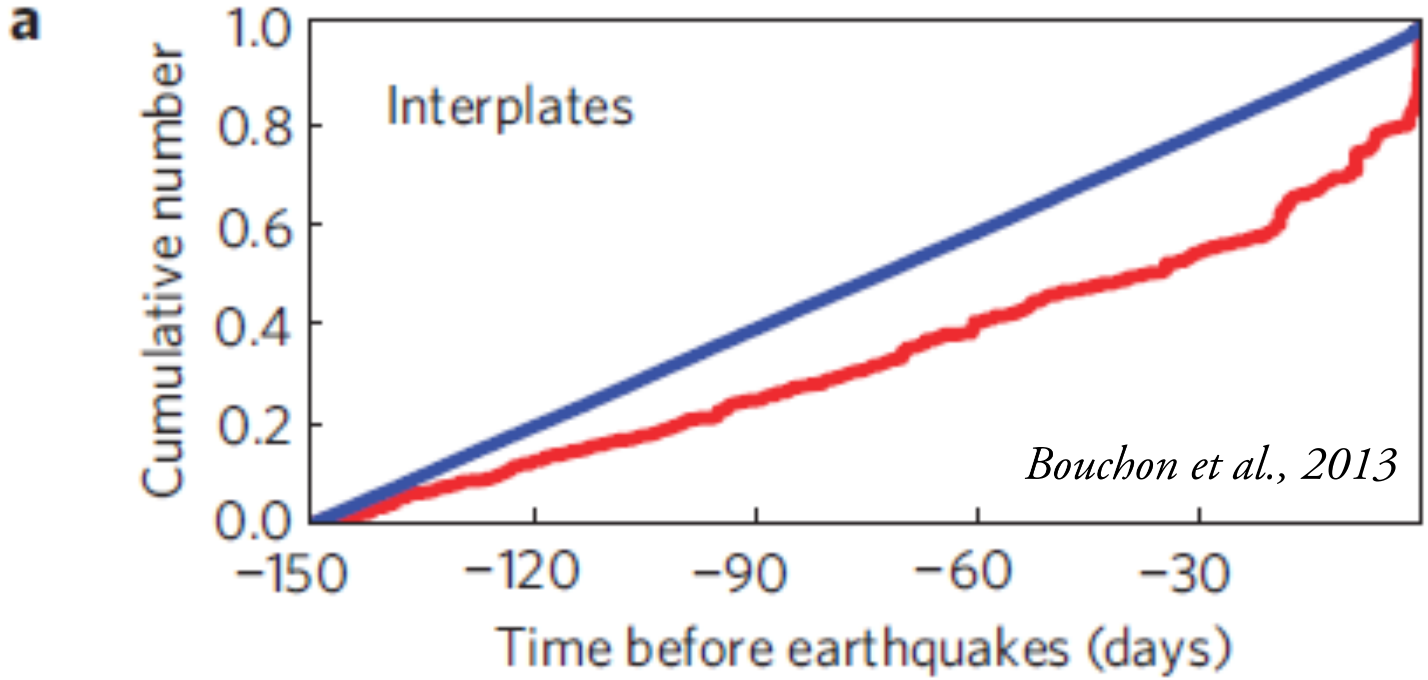
Yours truly,

B. Gutenberg
Director, Seismological Laboratory

BG:ml

MOTIVATION

Many earthquakes are preceded by foreshocks



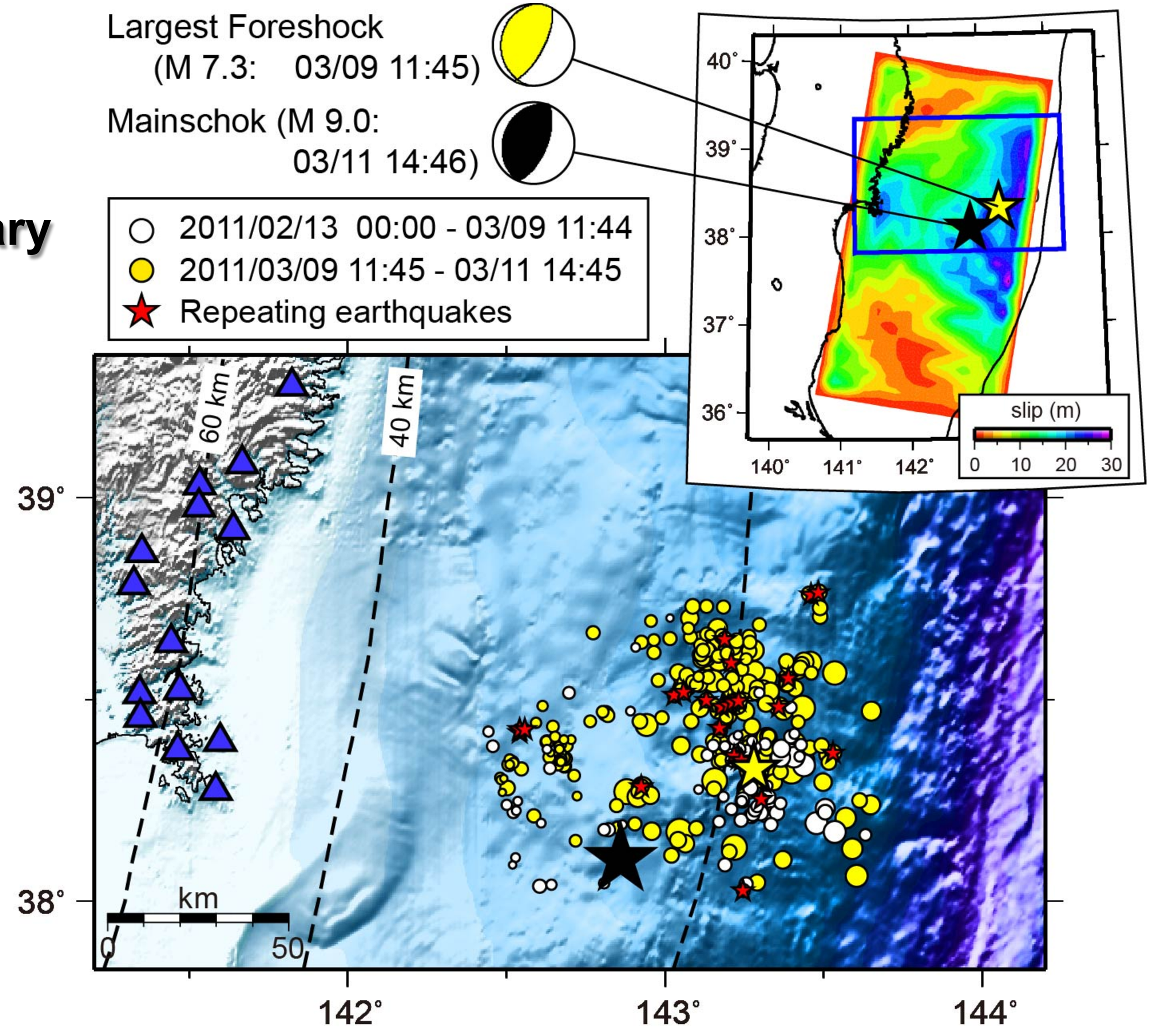
Foreshocks are due to the failure of small asperities prior the main rupture

MOTIVATION

Foreshock sequences before Tohoku-Oki

Sequence initiated in mid-February

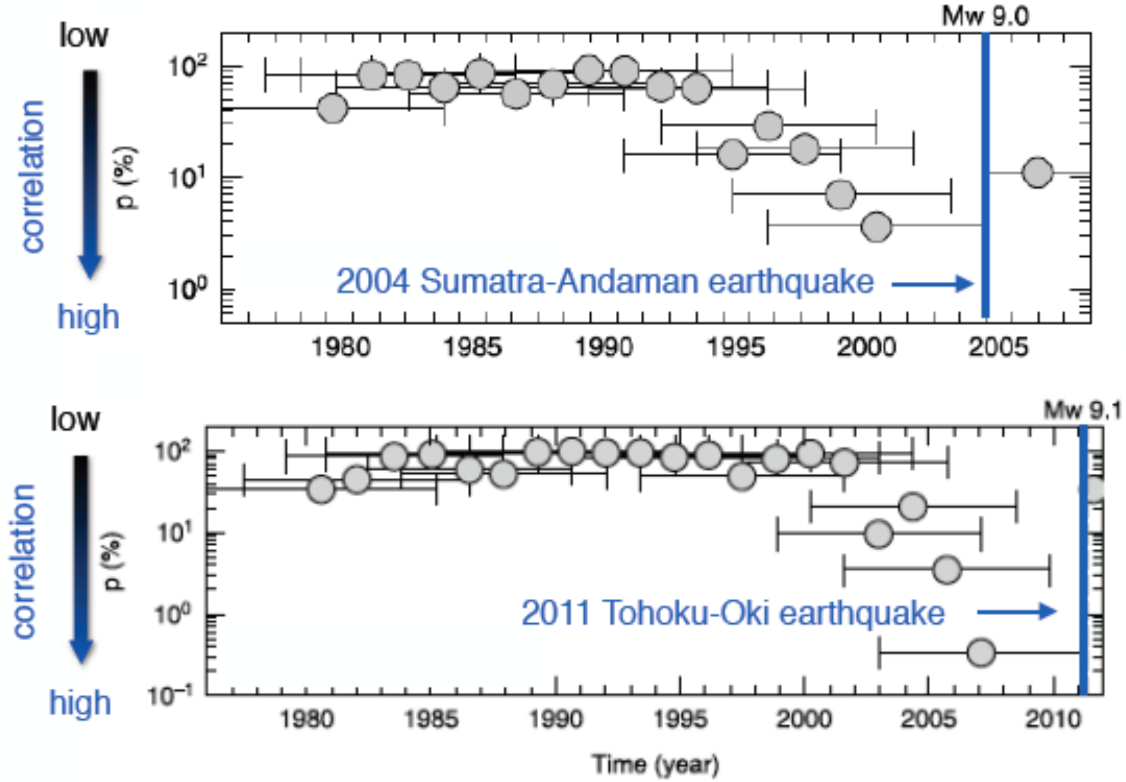
Kato et al. (2012)



The largest foreshock:
***M_w* 7.3 event along the plate interface on March 9th and had a low-angle thrust mechanism.**

Tidal triggering during large EQ nucleation

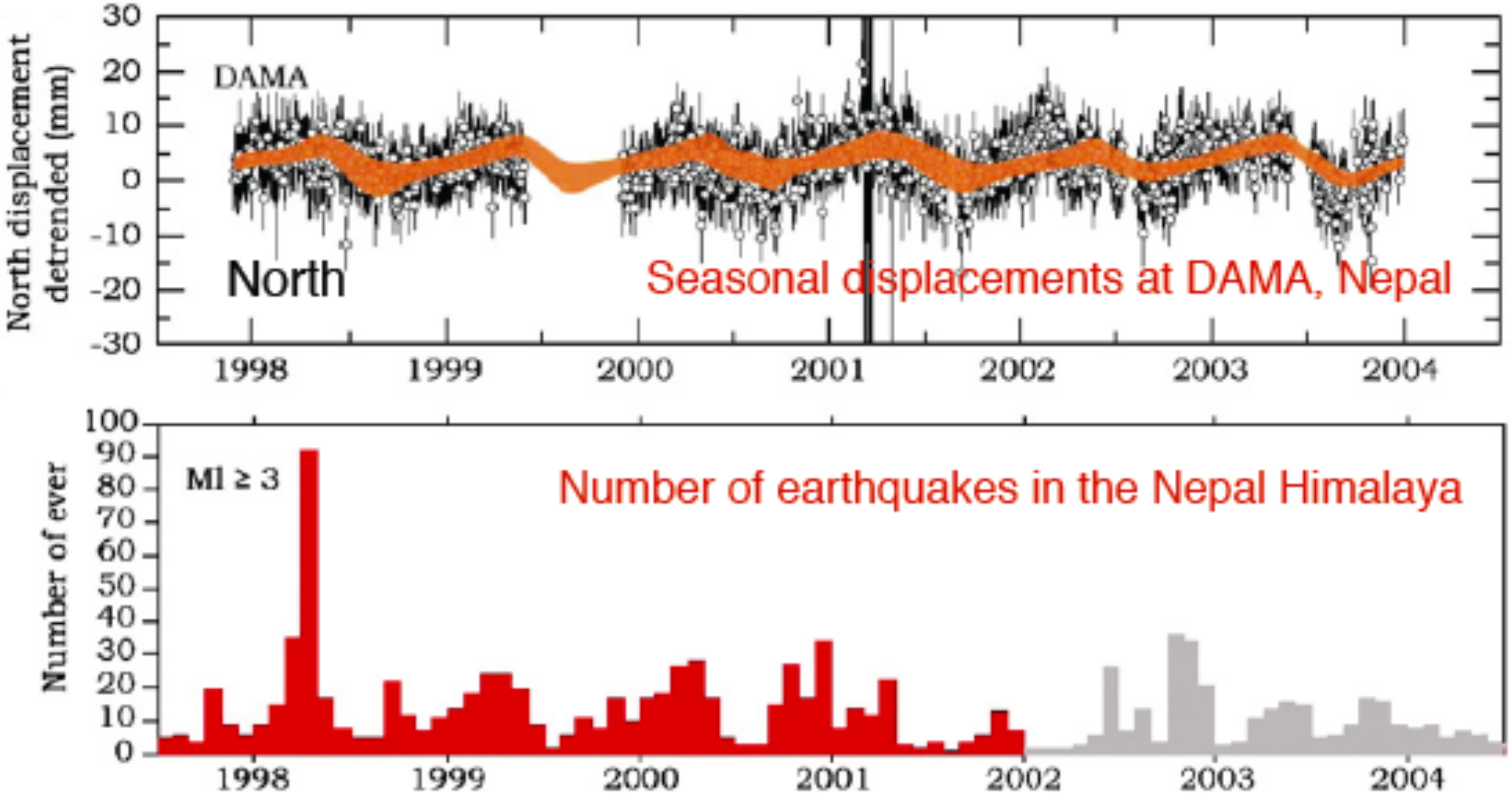
Observation: increase of correlation between seismicity and oceanic tides prior to large earthquakes



(Tanaka et al., 2010, 2012)

Tidal or seasonal earthquakes triggering might occur favorably during the long nucleation phase

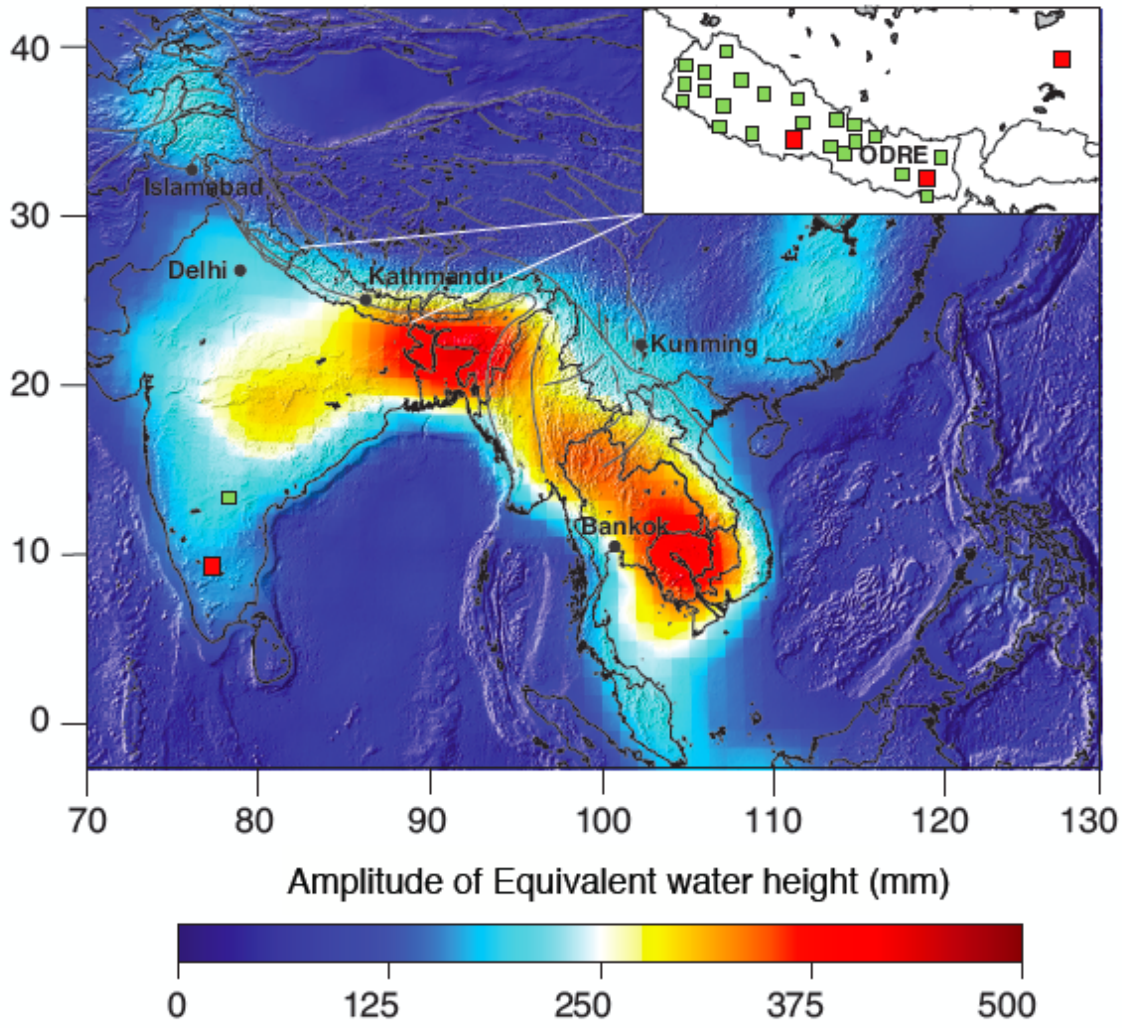
Seasonal seismicity in the Himalayas



(Bettinelli et al., 2008)

Seasonal seismicity in the Himalayas

Seasonal load in South Asia derived from GRACE (2002-2012) & GPS stations



Outline

- Rock fracture in the lab.
- Precursory processes to Stick-slip
- Foreshock dynamics
- “Tidal” modulation

Quasi-static propagation

View from the lab - quasi static rupture in granite:

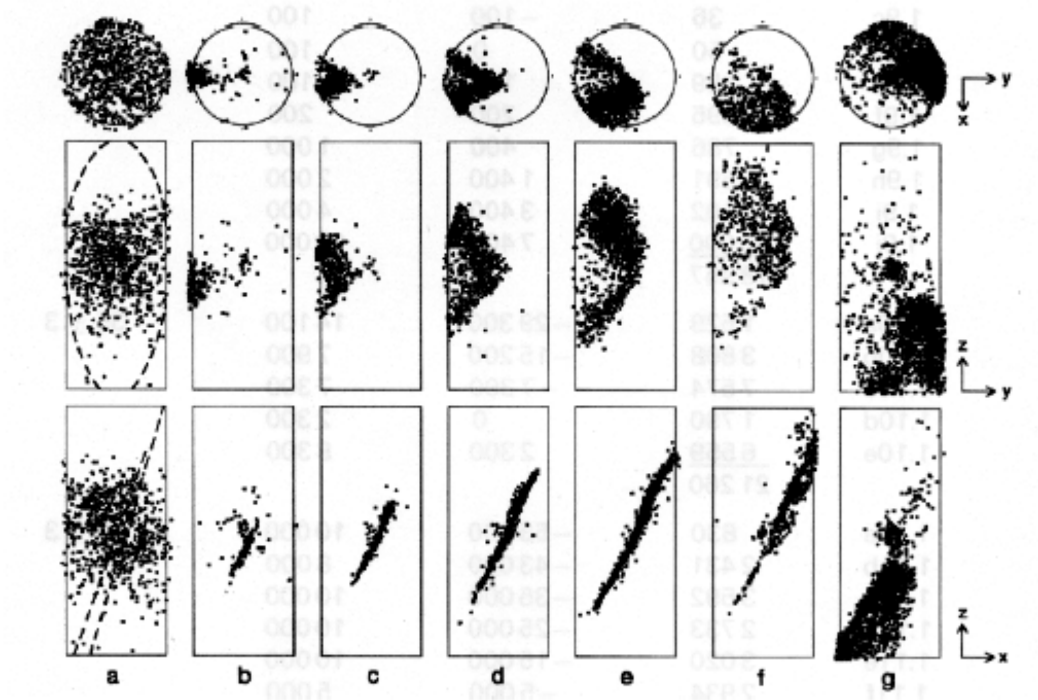
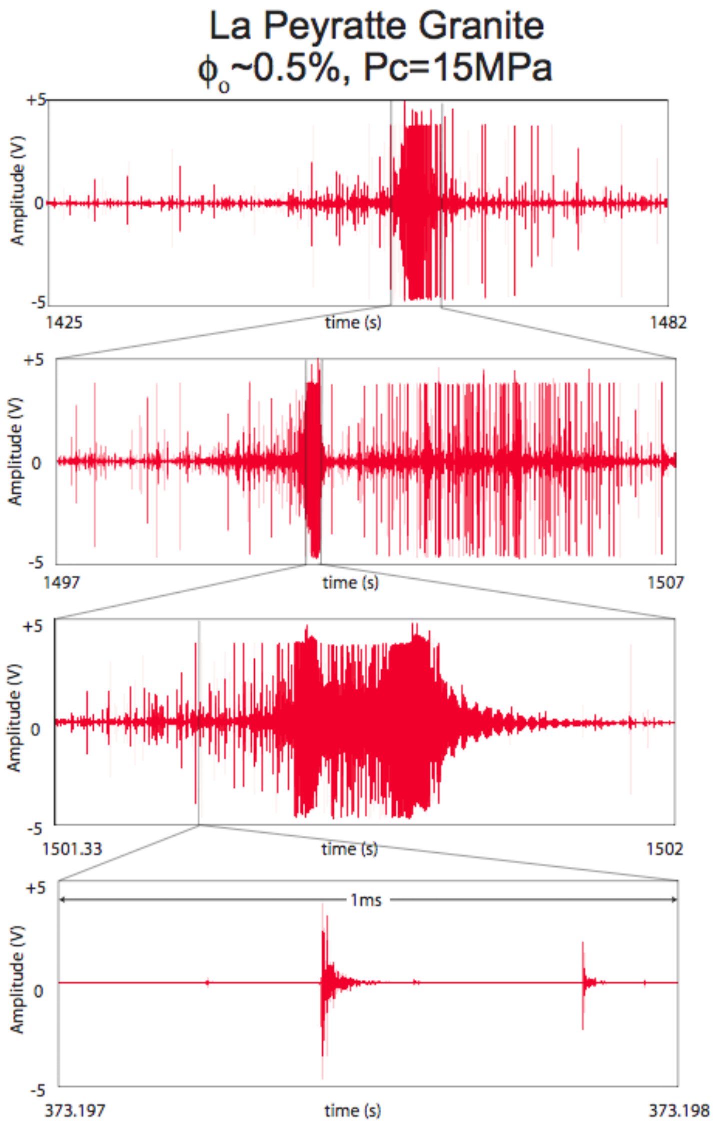


Figure 7. *Plots of AE locations for sample G1. Bottom plot of each set is view looking along-strike of eventual fracture plane. Middle plot is face-on view of fault in which sample has been rotated counterclockwise 90°. Top plot is view looking down on sample. Projections of surface trace of eventual fault plane are shown in (a) for reference. Each point represents one AE event. Associated statistics are given in Table 1. Stress intervals for each plot are indicated in Figures 3a and 5a. Fault nucleation occurs in plot (b).*

Lockner et al 1991

Failure of granite = the B(rac)enchmark

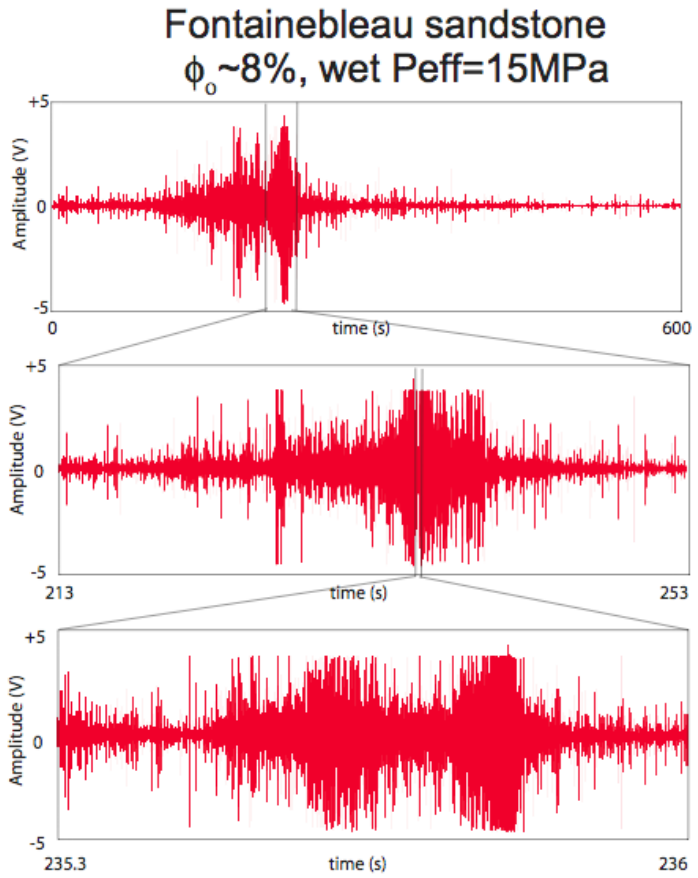


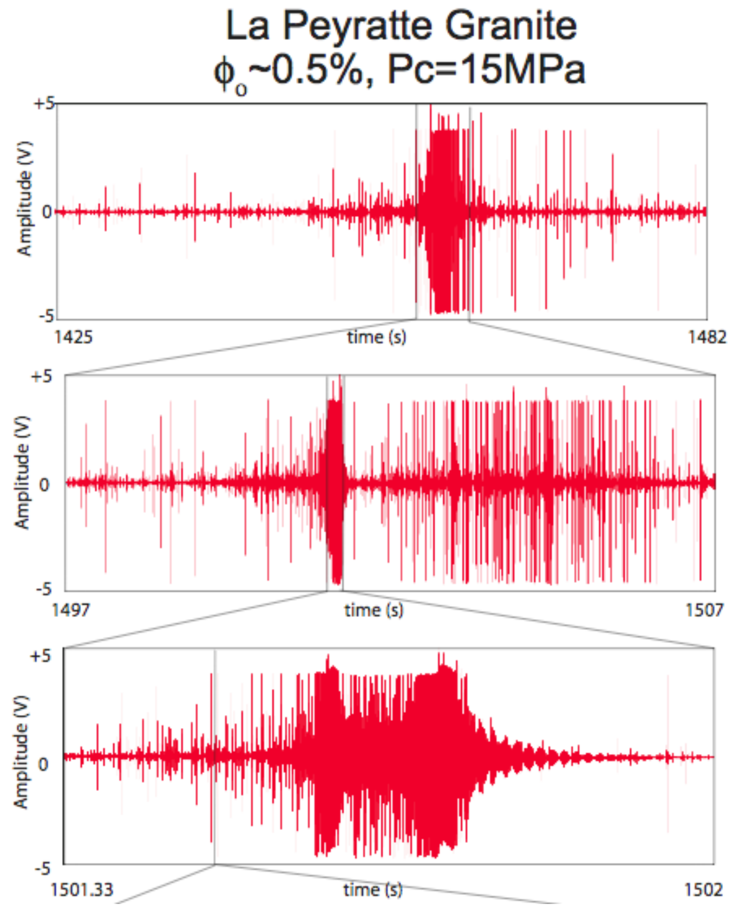
Continuous ultrasonic records of failure (10MHz)

Effect of lithology

Continuous ultrasonic records of failure (10MHz)

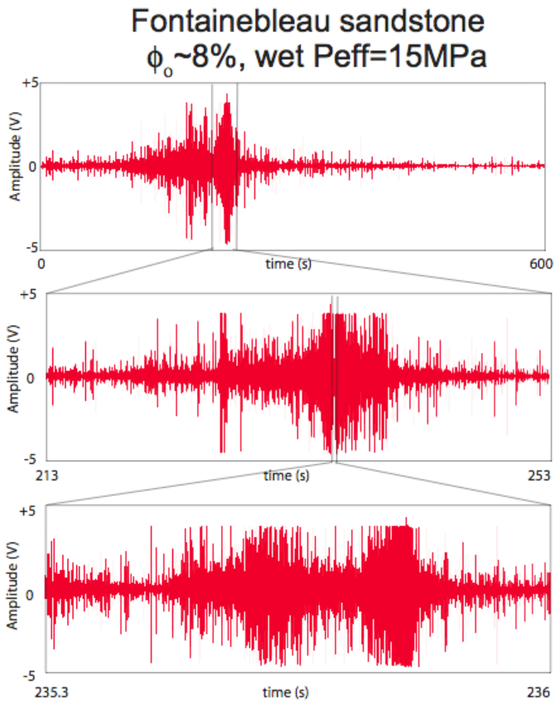
Sandstone vs. granite

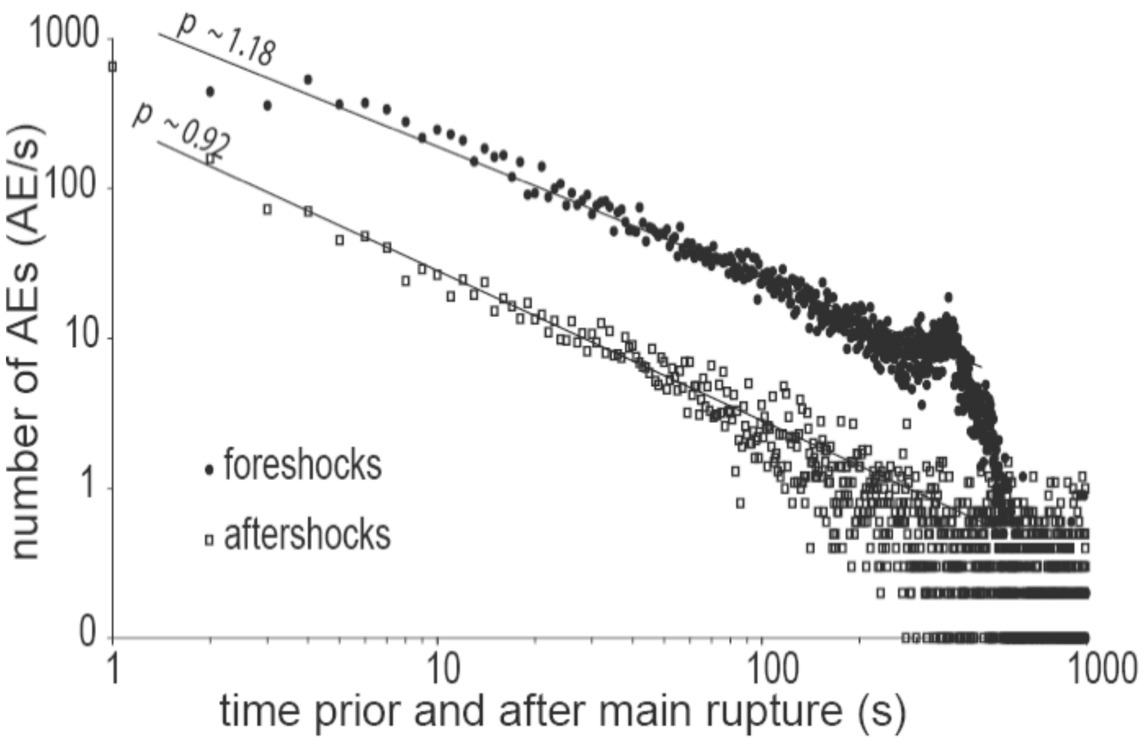




Omori's law

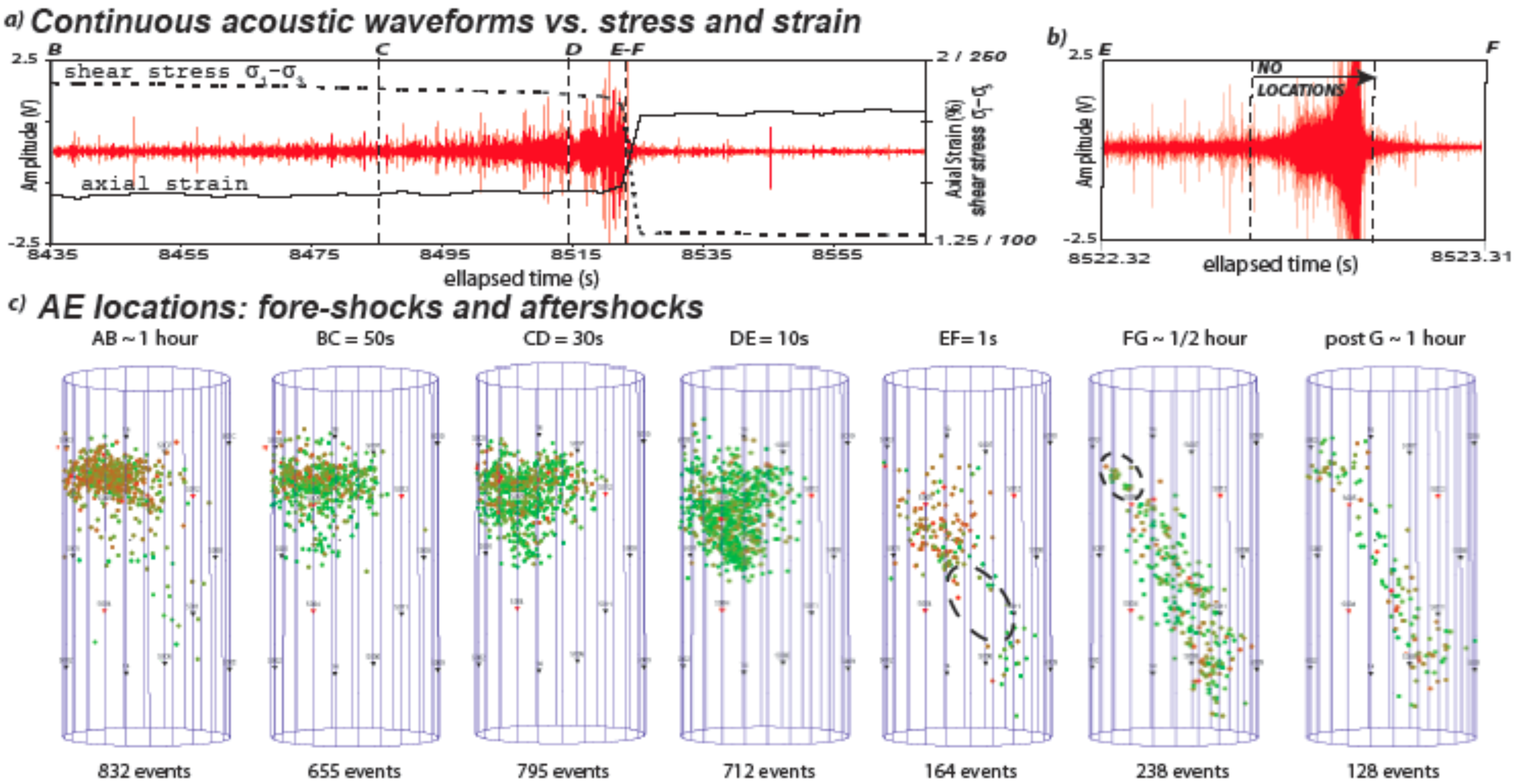
In the lab., foreshocks and aftershocks follow Omori's law, with exponents close to 1





Quasi-dynamic ruptures

Nucleation zone (~1cm^3)
Quasi static to dynamic @ >mm/s)
Terminal rupture speed (that can be resolved!) <100m/s

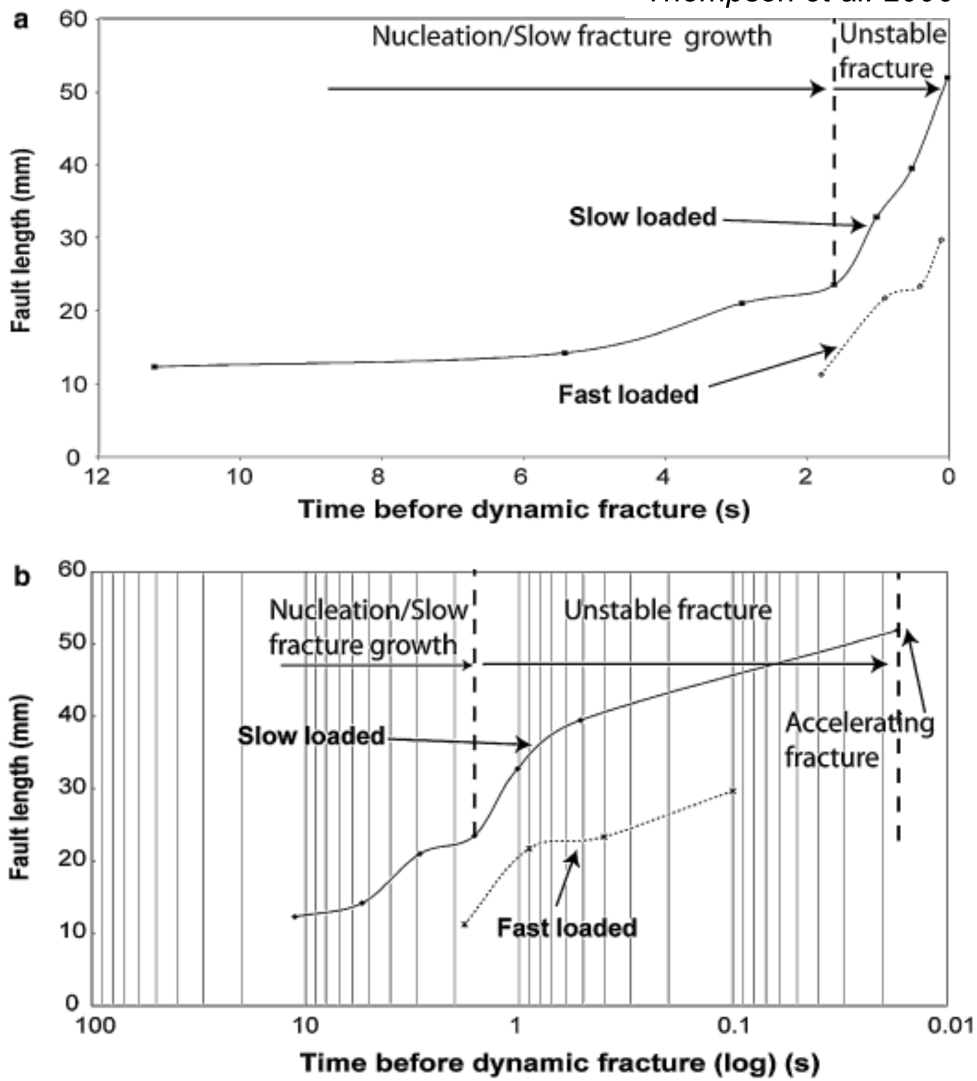


Schubnel et al., 2007

Quasi-dynamic ruptures

- **Nucleation and fracture propagation speed**

Thompson et al. 2006



MOTIVATION

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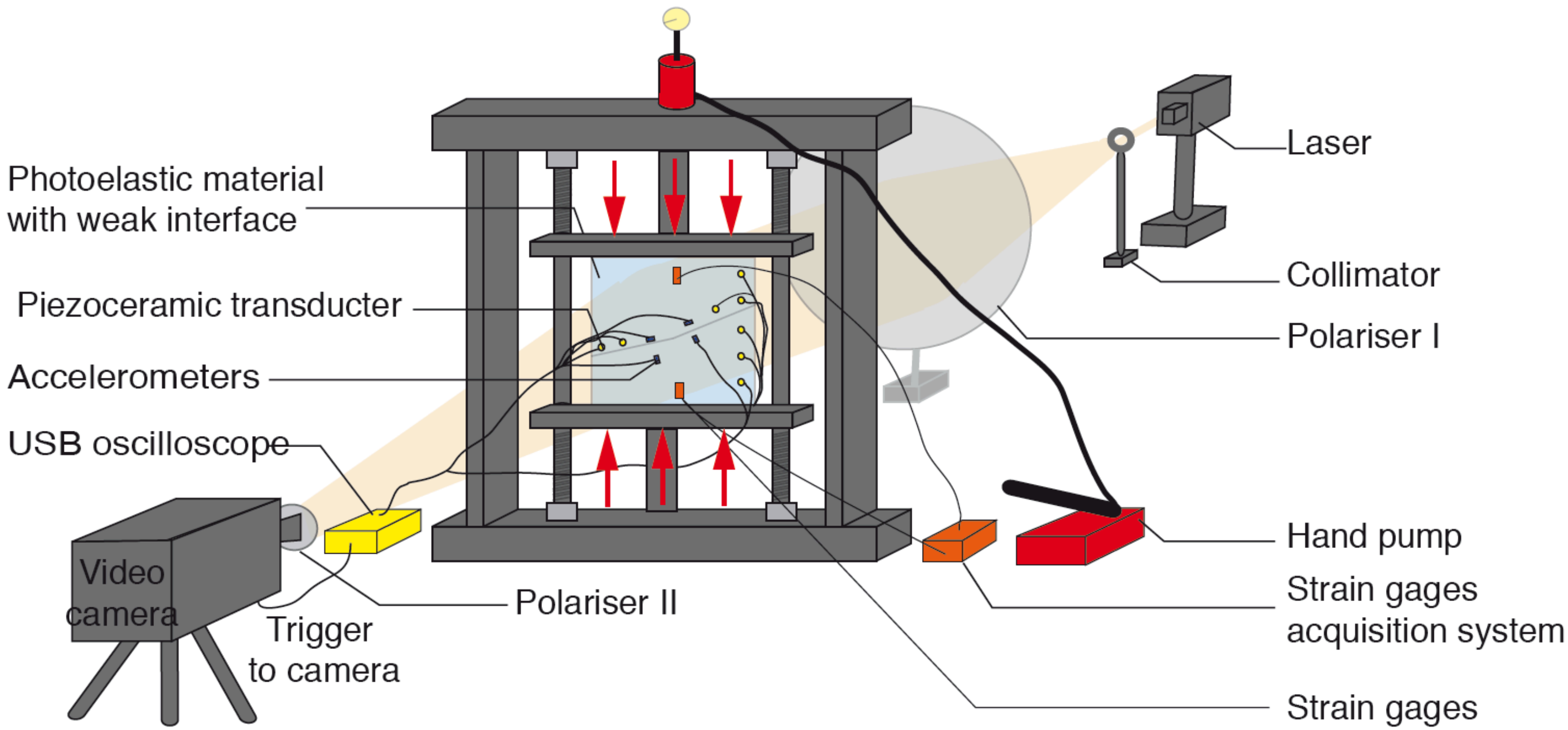
Stick-Slip in photo-elastic material: experimental set-up



Mode II dynamic rupture propagation on pre-cut, critically oriented, Columbia resin

(Nielsen et al. 2010)

Combining ***high speed photo-elasticity*** (rupture dynamics)
AND ***high frequency accelerometry and acoustics*** (near field strong motion and radiated wavefield) (*Schubnel et al. 2011*)

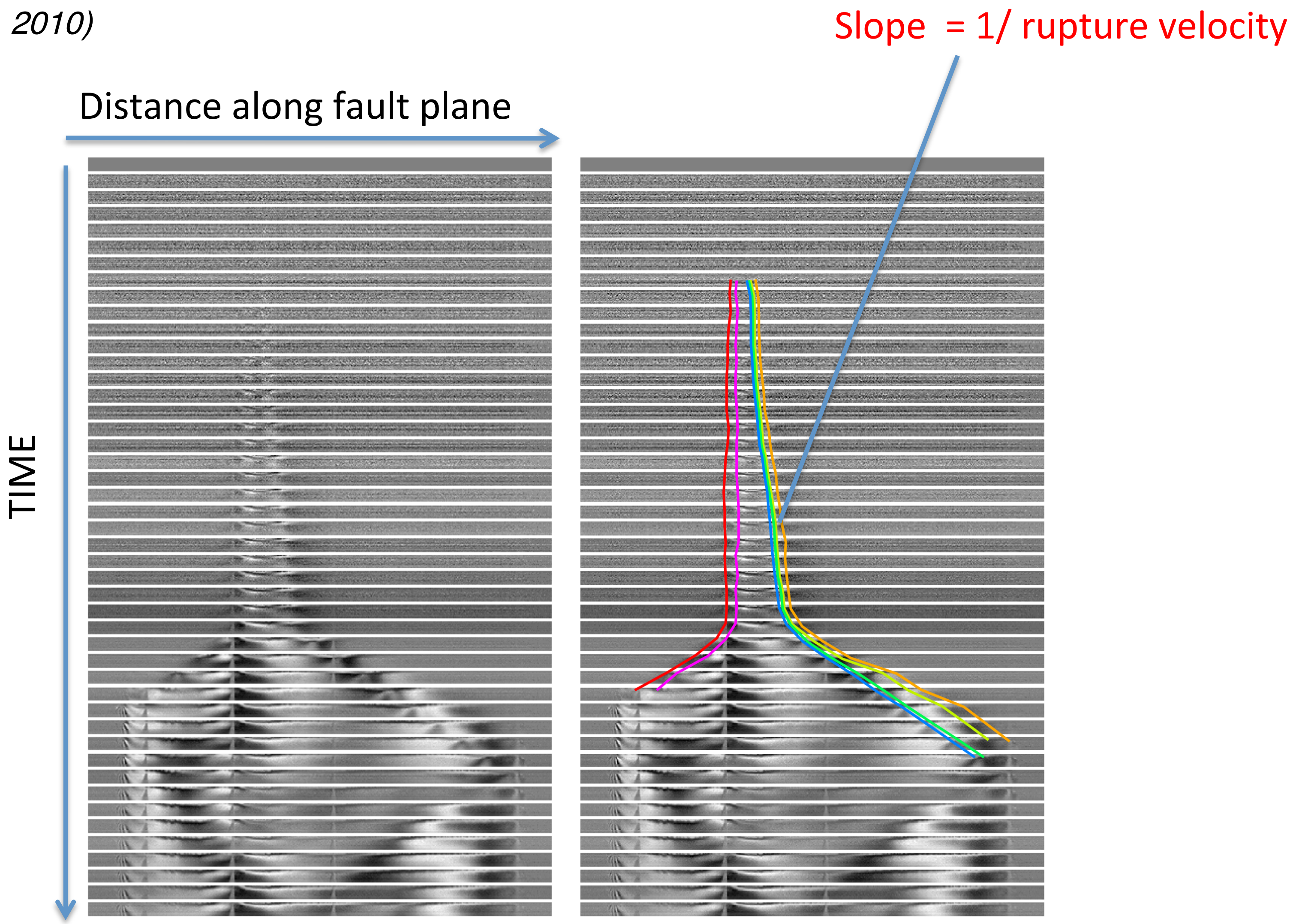
Propagation of a stick slip instability

- Rupture propagation on fault using High speed camera

Rupture propagation speed of stick slip

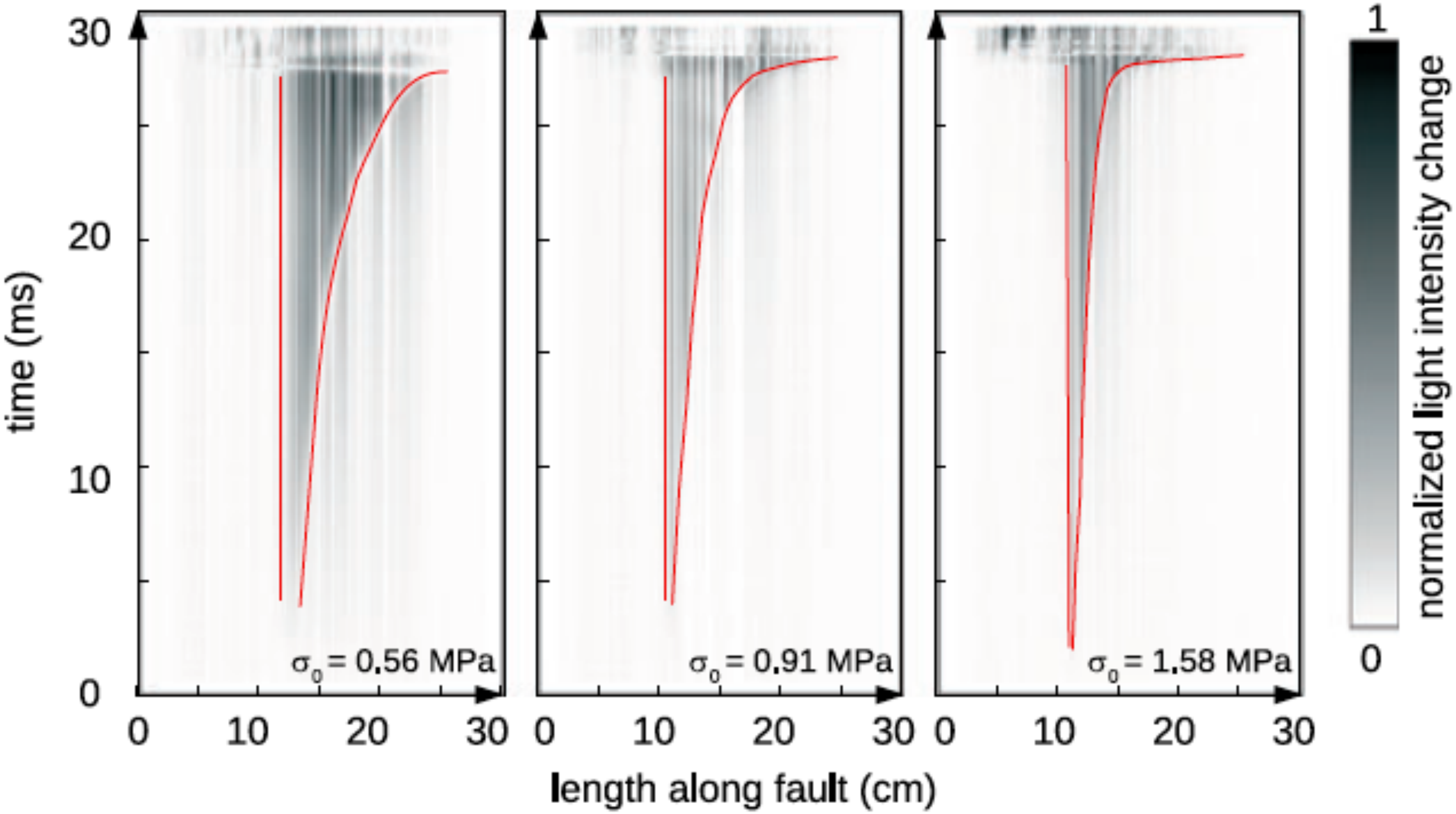
- Spontaneous ruptures studied using photoelasticity

(Nielsen et al. 2010)

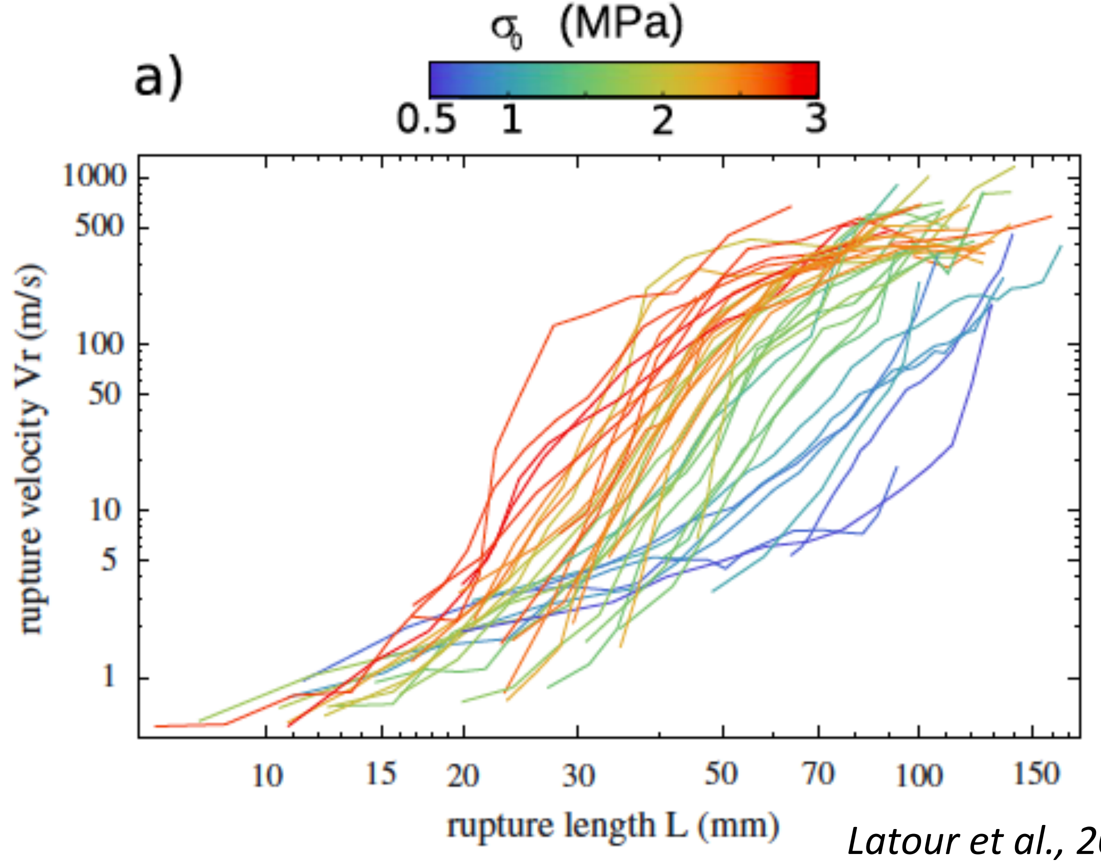


Nucleation of stick slip instabilities
Influence of normal stress

Latour et al., 2013

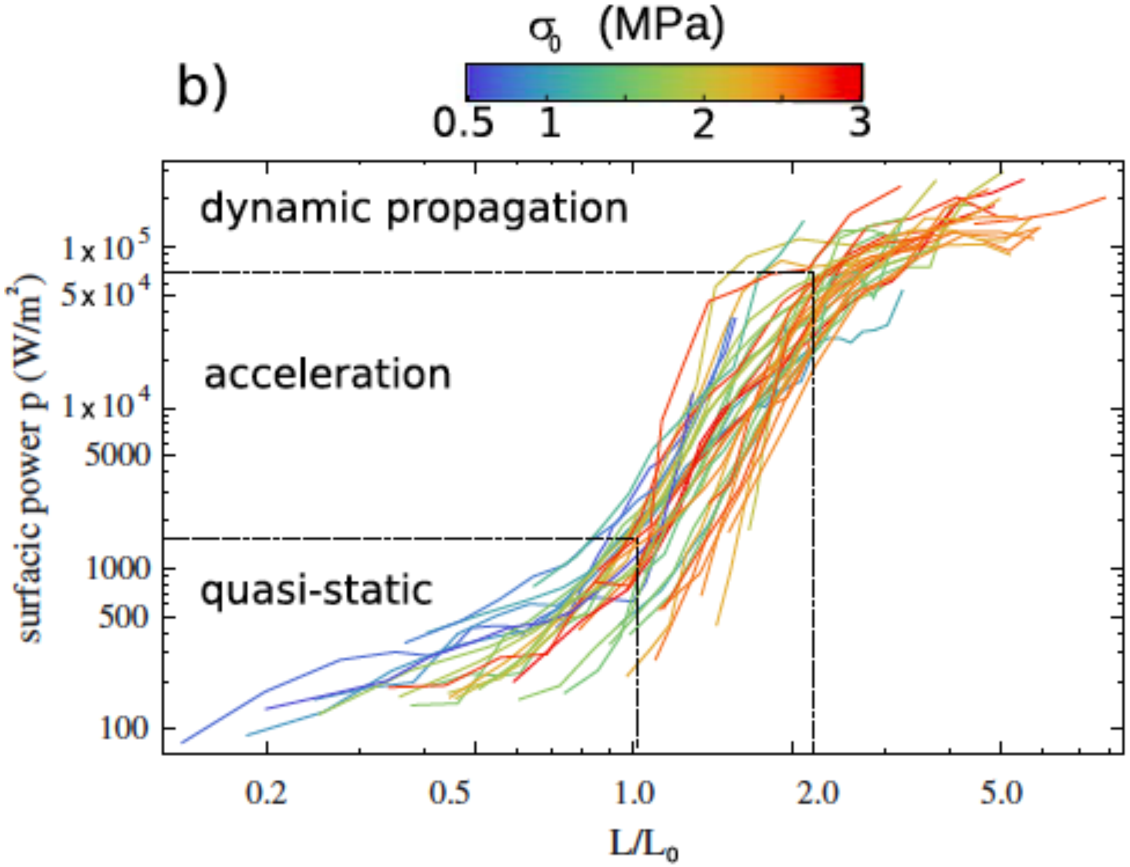


Nucleation of stick slip instabilities scaling



Latour et al., 2013

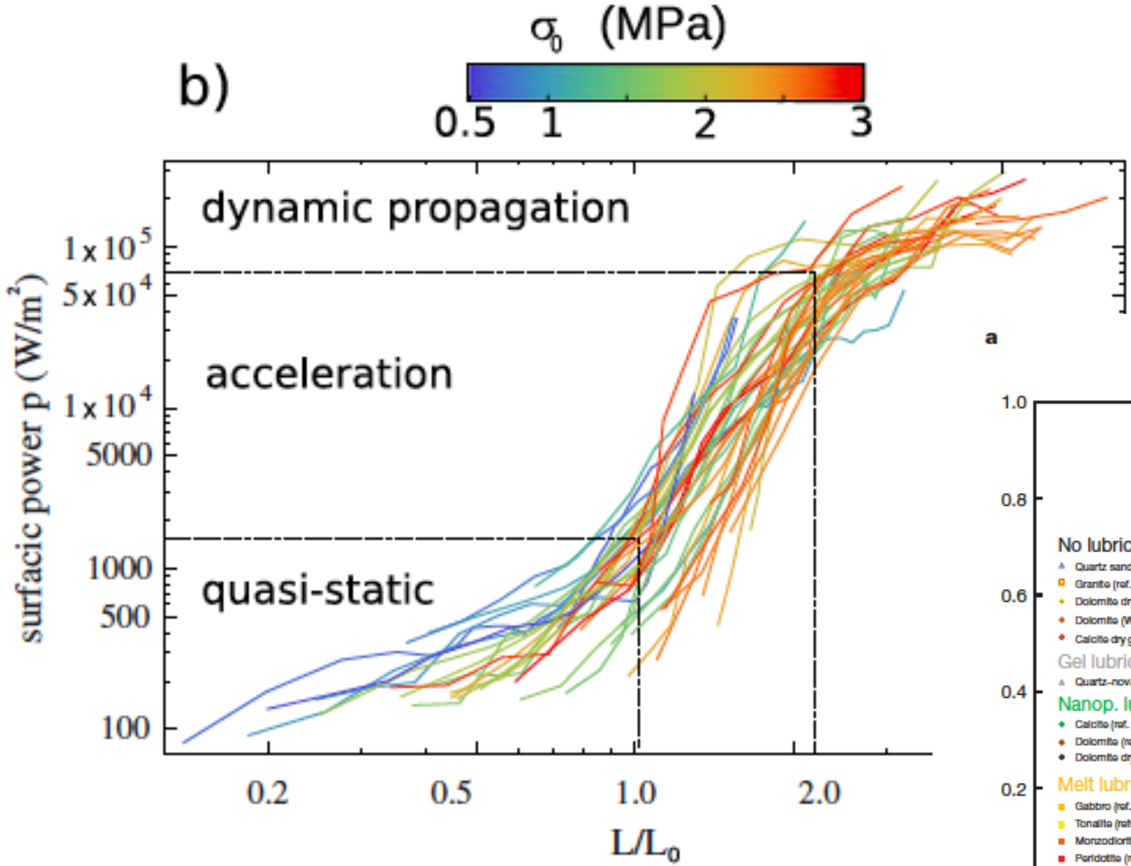
Nucleation of stick slip instabilities scaling



Latour et al., 2013

$$L_c = \beta \frac{\mu D_c}{\sigma_0 \, (f_s - f_d)}$$

Nucleation of stick slip instabilities scaling



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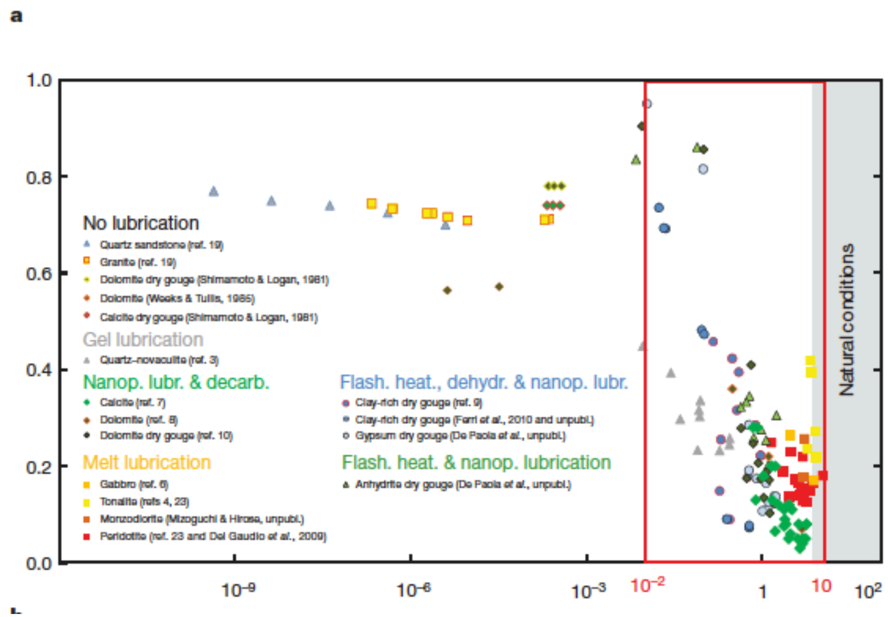
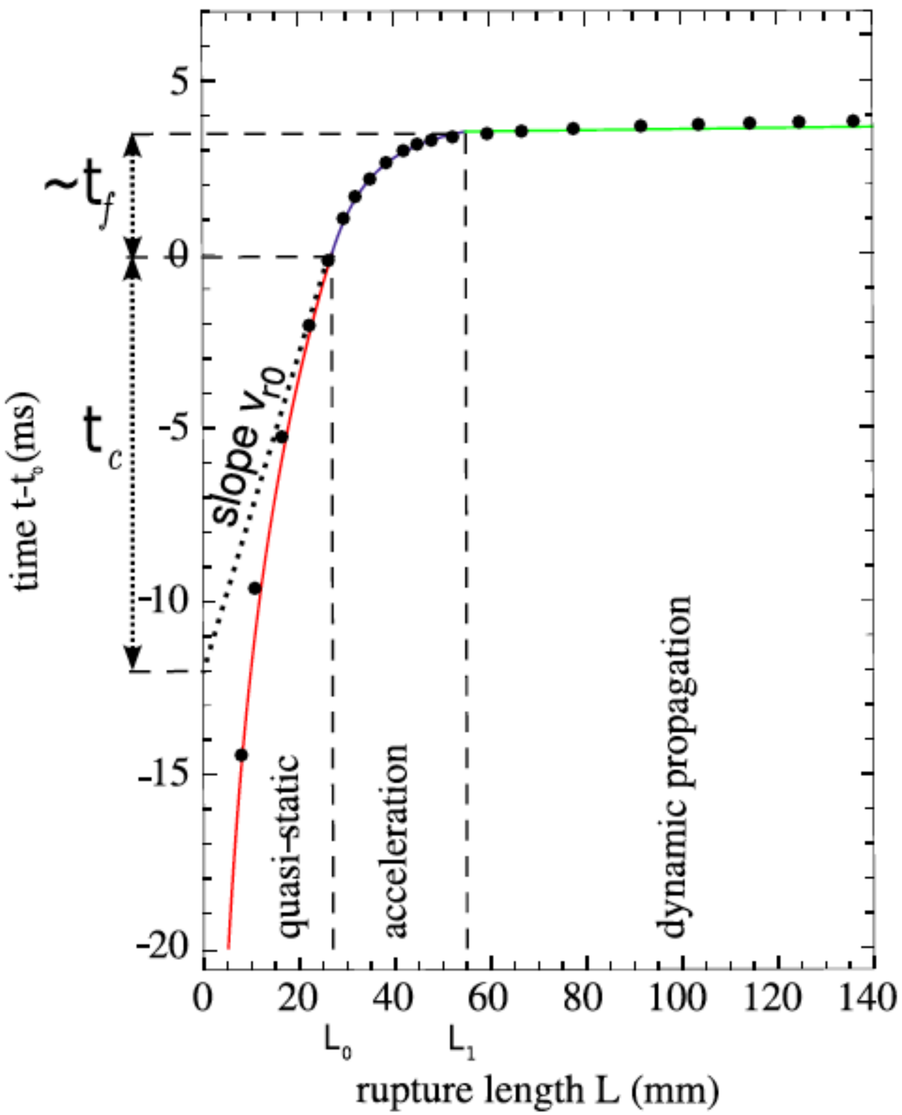


τV (MW.m⁻²)

Di Toro et al., Nature 2011

Nucleation of stick slip instabilities: an exponential growth

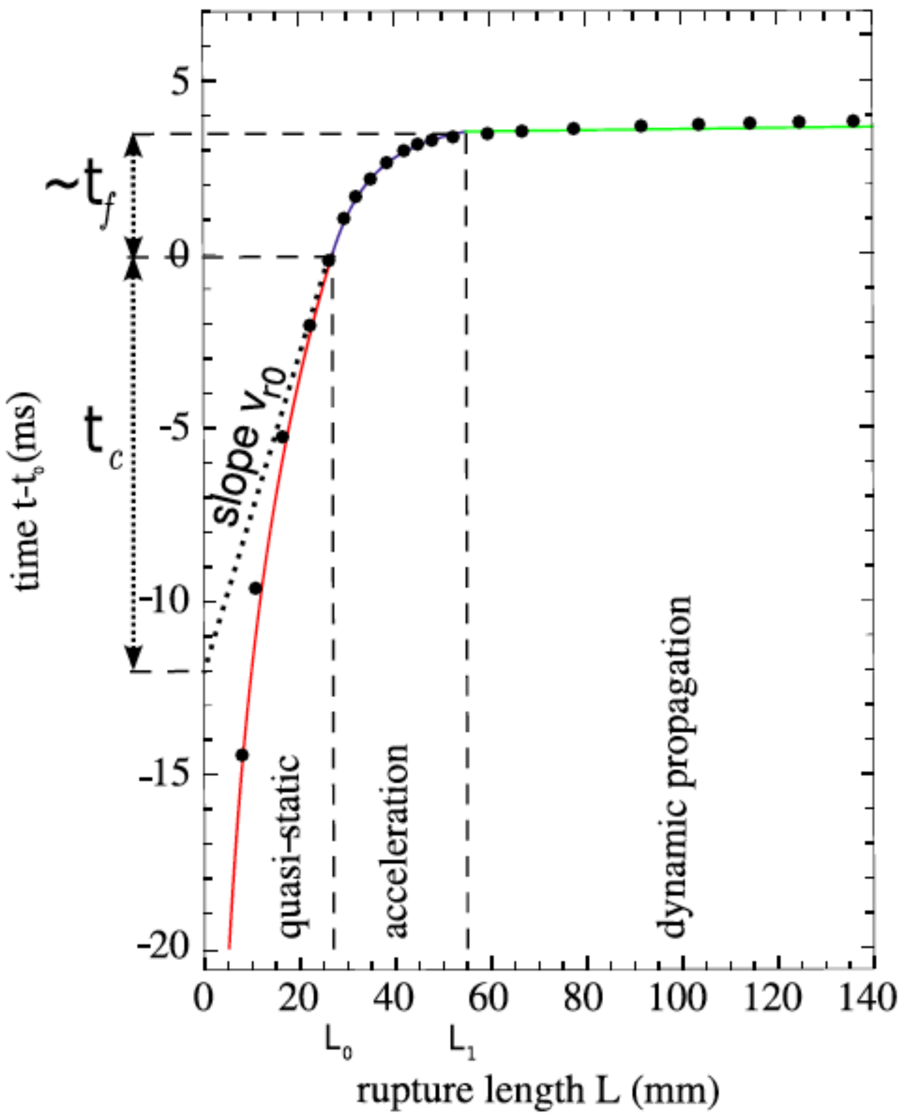
Latour et al., 2013



$$t_c = L_0/v_{r0}$$

Nucleation of stick slip instabilities: an exponential growth

Latour et al., 2013



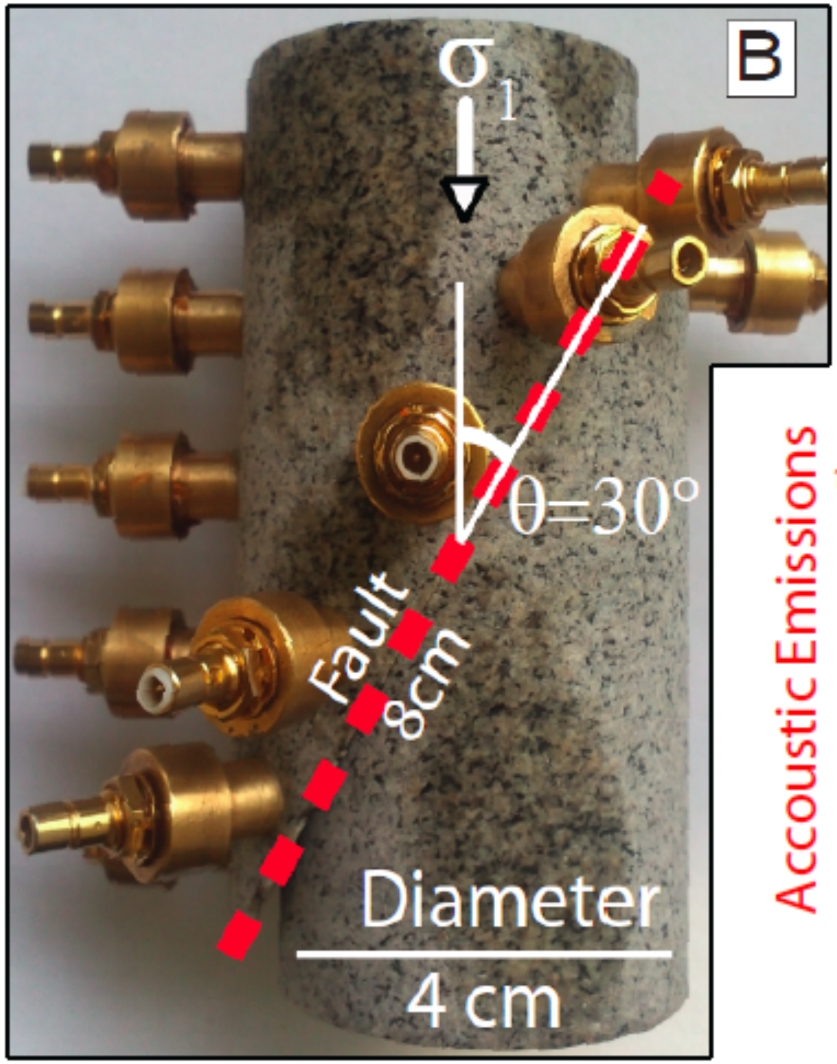
$$t_c = L_0/v_{r0}$$

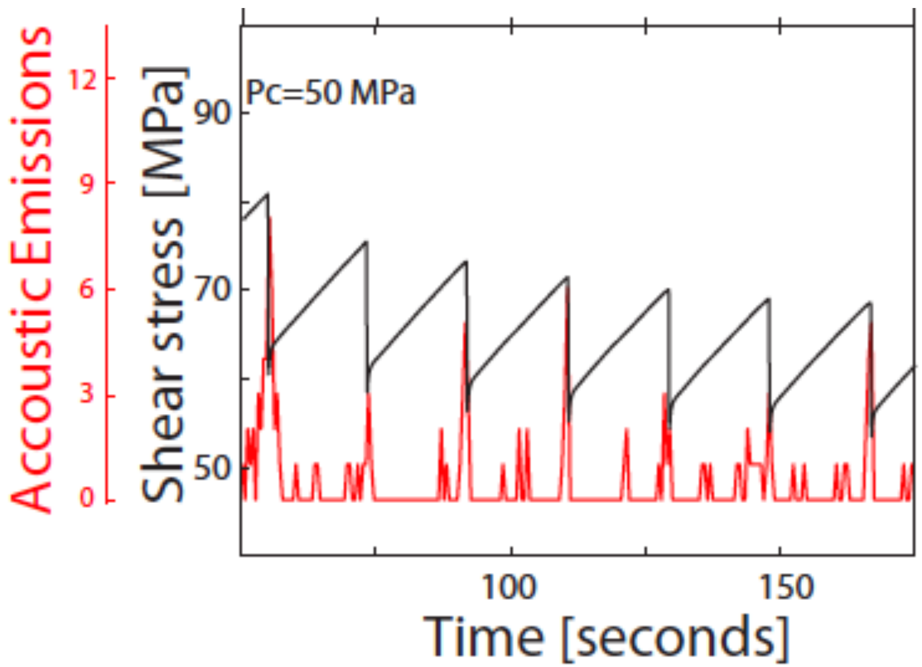
With k proportionality between rupture speed and sliding velocity ≈ $3x10^3$ (measured experimentally)

$$t_c = \frac{k\mu}{p_0}\frac{D_c}{f_s - f_d}$$

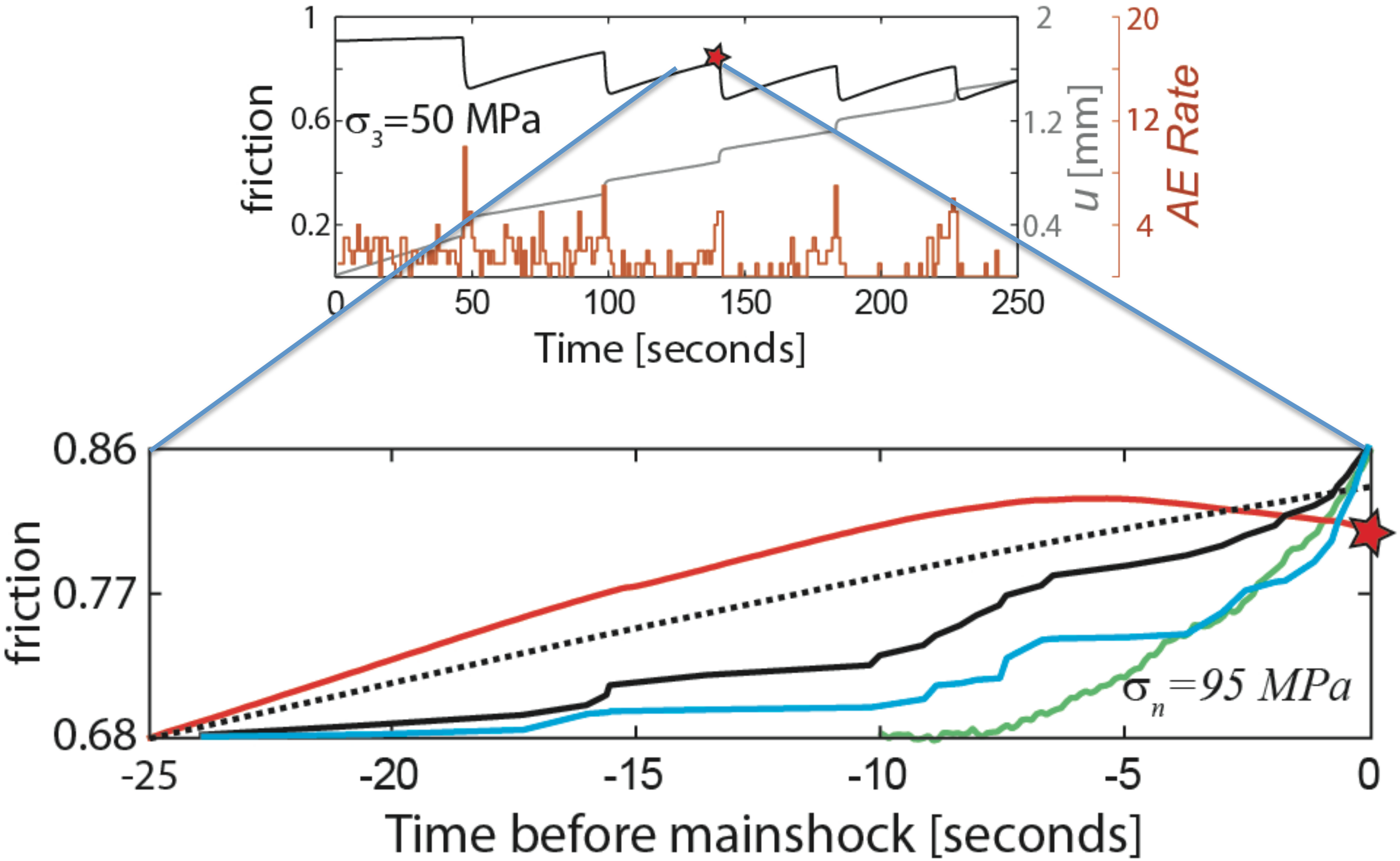
Stick-Slip in rocks (WG)

Saw cut Westerly granite – strain rates: 1-10 μm/s



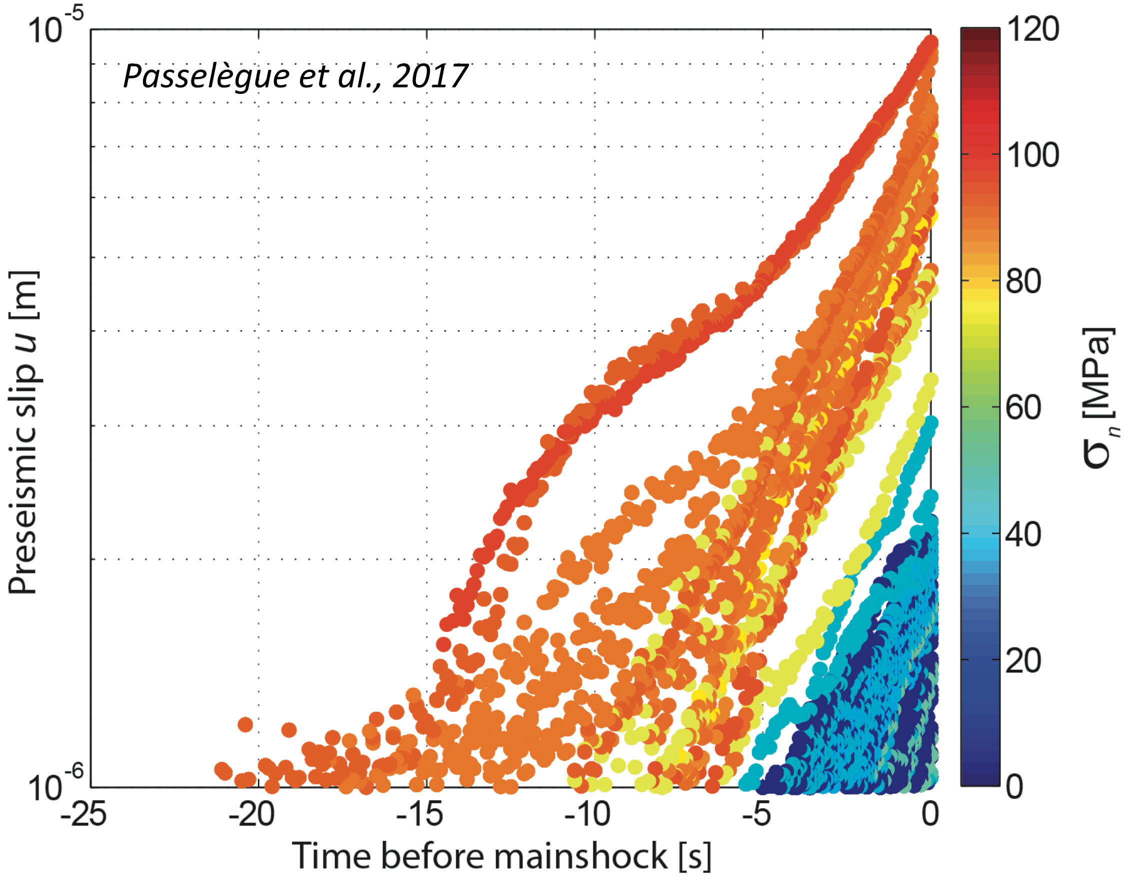


Precursories to Stick-Slip



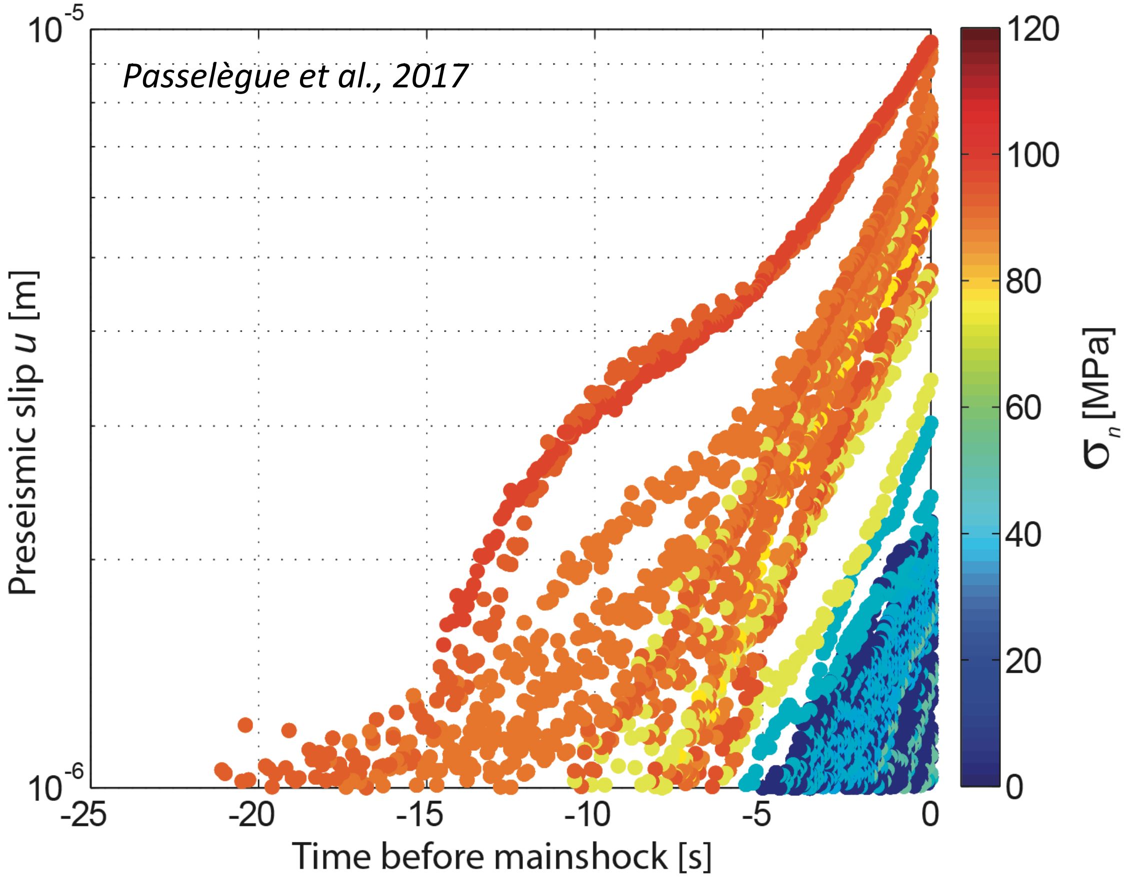
Passelègue et al., 2017

Precursory slip



$$u(t) = u_c e^{\frac{t}{t_c}}$$

Precursory slip



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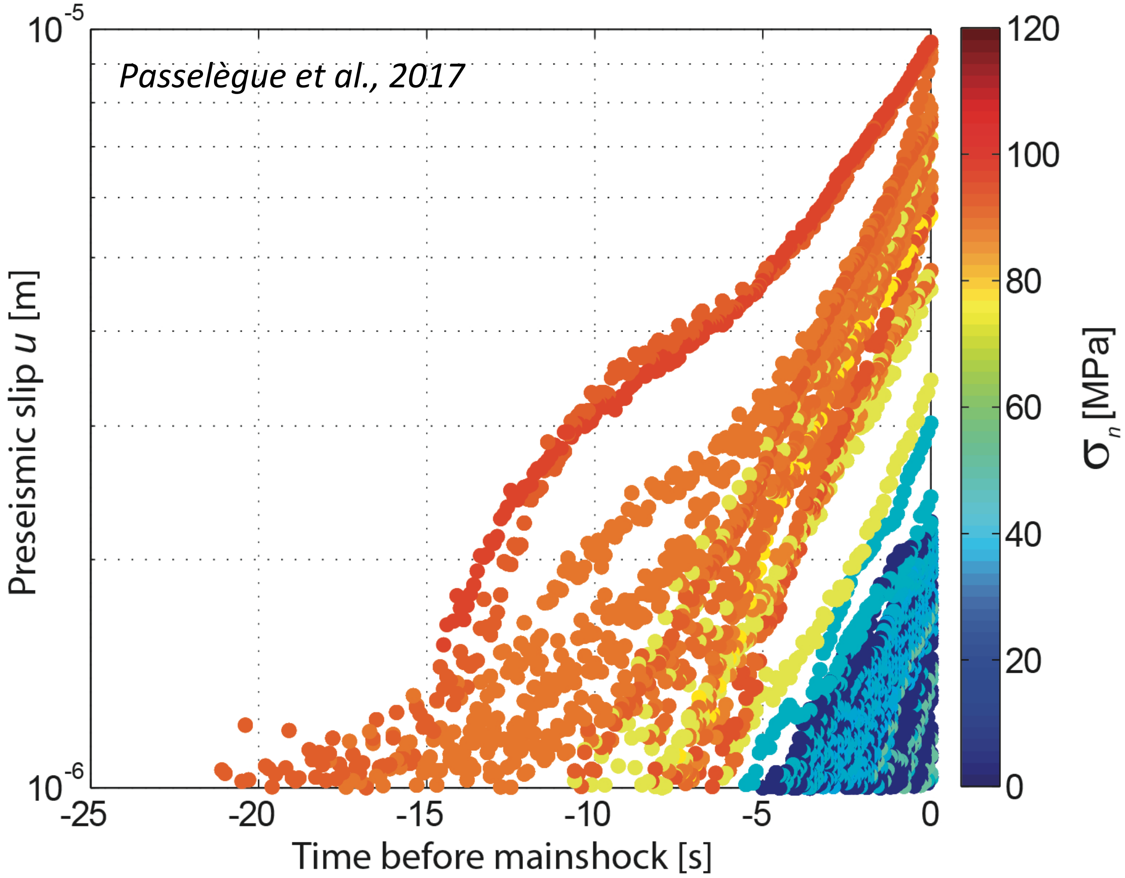
Here $t_c \approx$ cst $\approx$ 7s

Precursory slip



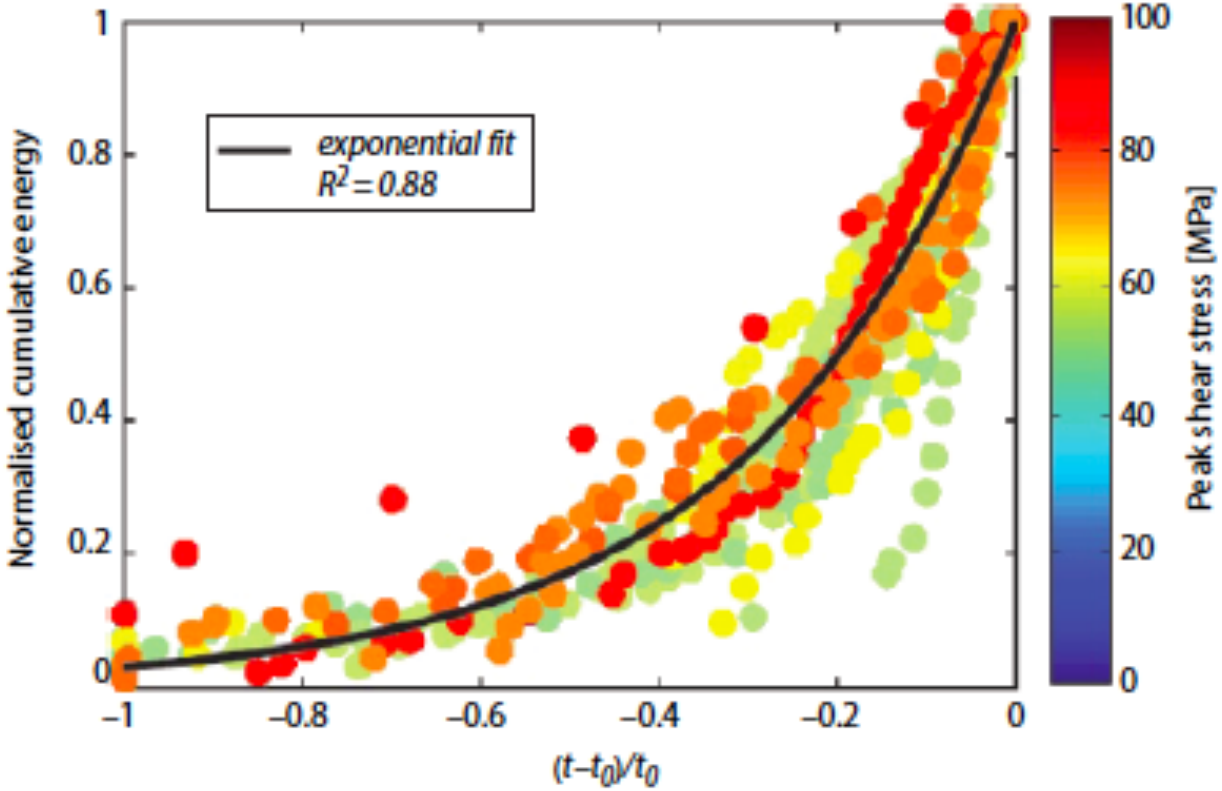
$$u(t) = u_c e^{\frac{t}{t_c}}$$

Here $t_c \approx$ cst $\approx$ 7s $\approx \frac{k\mu}{p_0}\frac{D_c}{f_s - f_d} = L_0/v_{r0}$

Latour et al., 2013

Foreshock dynamics

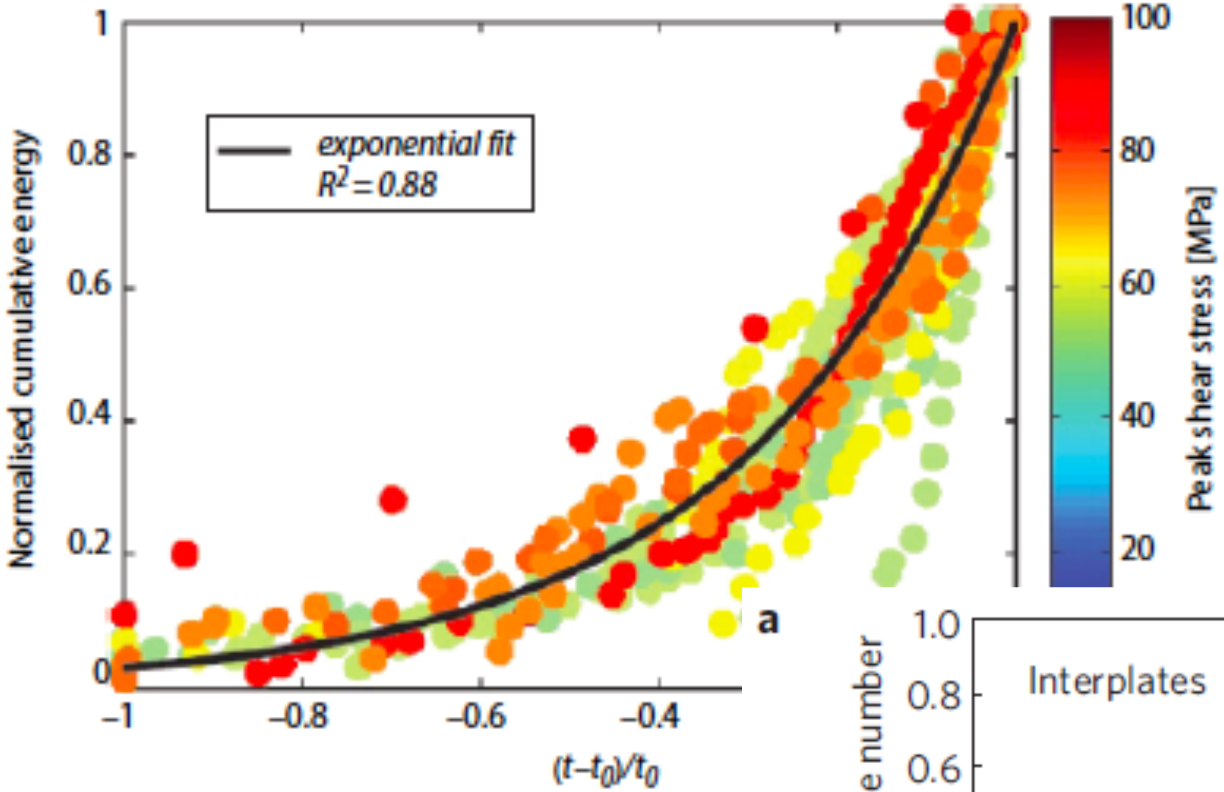
Passelègue et al. 2017



$$\frac{M(t)}{M_p} = e^{\alpha \frac{(t-t_0)}{t_0}}$$

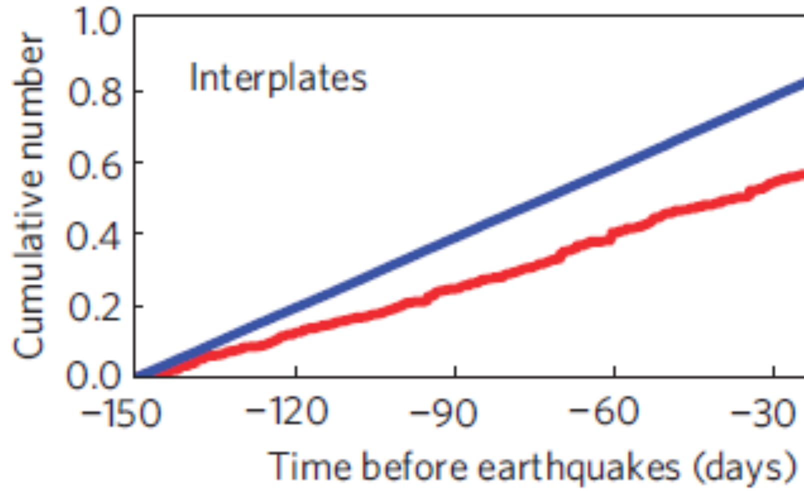
Foreshock dynamics

Passelègue et al. 2017

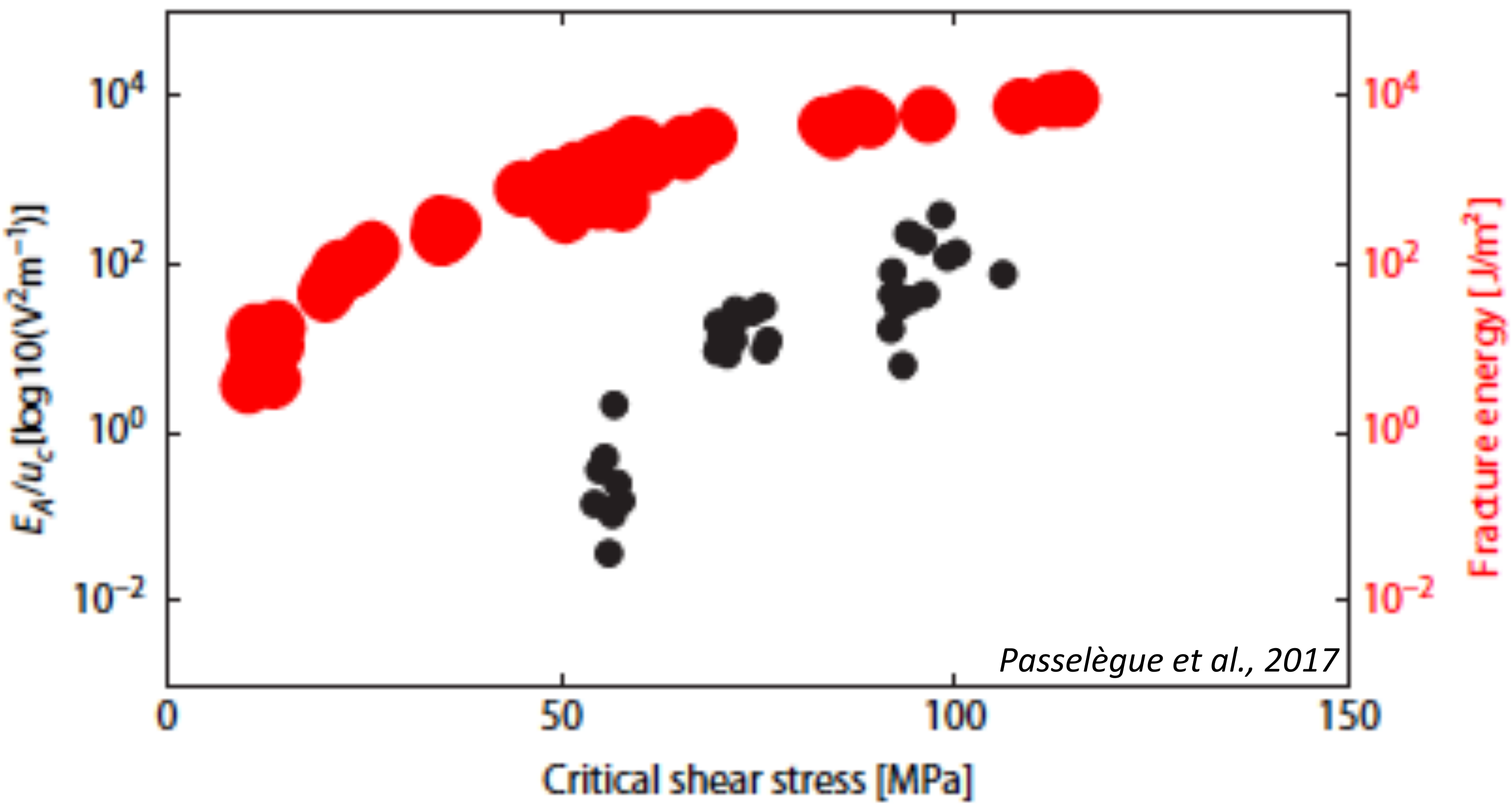


$$\frac{M(t)}{M_p} = e^{\alpha\frac{(t-t_0)}{t_0}}$$

Similar to
Bouchon et al., 2013



Evolution of seismic/aseismic coupling with fracture energy G & shear stress



MOTIVATION

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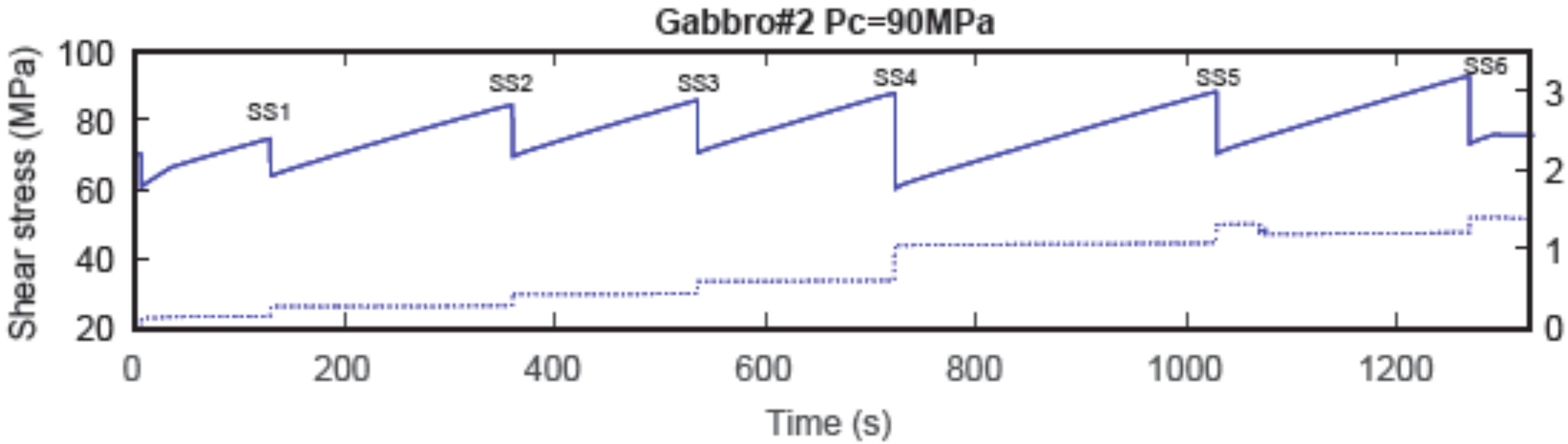
- “Tidal” modulation

Foreshock dynamics

- Continuous record of stick-slip failure in Gabbro



Marty et al. AGU, 2017

Foreshock dynamics

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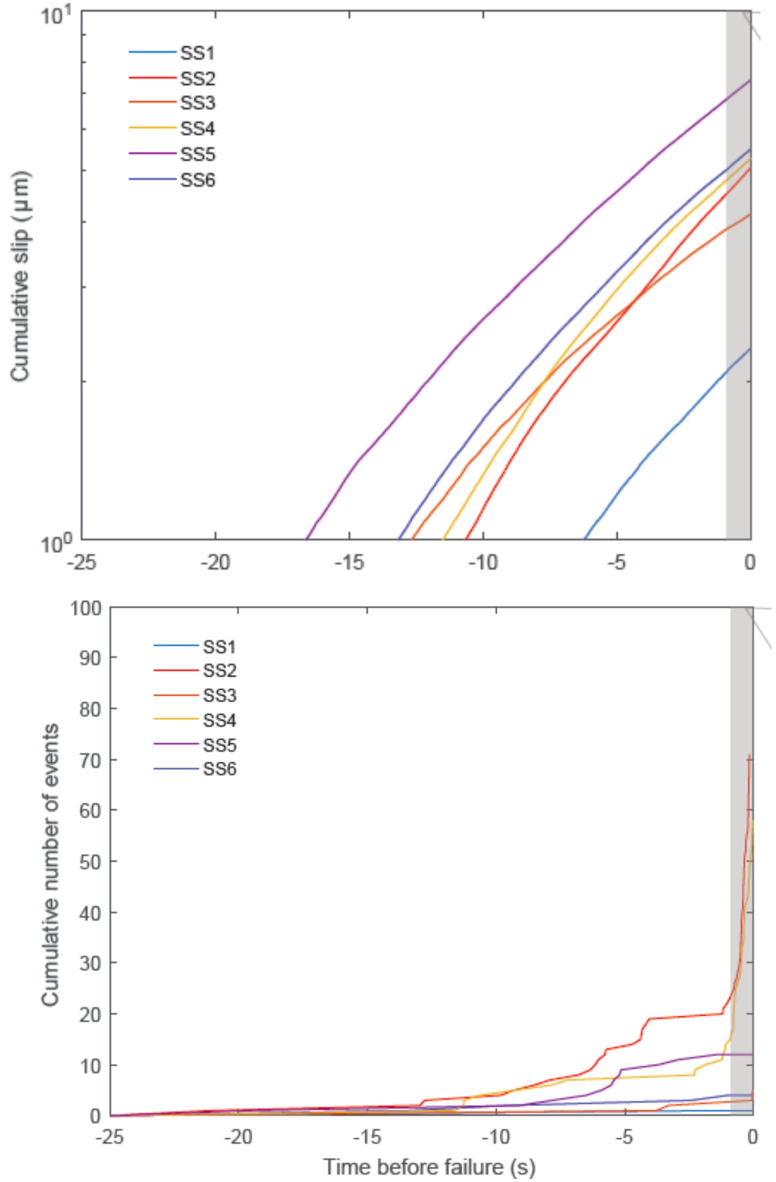

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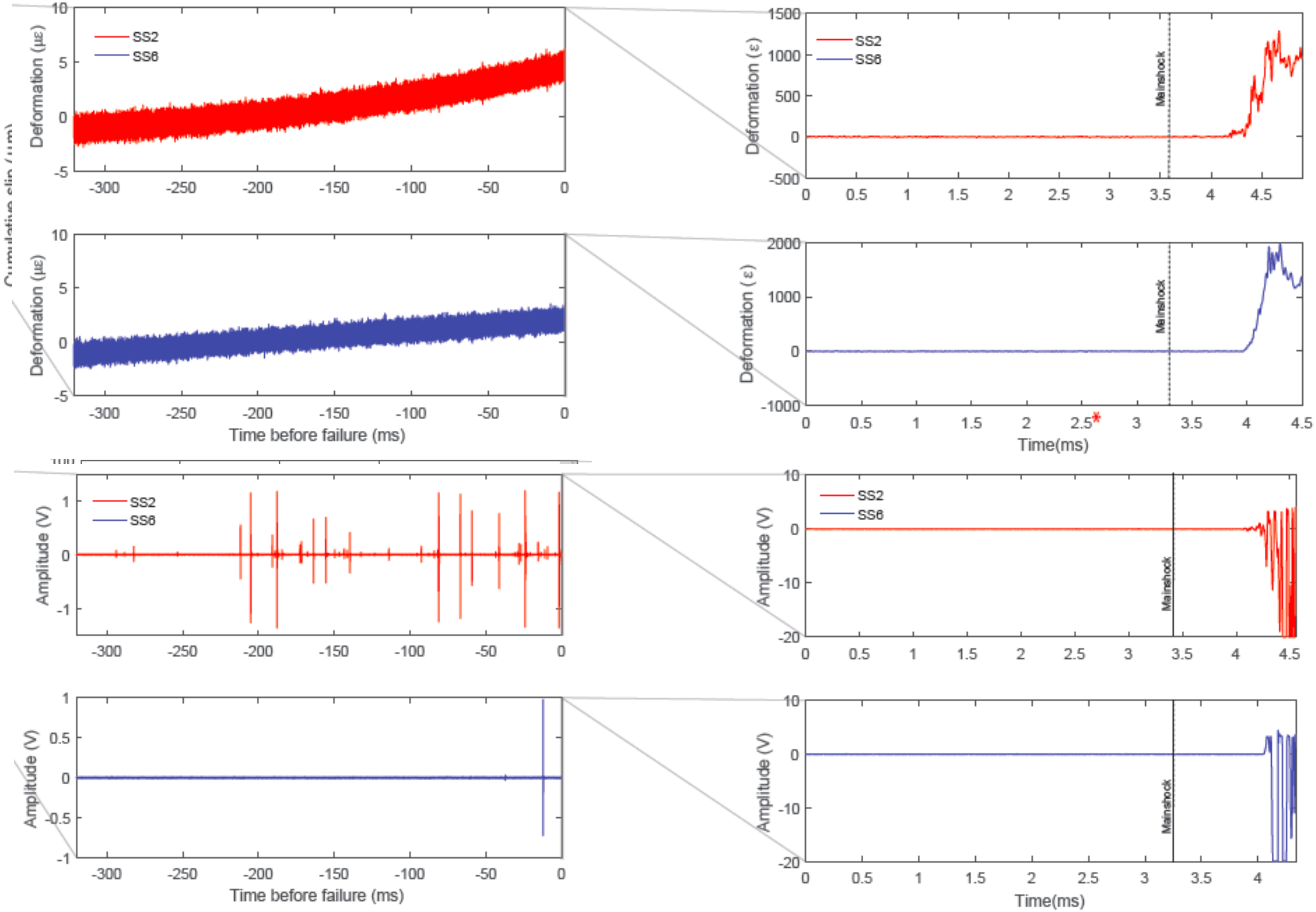
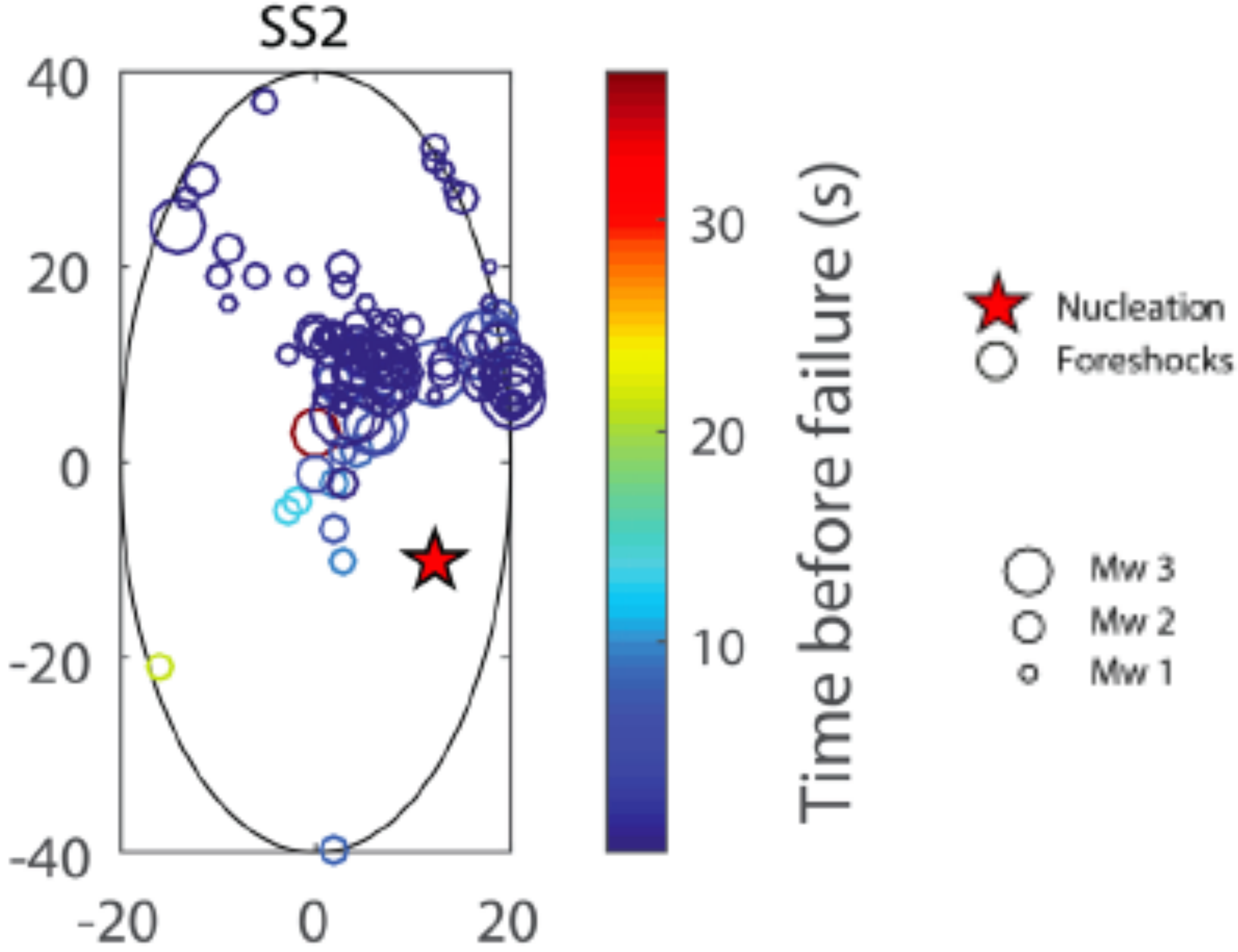


Foreshock dynamics

- Foreshocks are spatially and temporally correlated



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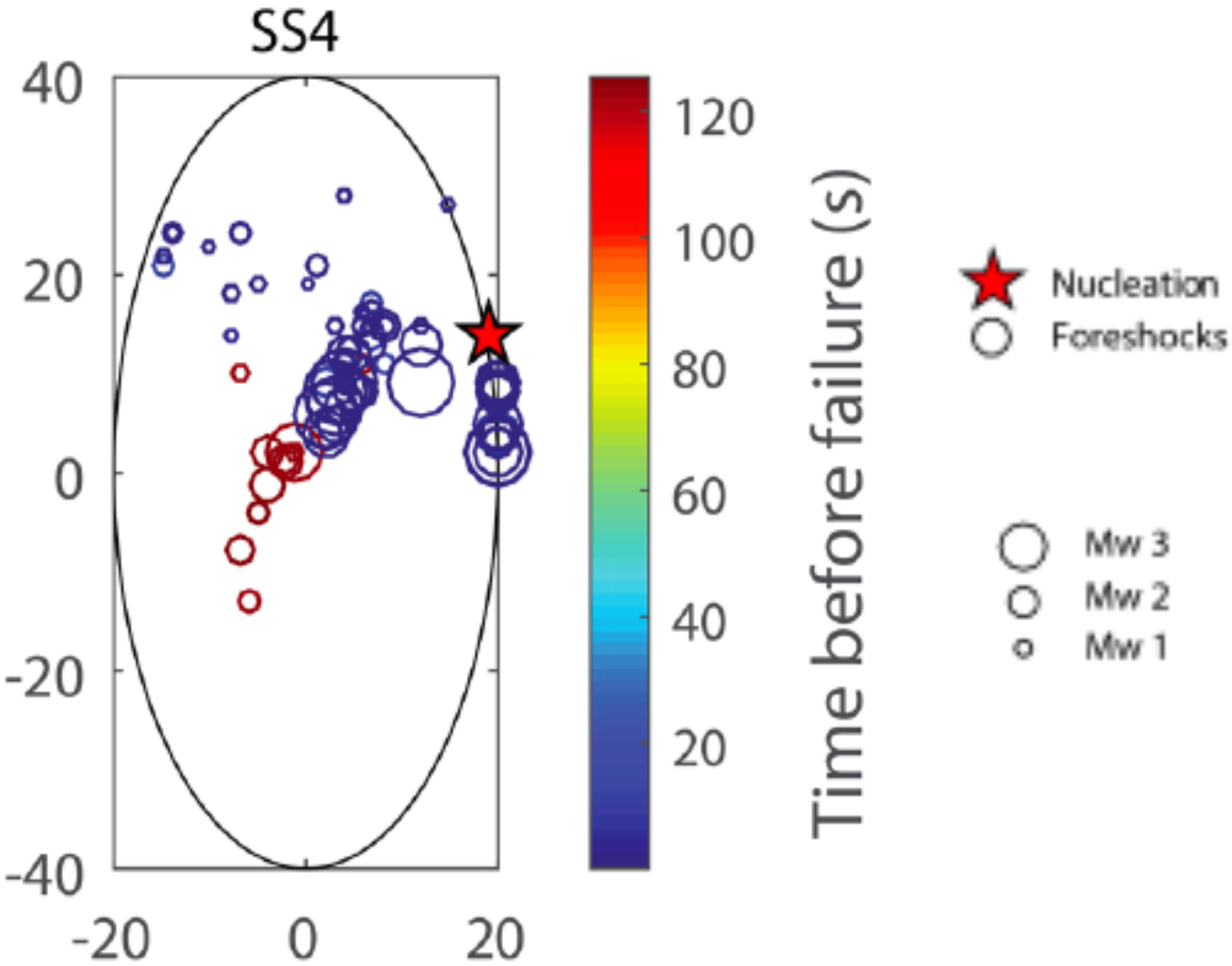

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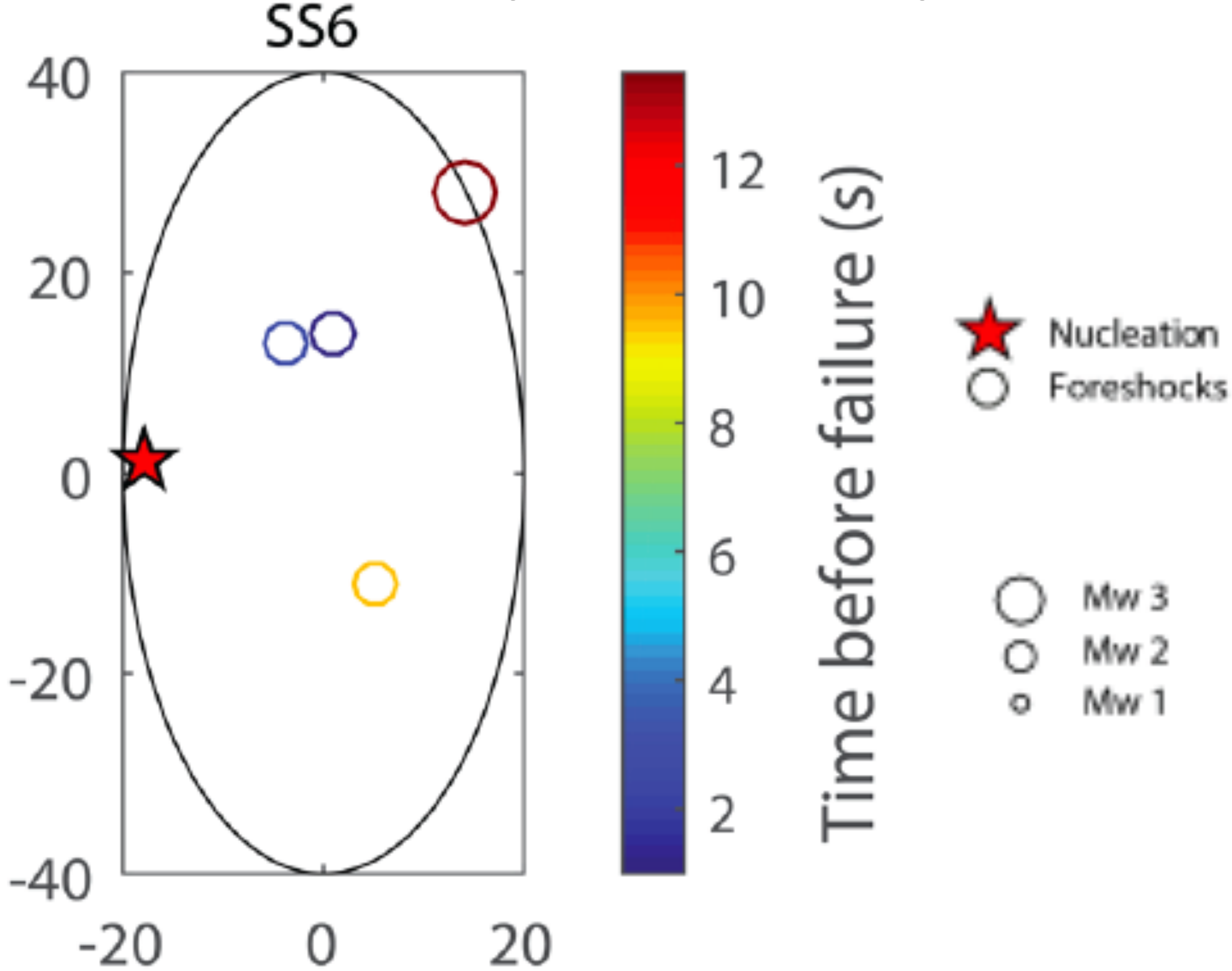
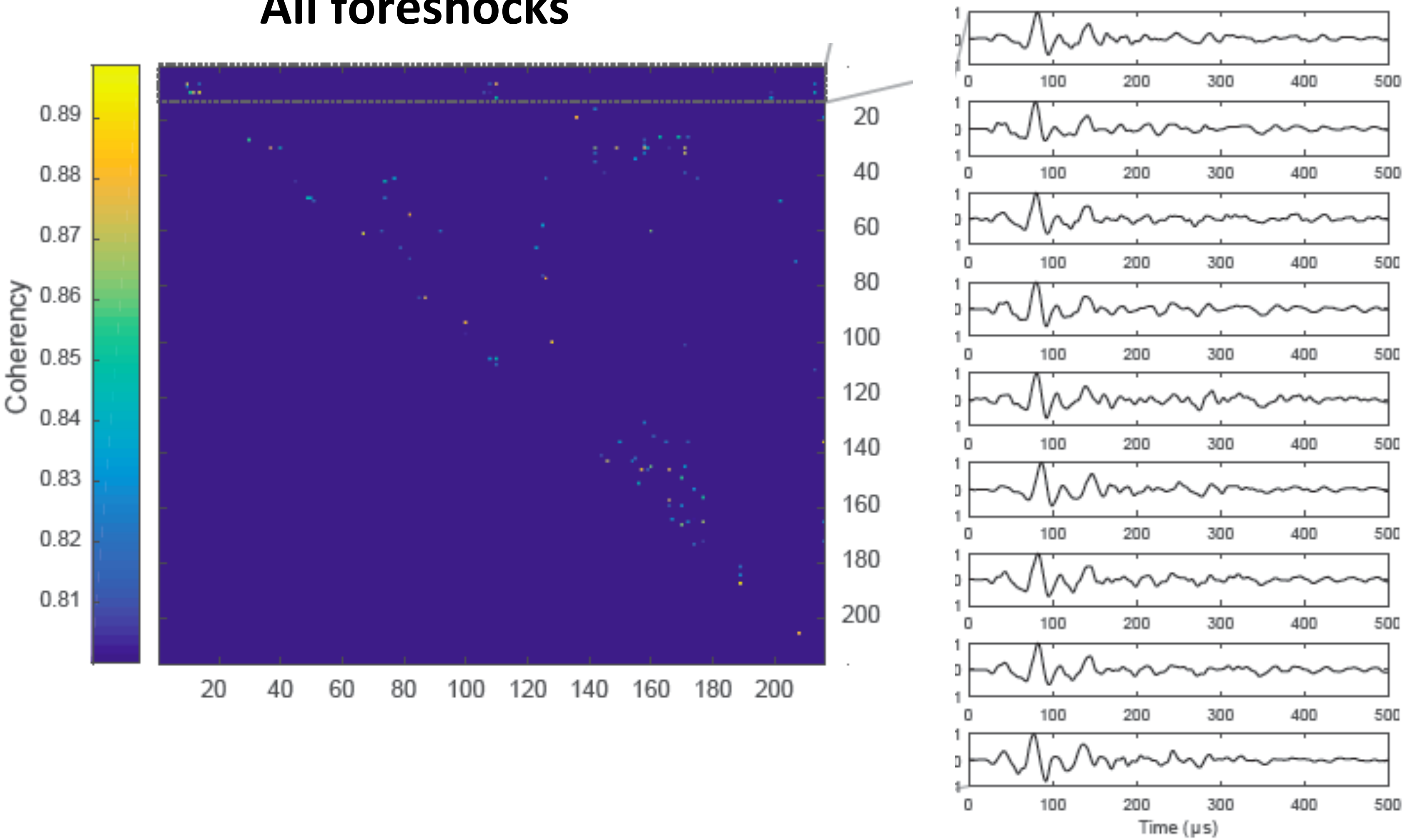


Marty et al. AGU, 2017

Foreshock dynamics

- Life of a single asperities during and over several cycles

All foreshocks

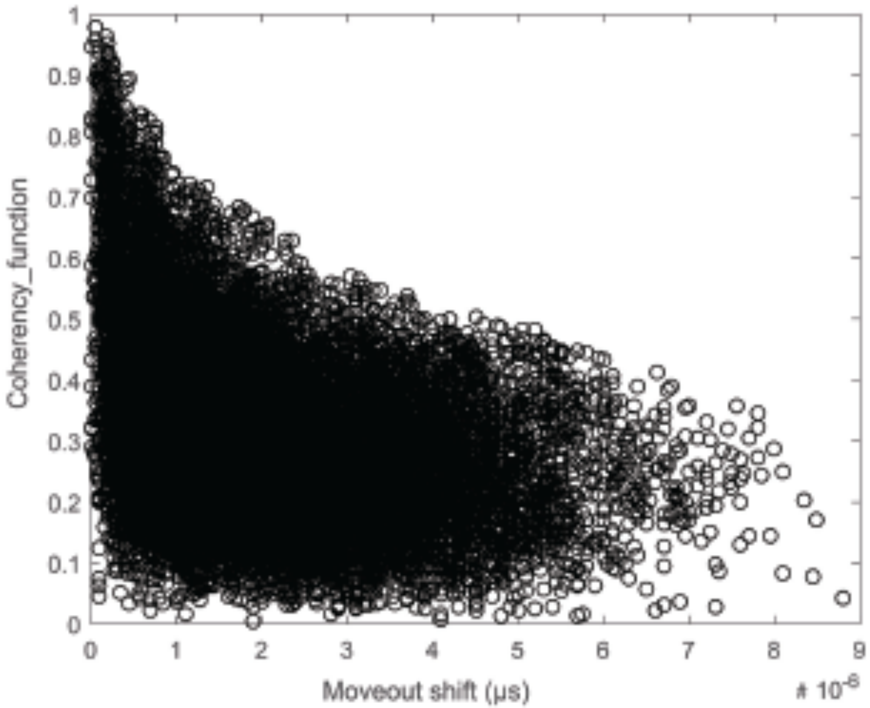


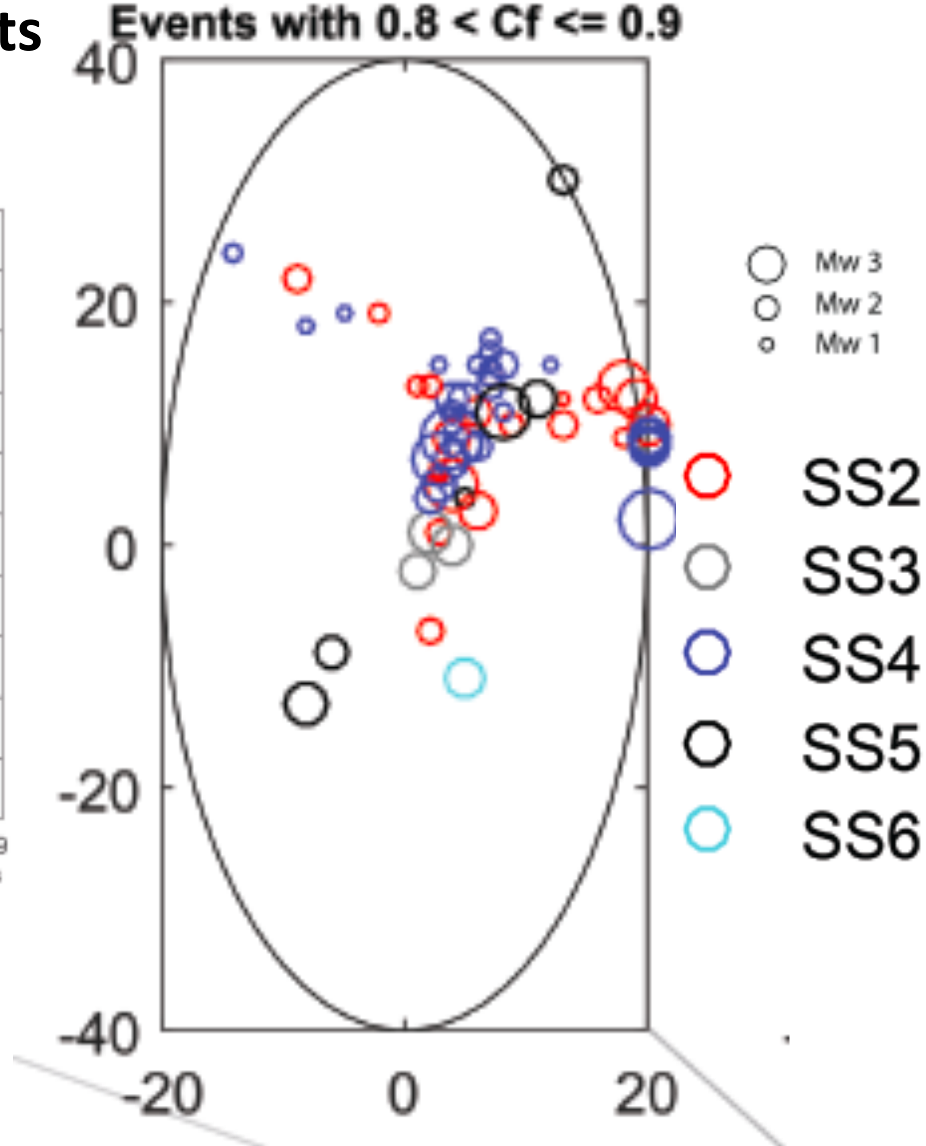
Marty et al. AGU, 2017

Foreshock dynamics

- Life of a single asperities during and over several cycles

Repeaters/similar family of events





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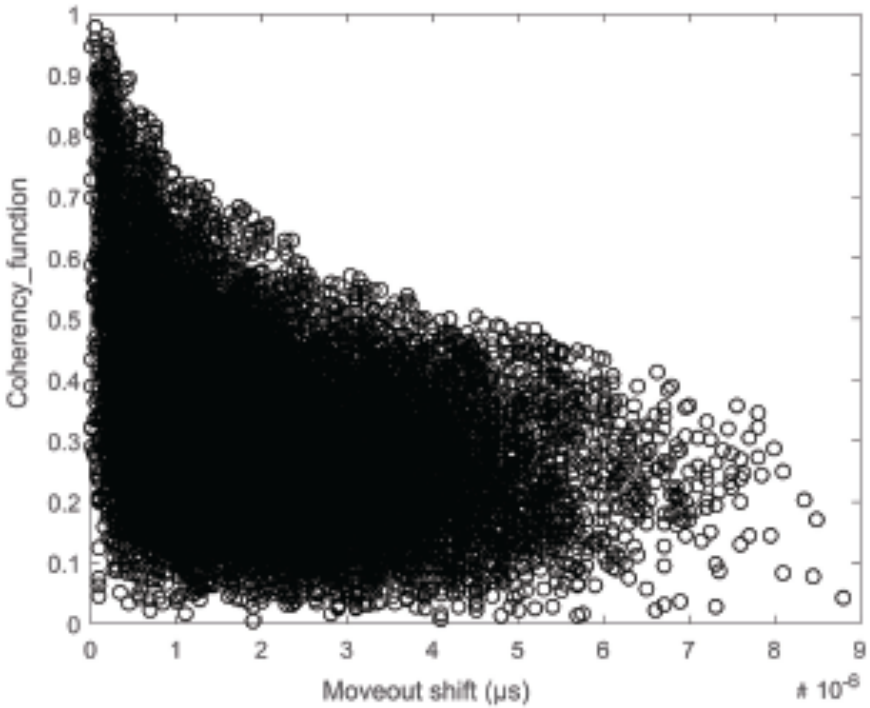

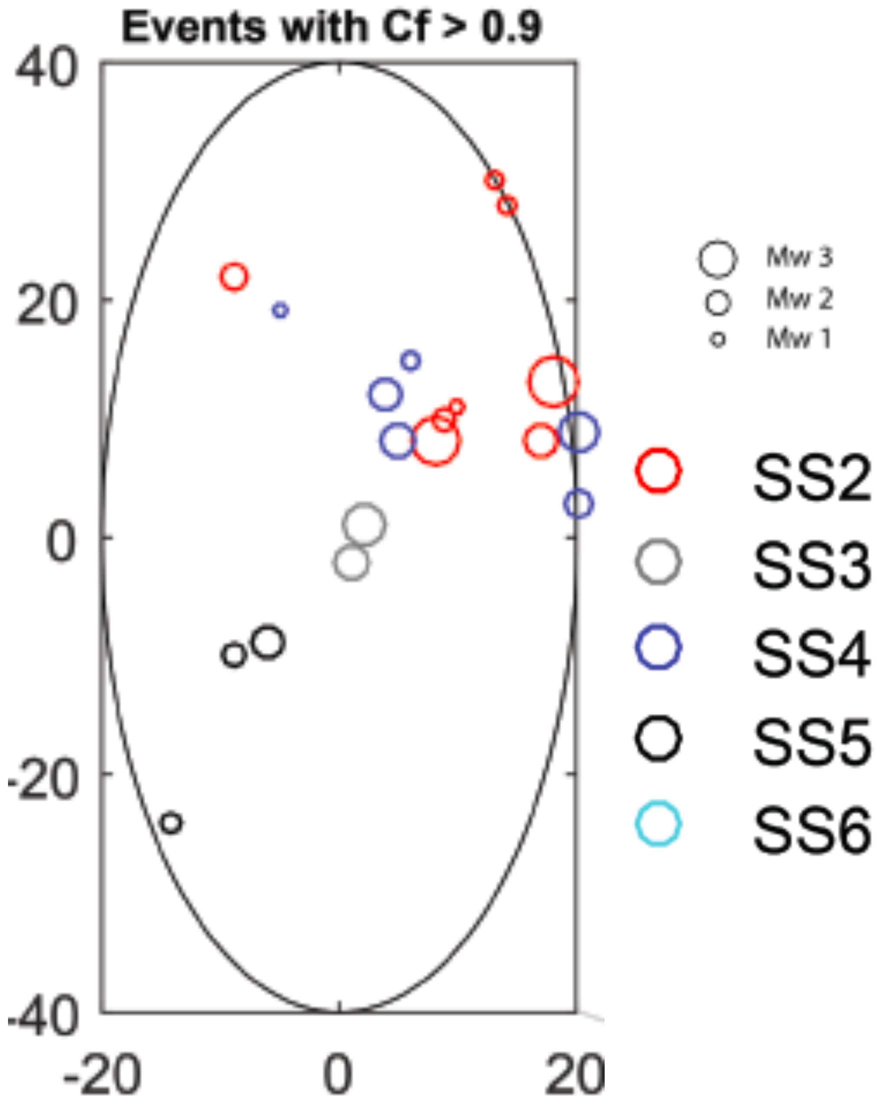

Marty et al. AGU, 2017

MOTIVATION

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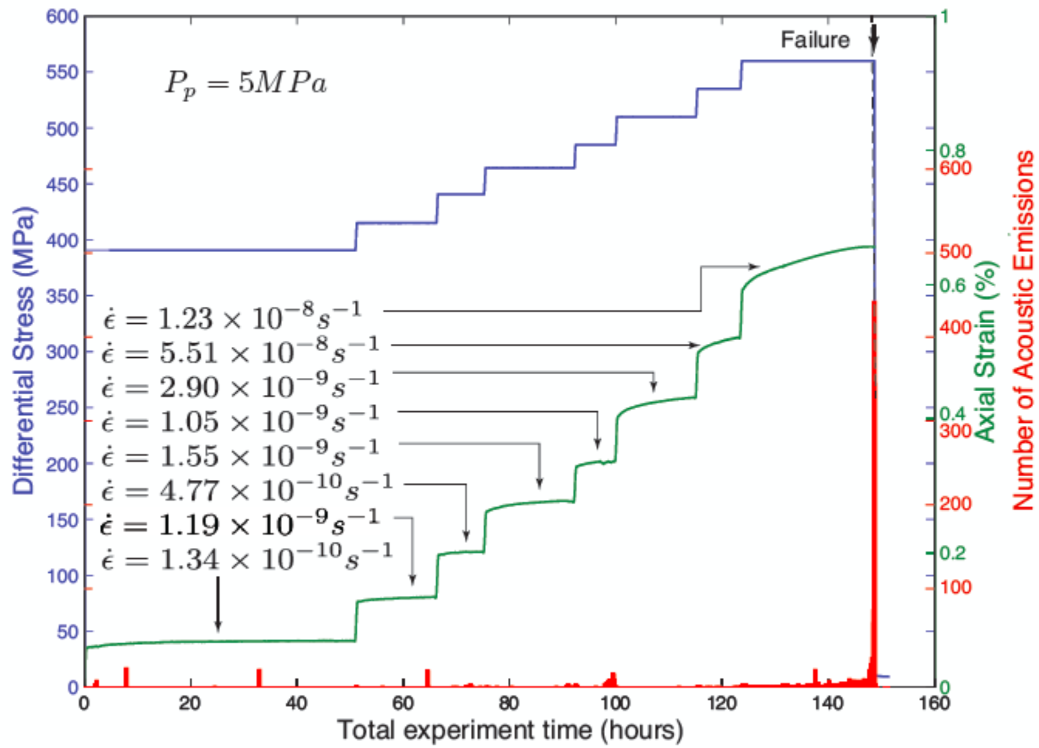
- “Tidal” modulation

How to simulate tidal modulations?

Typical Stress and Strain functions



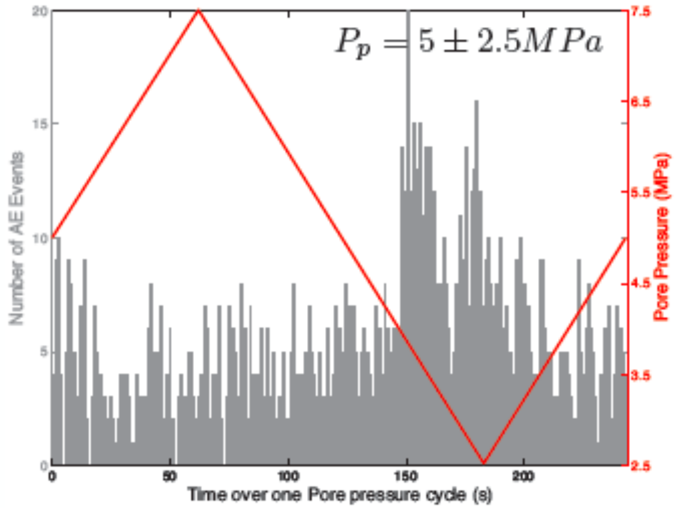
- Set of triaxial deformation experiments on water-saturated Fontainebleau sandstones, 7% porous, T=35ºC, Pc=35MPa

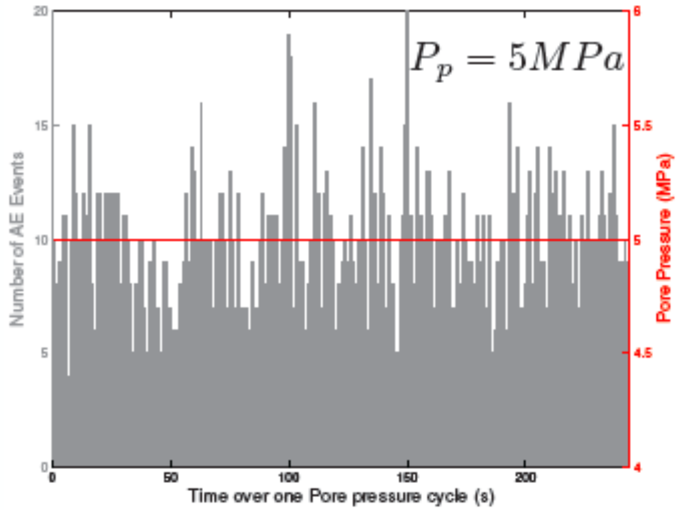
- Samples loaded by:
  - constant stress (creep) → tectonic loading
  - sinusoidal pore pressure variations → tidal or seasonal loading

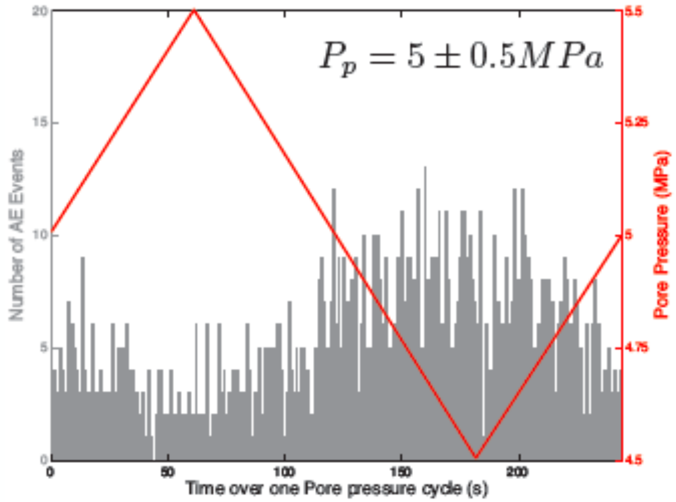
GLOBAL AVERAGE (over one Pp cycle) of AE catalog

Experimental Results: Acoustic Emissions during failure stress step

Acoustic emissions triggering occur significantly more when the pore pressure is at its lowest







Chanard 2015; Chanard et al. in prep.

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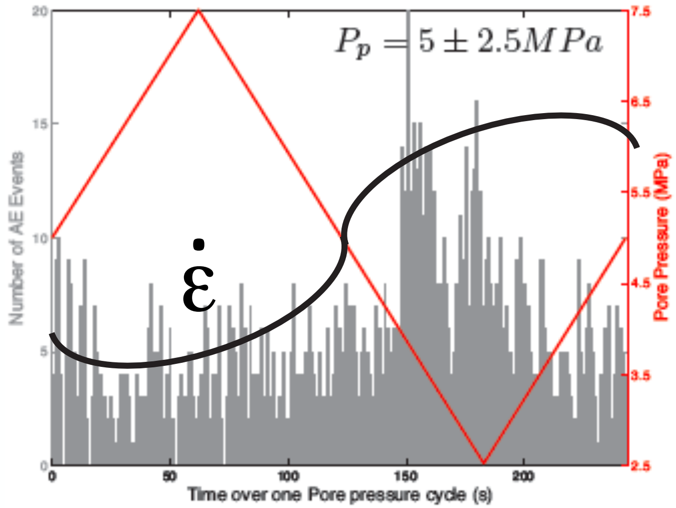
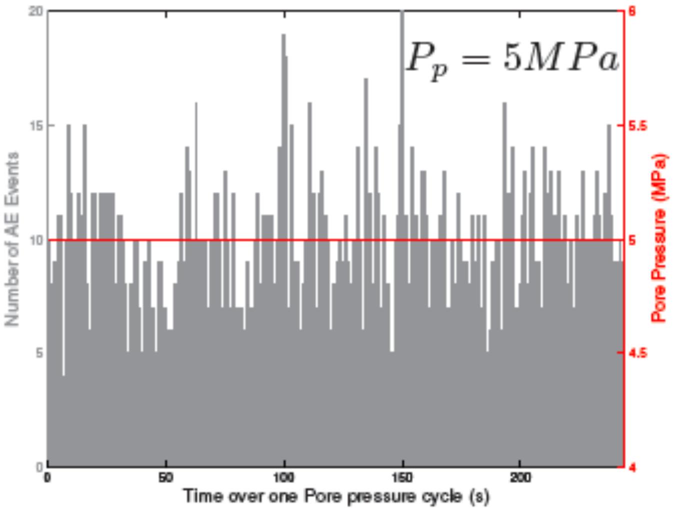
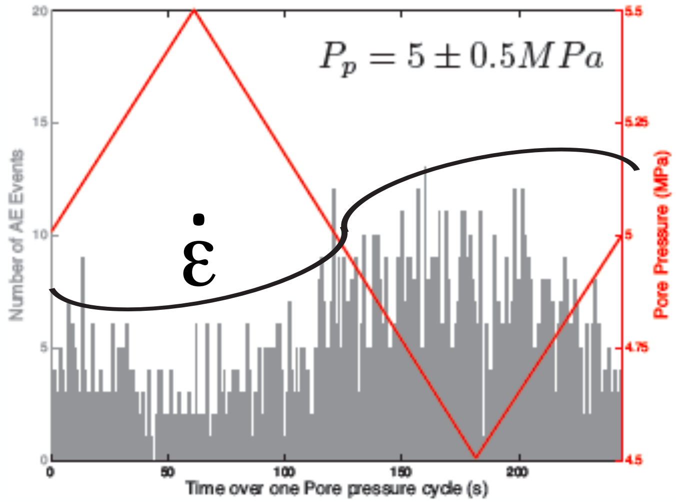






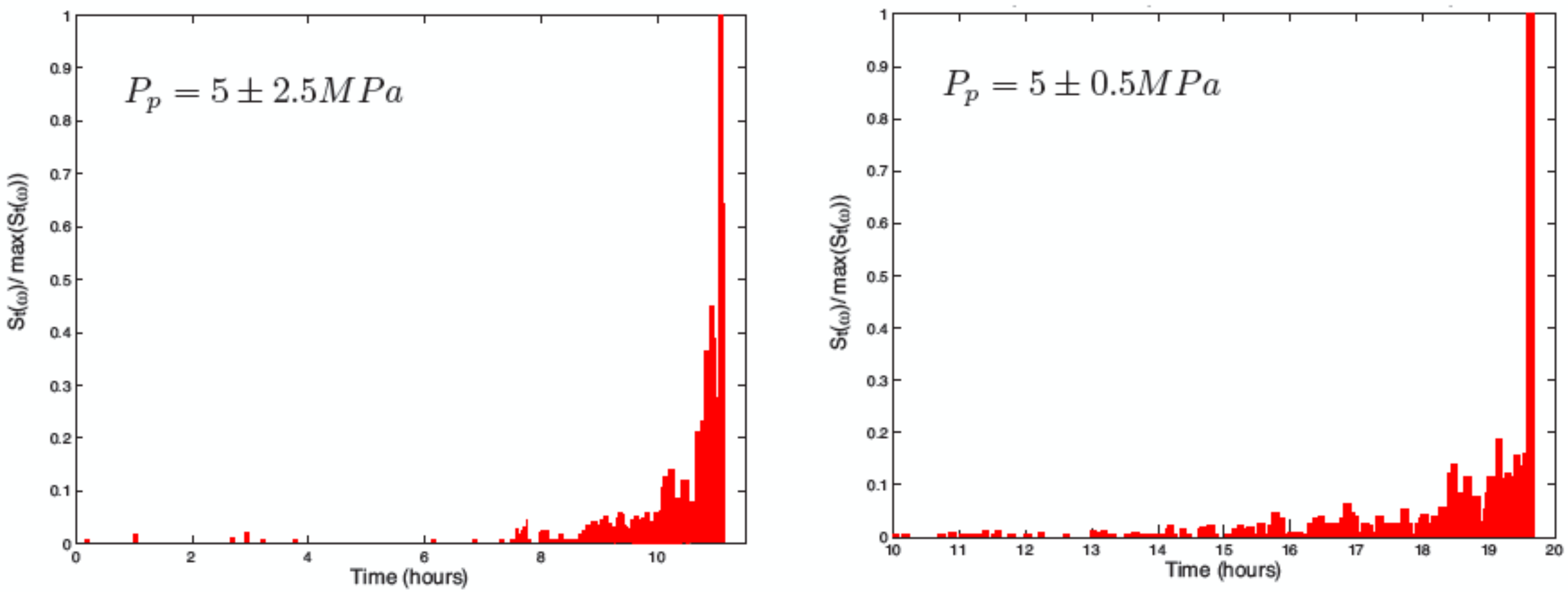
Chanard 2015; Chanard et al. in prep.

A growing stress suceptibility (i.e. sensitivity)

Experimental Results: Acoustic Emissions triggering during failure stress step

Correlation coefficient between AE and pore pressure:

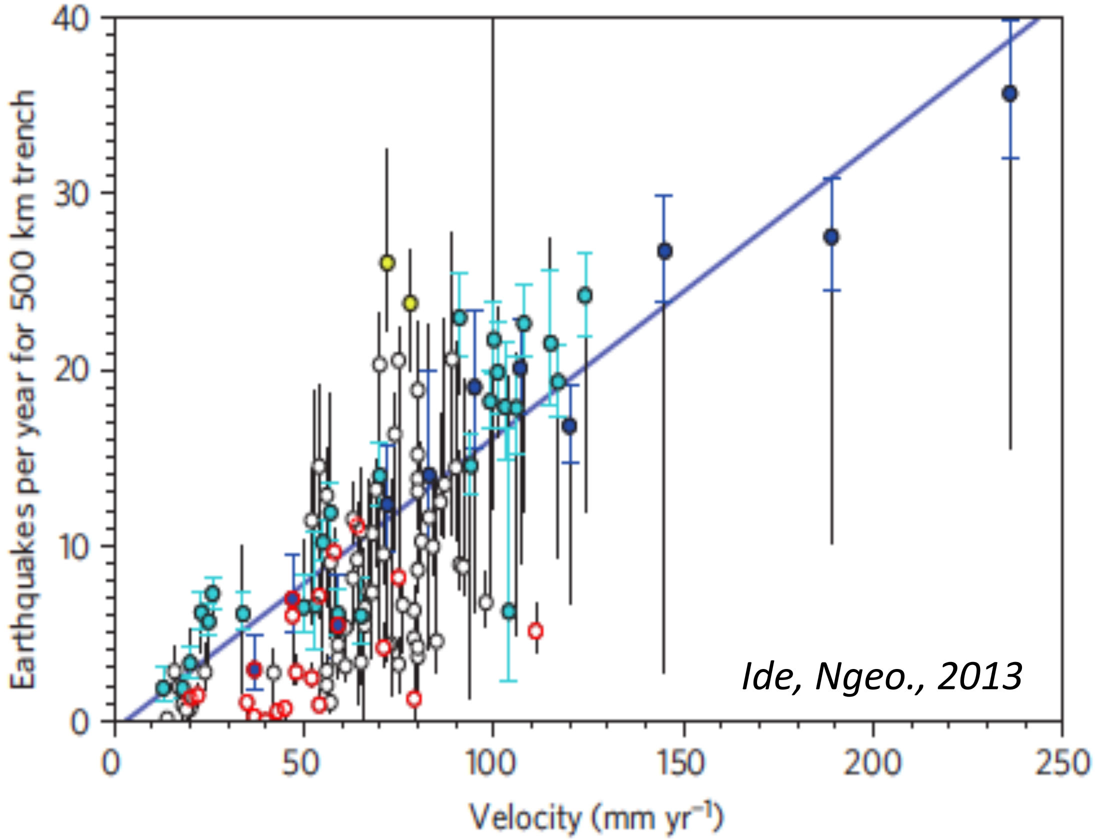
$S_t(\omega) =$ f(pulsation of the pore pressure oscillations, AE rate)



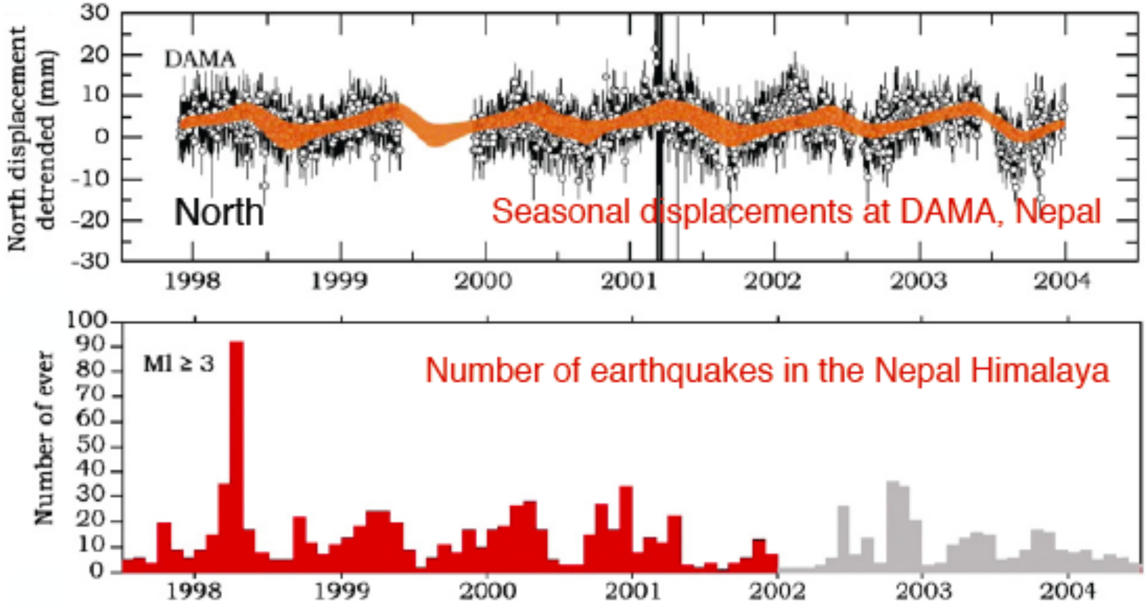
Progressive increase of the correlation coefficient between pore pressure oscillations and acoustic emissions triggering in time as the rock approaches failure

Chanard 2015; Chanard et al. in prep.

The proportionality between relative plate velocity and seismicity in subduction zones



Seasonal seismicity in the Himalayas

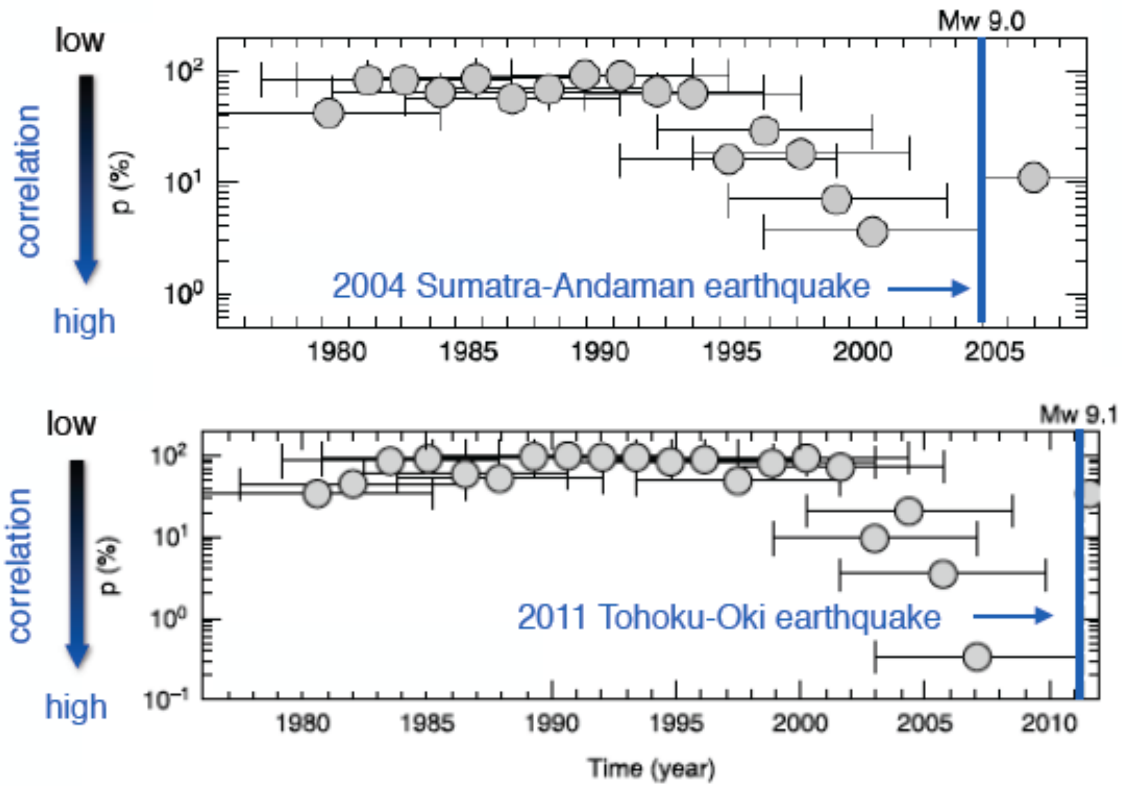


(Bettinelli et al., 2008)

- Seismicity rate in the winter twice as high as in the summer in the Nepal Himalaya
- Other regional observations of seismicity rate with periodic loading (tidal, seasonal)
- No global systematic correlation of seismicity with amplitude or frequency of periodic loading

Tidal triggering during large EQ nucleation

Observation: increase of correlation between seismicity and oceanic tides prior to large earthquakes



(Tanaka et al., 2010, 2012)

Tidal or seasonal earthquakes triggering might occur favorably during the long nucleation phase

Conclusions

- During **rock fracture**, **Omori's law** is observed for **foreshocks and aftershocks**, and **small stress perturbations** can **modulate seismicity** rate. **Modulation** is **correlated with strain rate** and thus suceptibility **grows as failure approaches**.

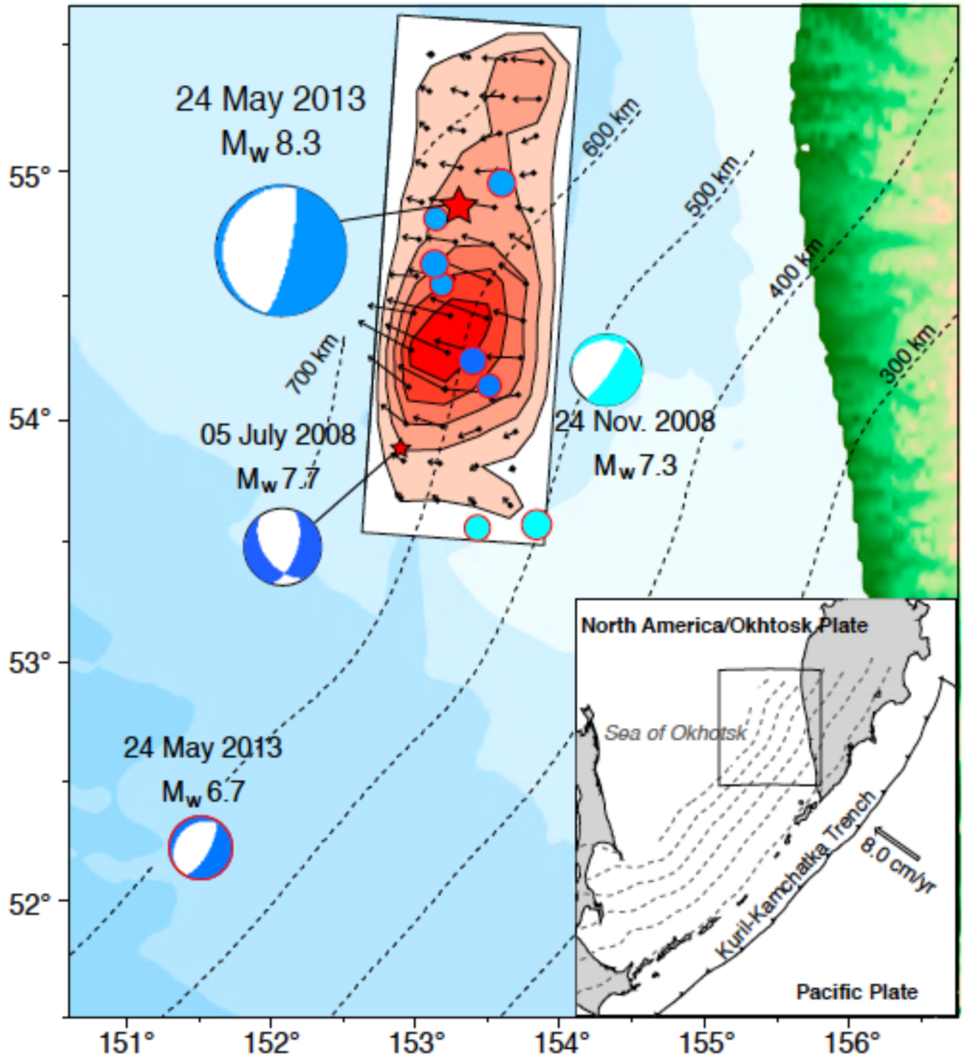
- **Nucleation phase of stick slip instability** corresponds an **exponential growth** of rupture length & slip, and thus slip velocity & rupture speed**. Foreshock and aseismic moment releases are also exponential**. Seismic/aseismic coupling increases with fracture energy and normal stress.

- **Nucleation phase** is also **charaterized by repeaters** (repetitive failure of the same asperity).

Do large deep earthquake…

The Okhotsk, May 24th 2013, Mw=8.3, 620km deep EQ

Ye et al. Science 2013



…have a nucleation phase?

Repeating Deep Earthquakes: Evidence for Fault Reactivation at Great Depth

Douglas A. Wiens and Nathaniel O. Snider

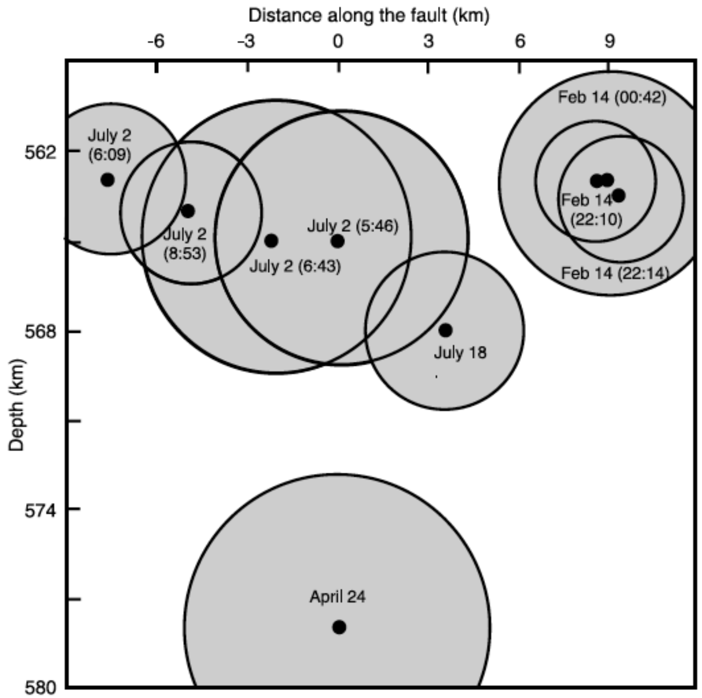
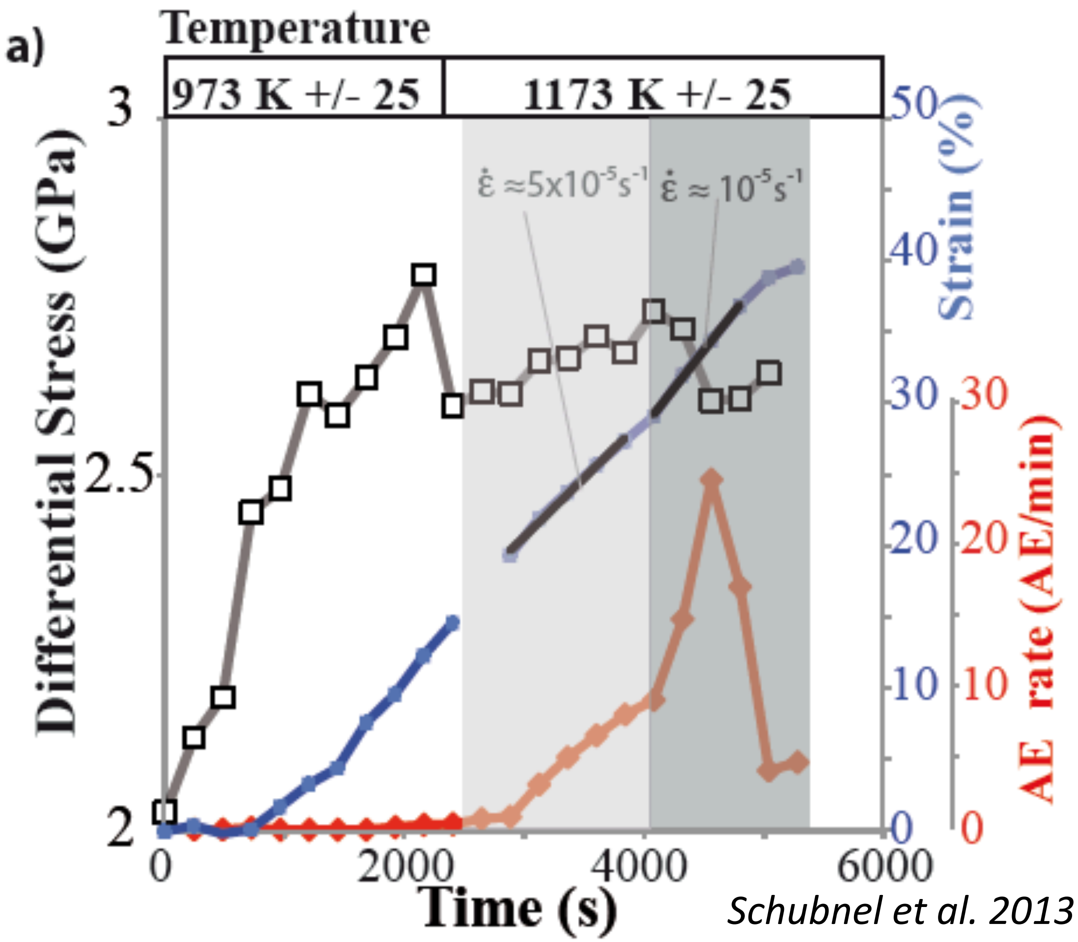


Fig. 3. Estimated rupture zones of earthquakes from cluster 1 assuming circular rupture. Rupture radius is calculated from the measured rise times determined by EGF deconvolution and assuming a rupture velocity of 3.8 km/s (70% of the shear velocity).

Nature 2001

Deep labquakes during Ge-olivine-spinel transition

Sintered Mg_2GeO_4 – 30µm grain size
Effective mean stress $(\sigma_1+2\sigma_3)/3$ = 4GPa +/-0,25
Strain rate = 10^{-4}/s



Schubnel et al. 2013

Deep labquakes during Ge-olivine-spinel transition

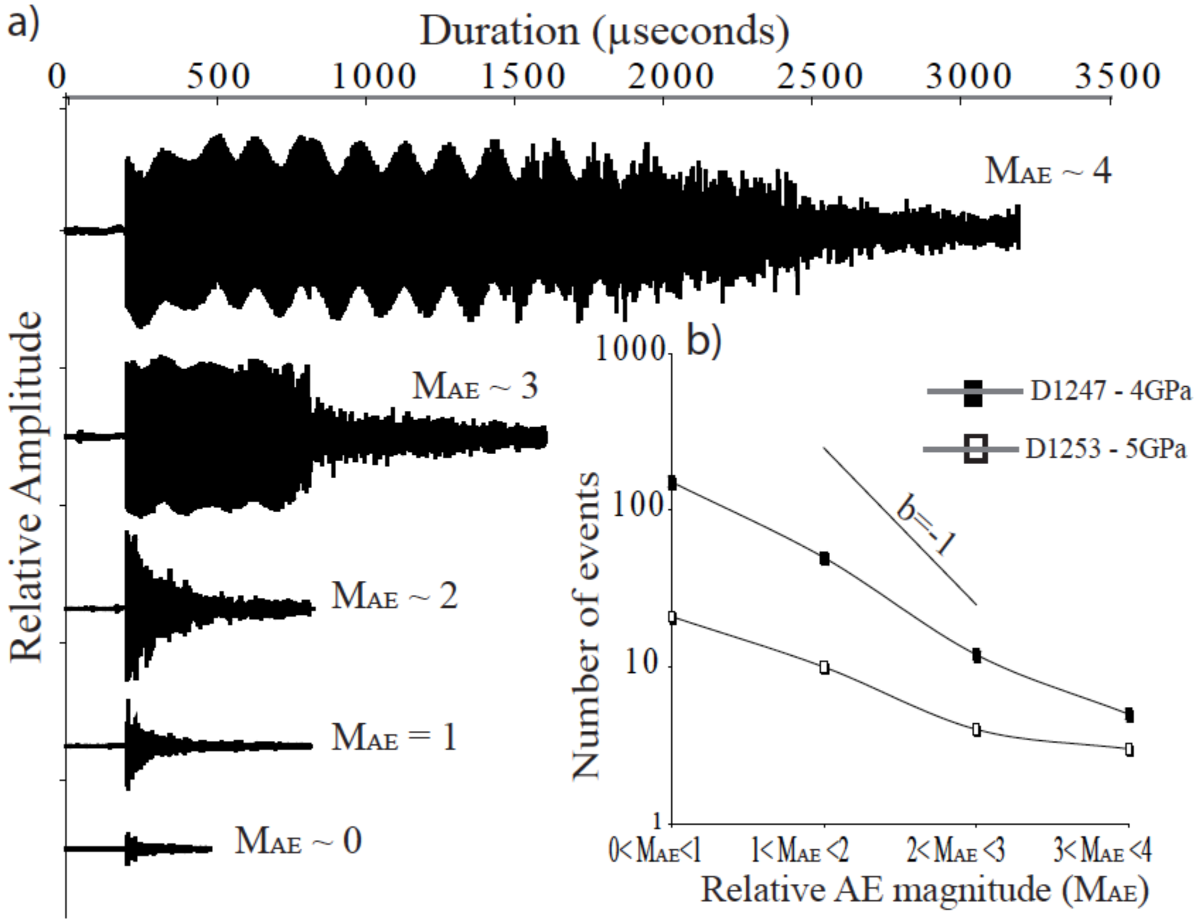
Two complete AE catalogues

D1247 Effective mean stress $(\sigma_1+2\sigma_3)/3$ = 4GPa +/-0,25

D1253 Effective mean stress $(\sigma_1+2\sigma_3)/3$ = 5GPa +/-0,25

Strain rate = 10^{-4}/s

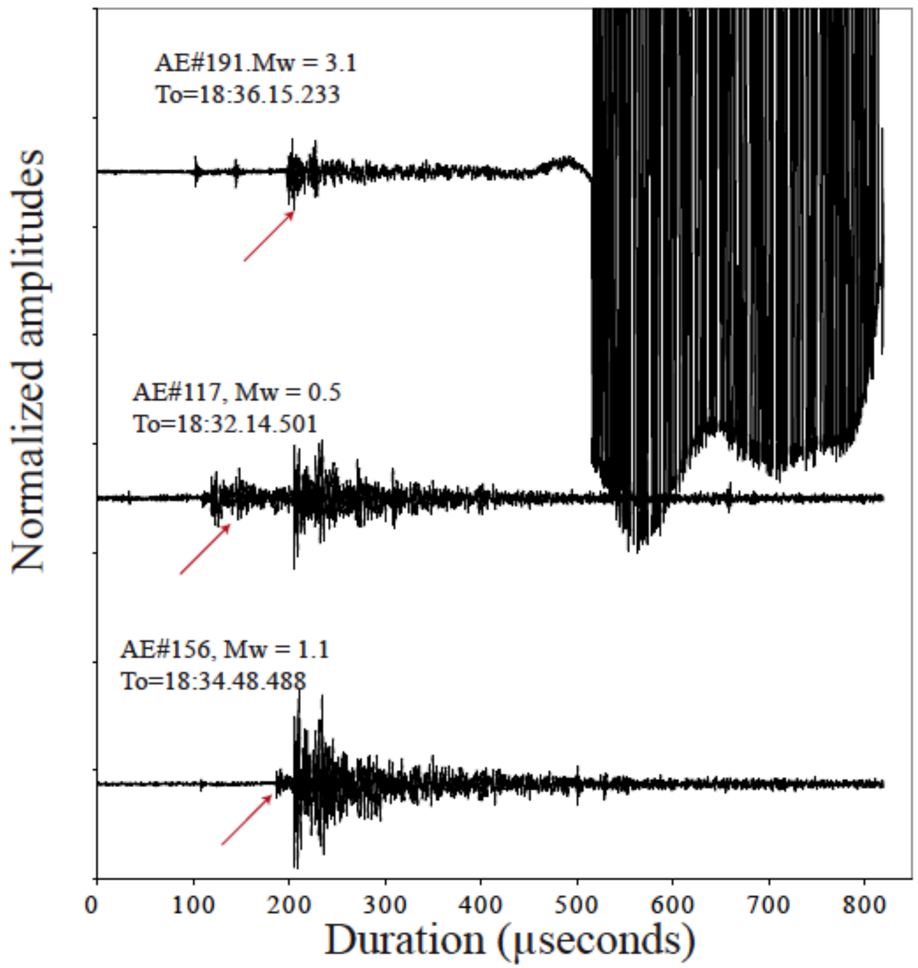
Sonification:
courtesy to Ben Holtzman
LDEO, U. Columbia NY
Visiting prof. ENS 2015



Schubnel et al. 2013

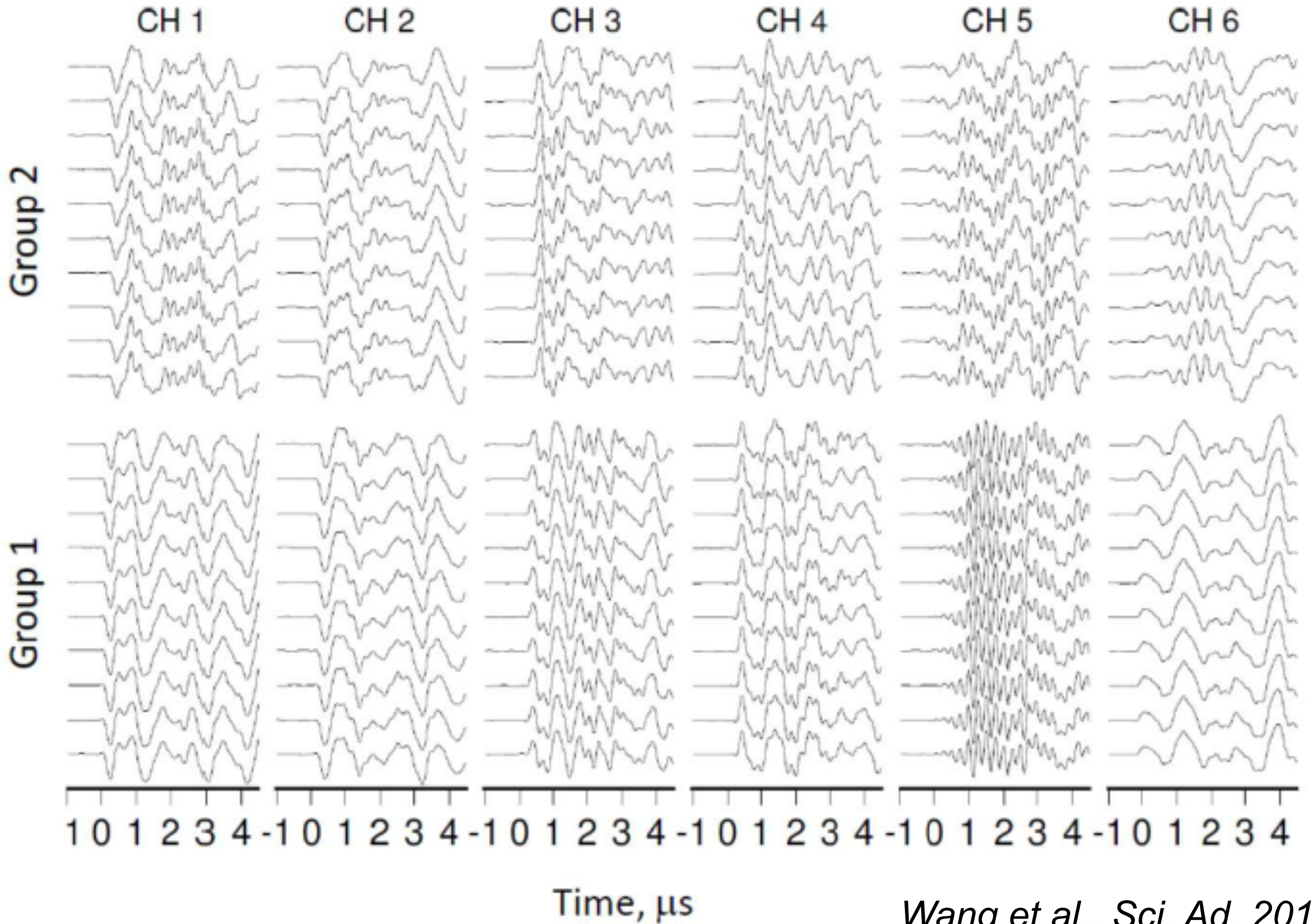
Deep labquakes during Ge-olivine-spinel transition

Looking closer into the AE source - *Double source or nucleation phase?*
Approximately 20% of the AEs have a complex source functions



Deep labquakes during Ge-olivine-spinel transition

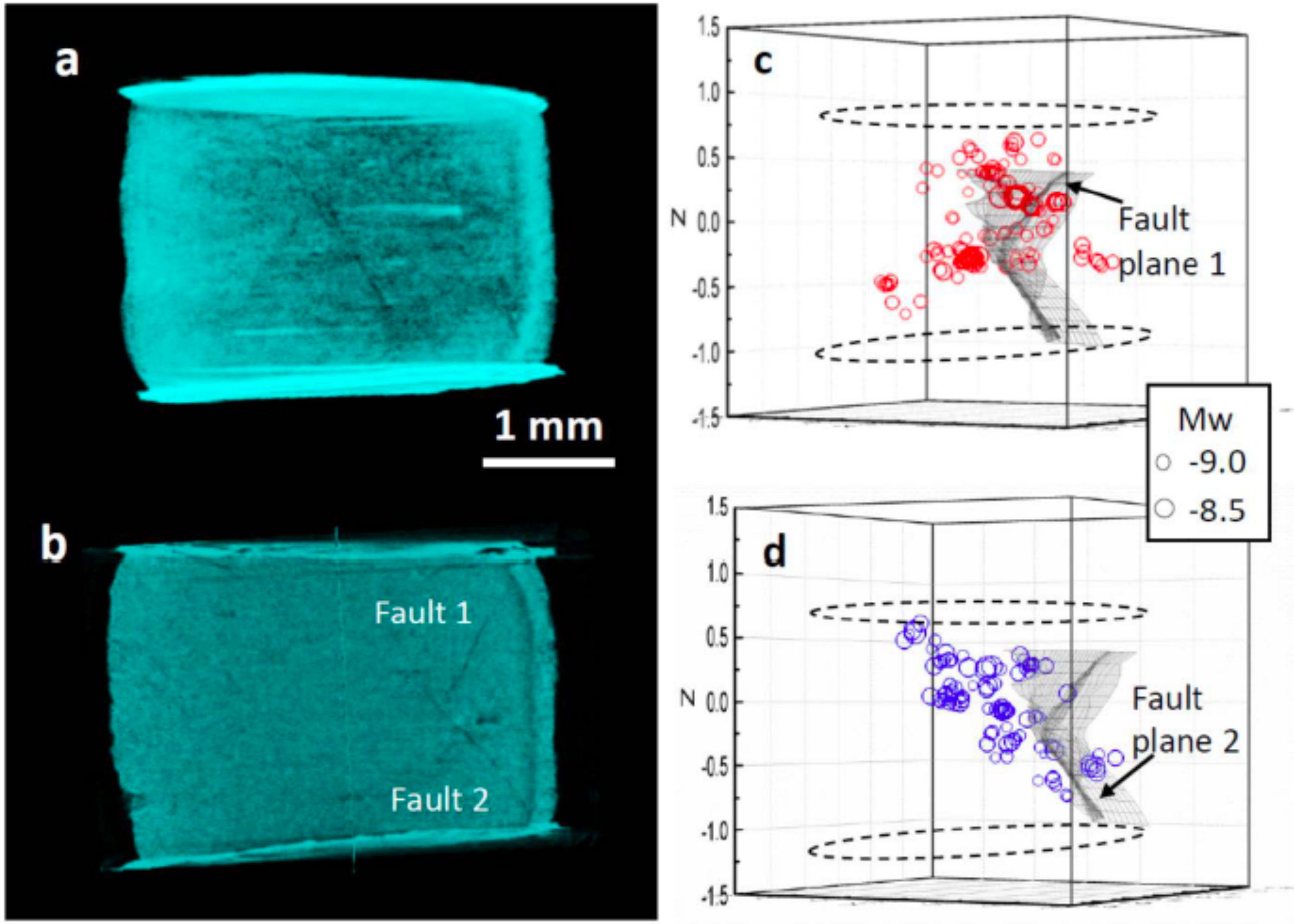
Double difference relocation (Waldhauser and Ellsworth 2000)



Wang et al., Sci. Ad. 2017

Deep labquakes during Ge-olivine-spinel transition

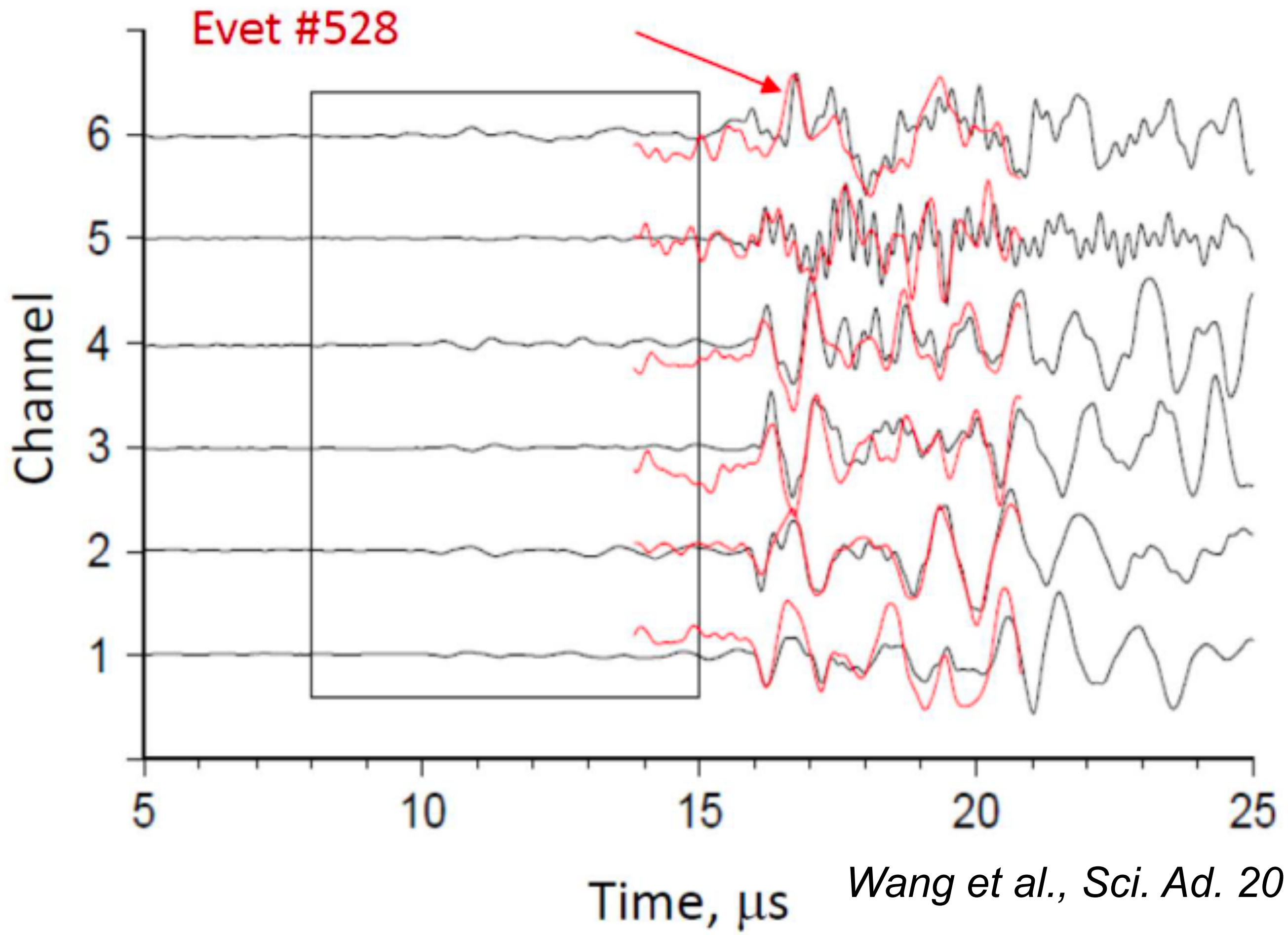
Correlating X-ray tomography and AE relocations



Wang et al., Sci. Ad. 2017

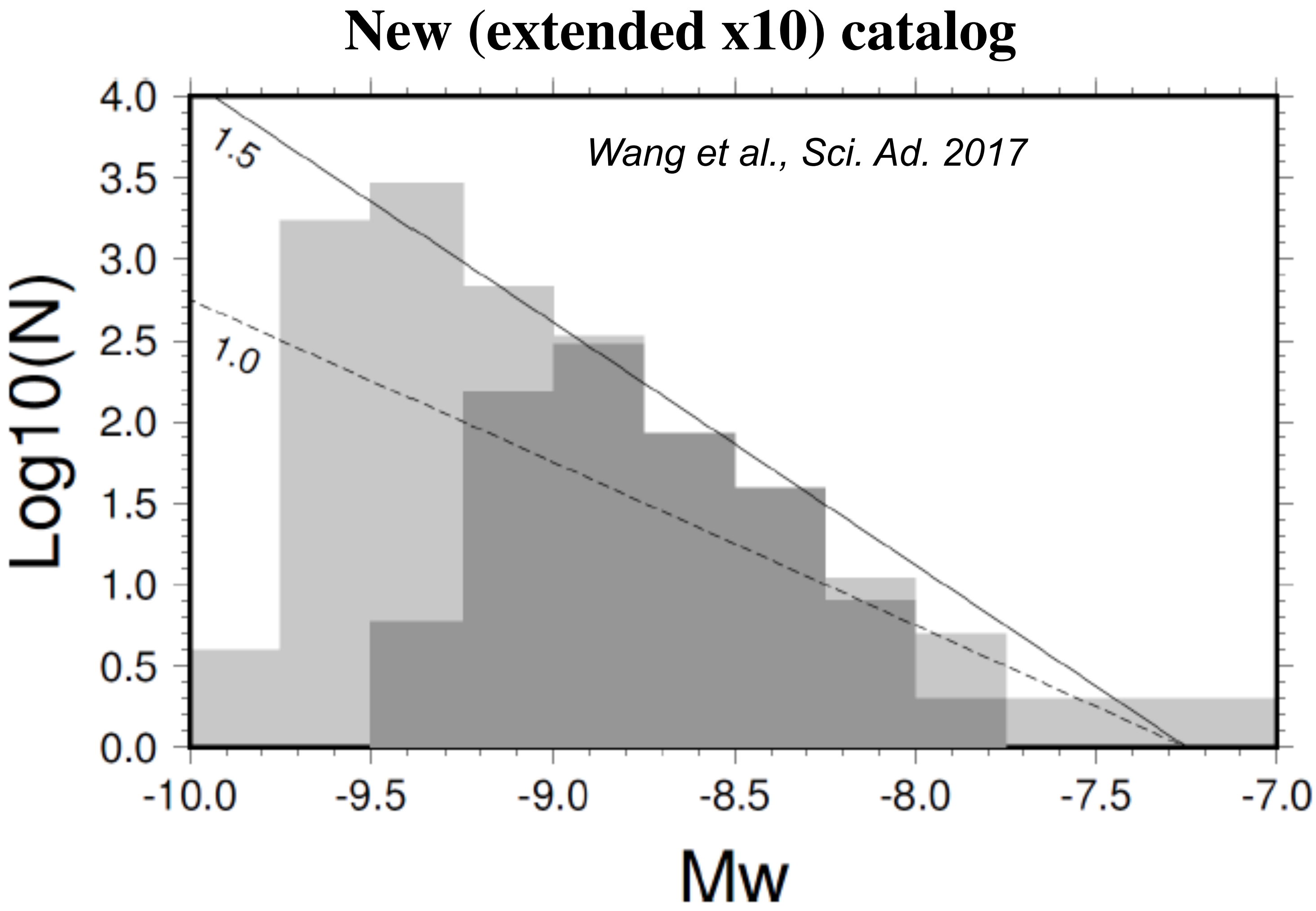
Deep labquakes during Ge-olivine-spinel transition

Template matching of continuous wfms



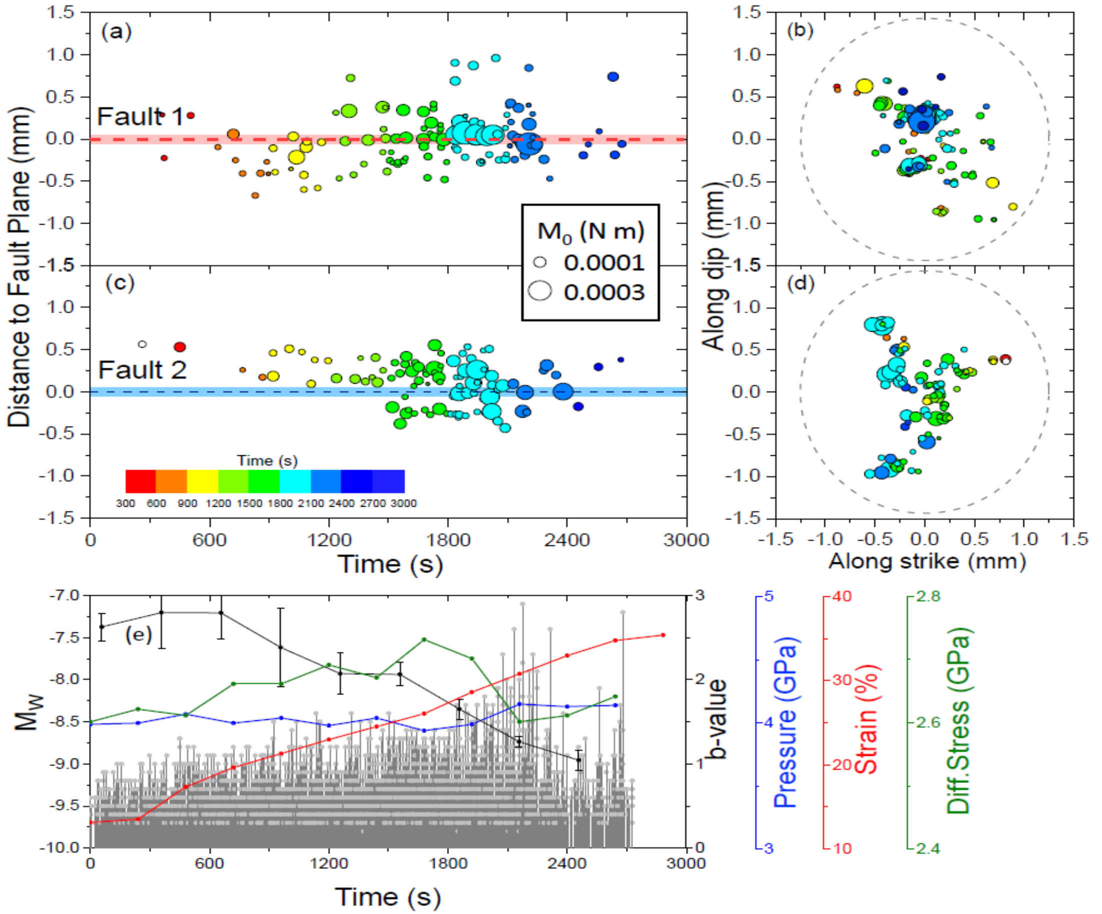
Wang et al., Sci. Ad. 2017

Deep labquakes during Ge-olivine-spinel transition



Deep labquakes during Ge-olivine-spinel transition

Signature of a nucleation phase?



Wang et al., Sci. Ad. 2017