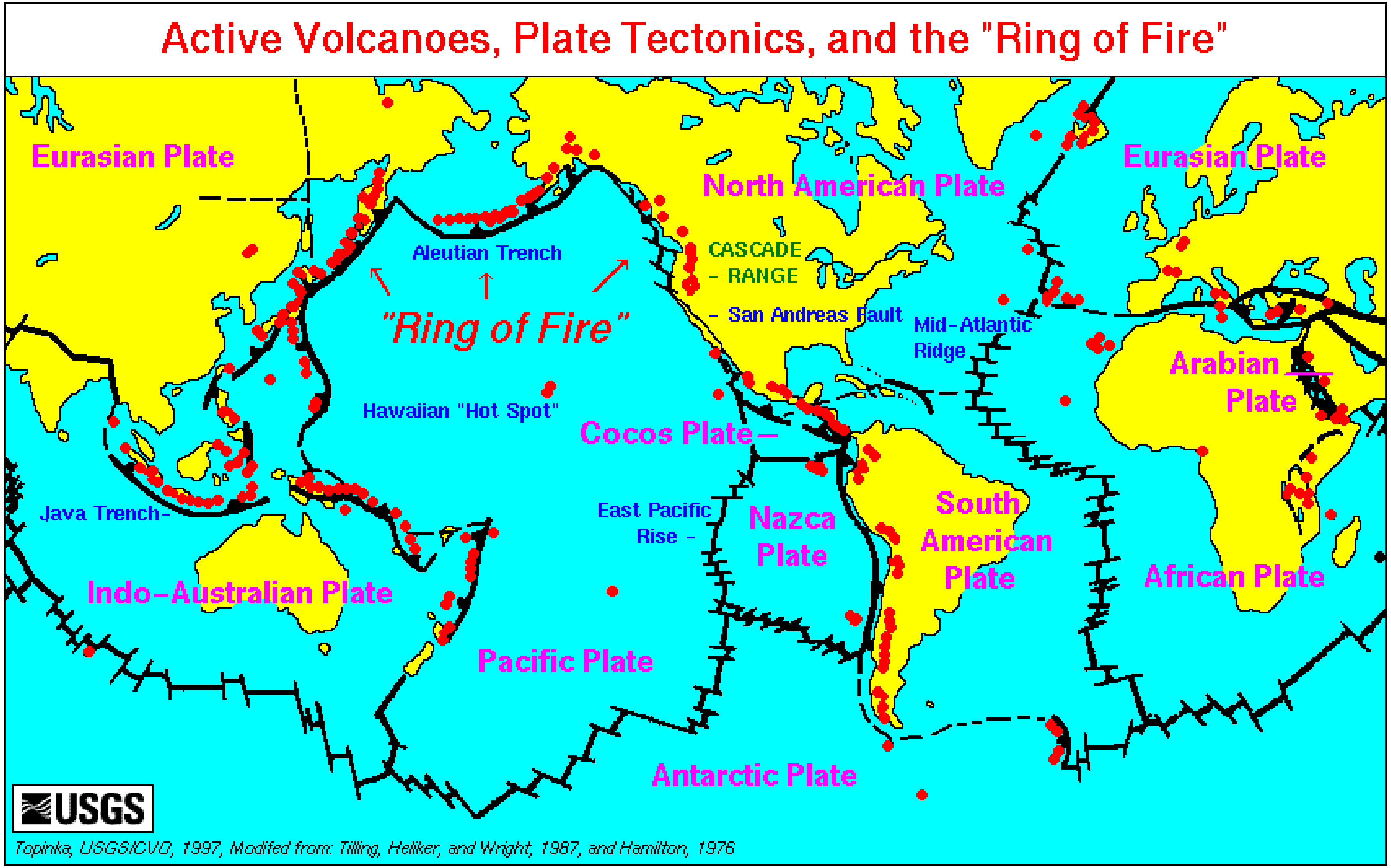
‘Ring of Fire’, Johnny Cash

the Ring of Fire



Los Alamos
NATIONAL LABORATORY

~~Laboratory earthquakes~~
Granular physics and slip processes

Paul Johnson et al.

Los Alamos

Marone, Jia, Gomberg, Carmeliet, ferdowsi, Guyer, Griffa, Ben-Zion, Brodsky, van der Elst, Ecke……

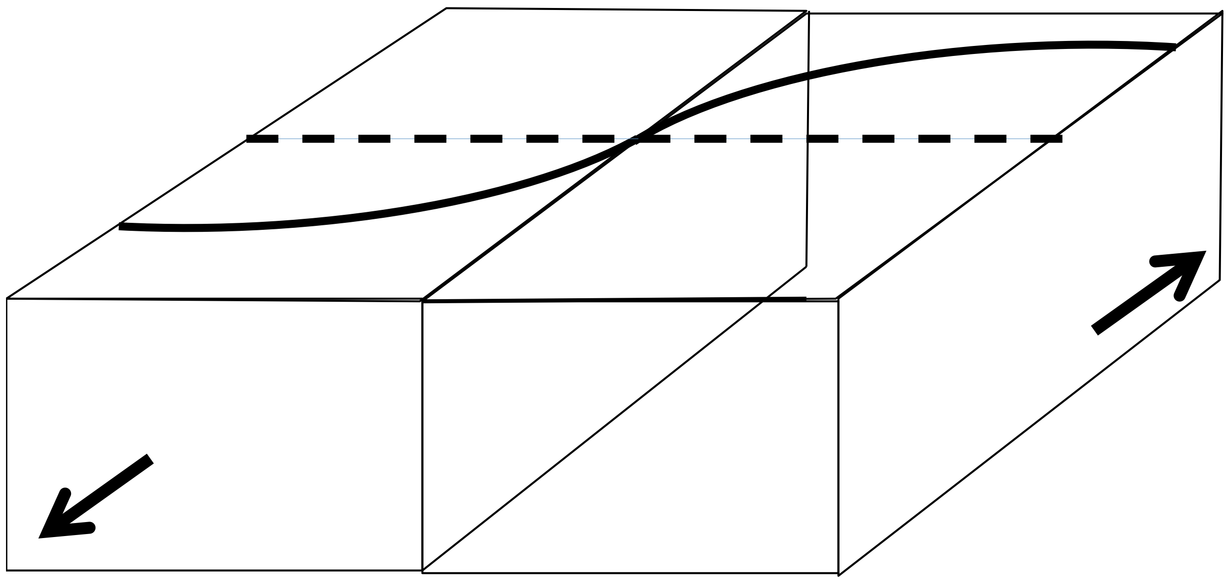
Complexity, Santa Barbara 2014

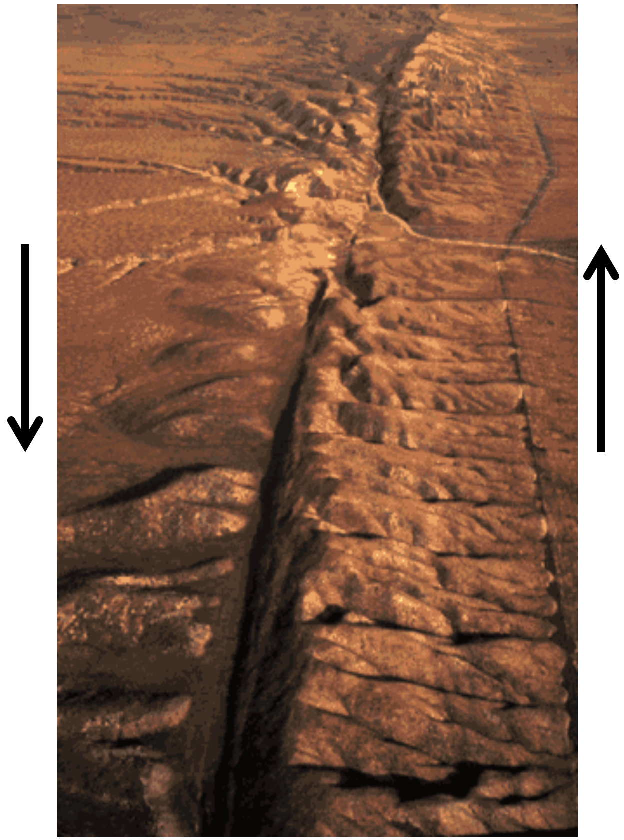
Outline

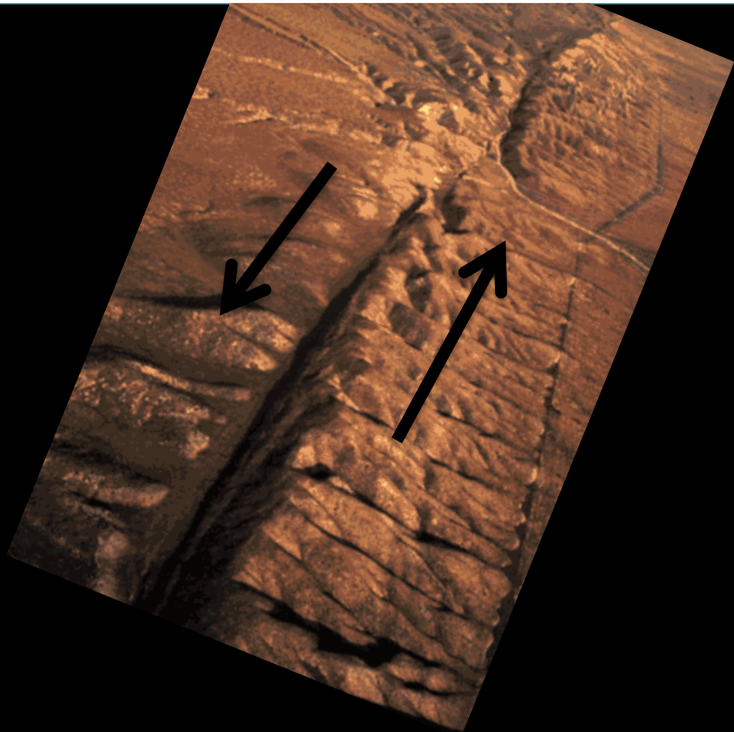
- earthquakes simply
- fault gouge a granular material
- earthquake triggering and clustering
- acoustic perturbation of granular material
- 3-D laboratory experiments
- DEM simulation
- summary

Plate tectonics and the engine below

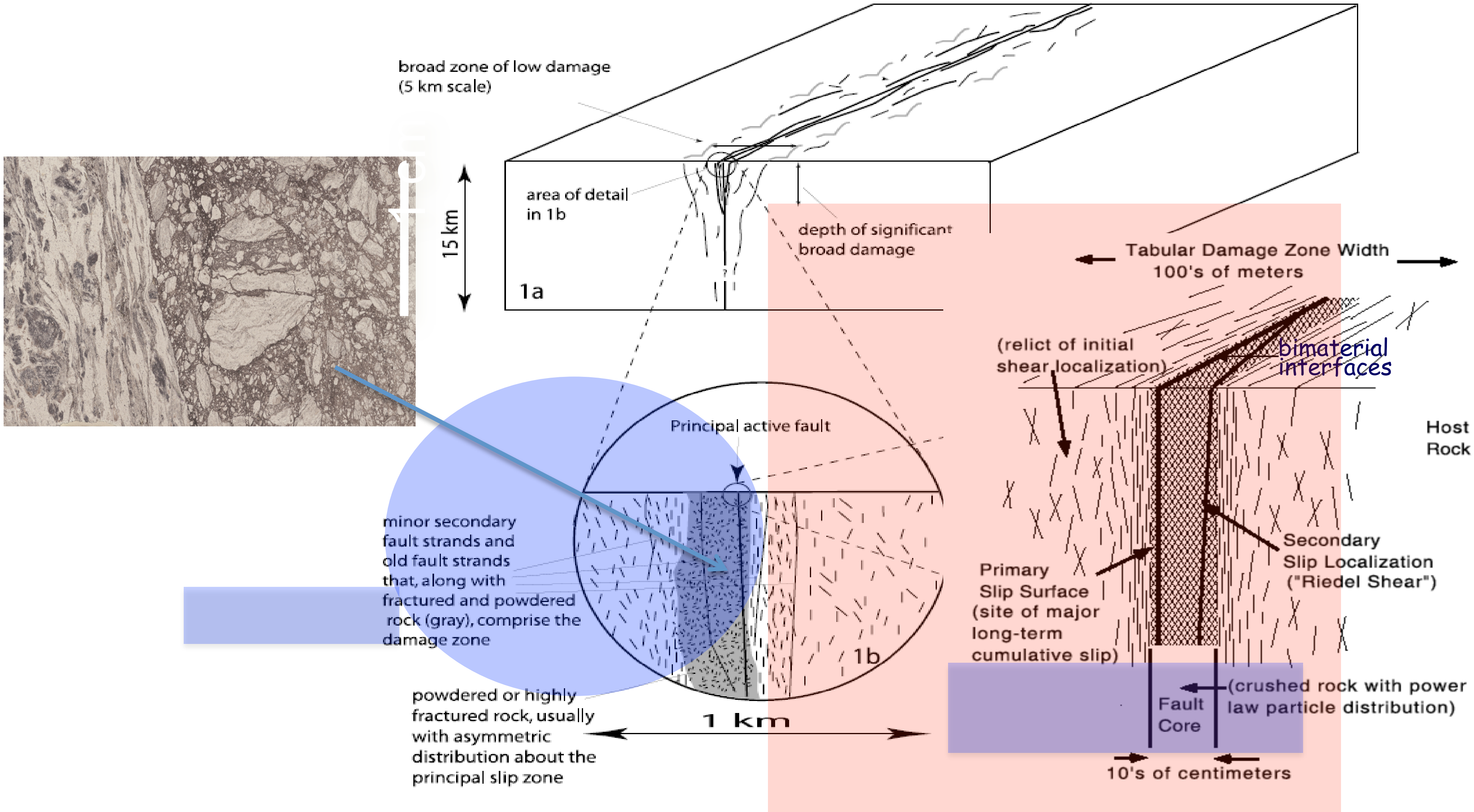
From the geo-Dharma
https://www.youtube.com/watch?v=ryrXAGY1dmE







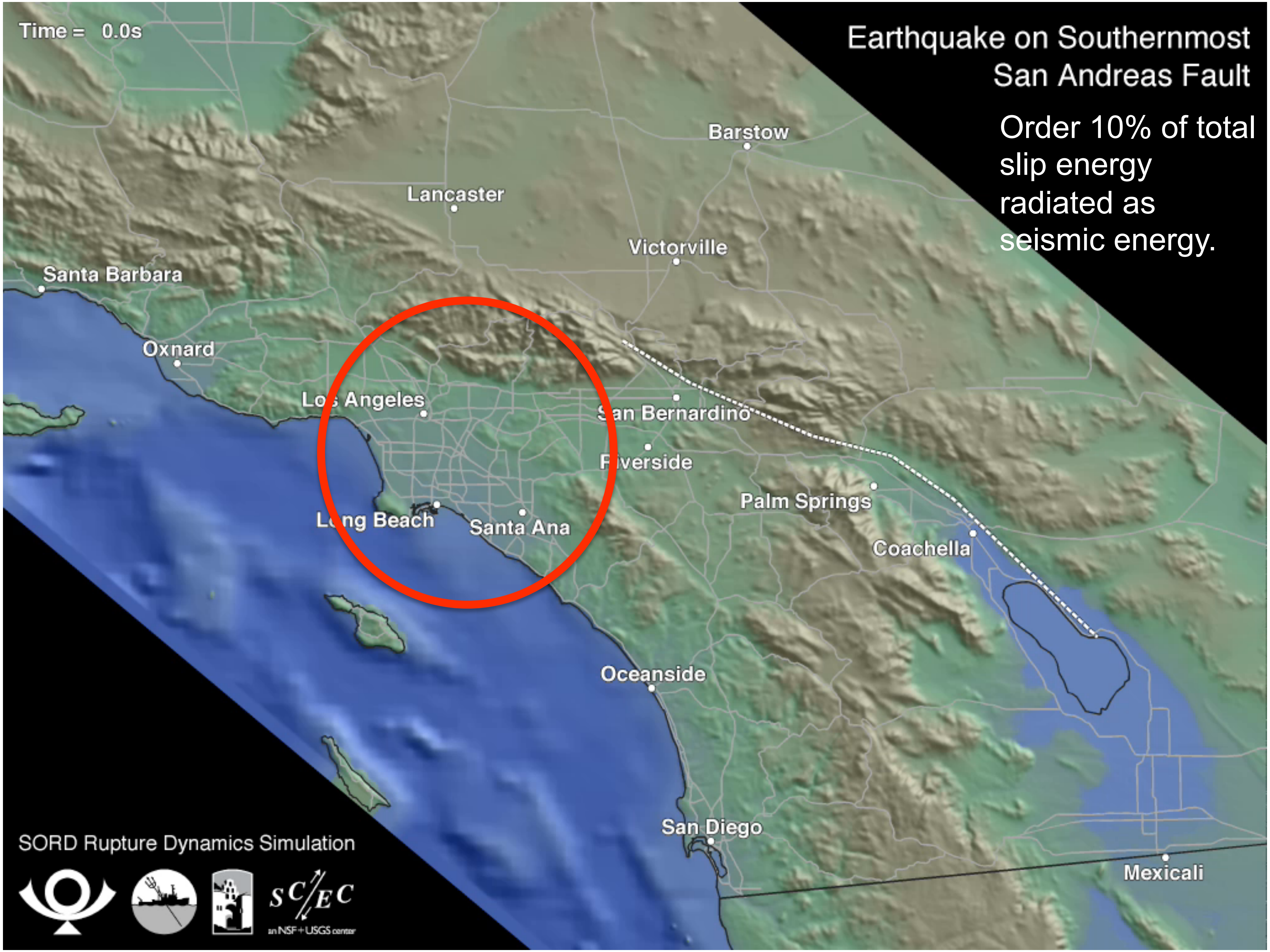
Multi-scale imaging of fault zone environments



Ben-Zion and Sammis (2003)
Rockwell and Ben-Zion (2007)

1957 rupture, Gobi-Altai fault, Mongolia

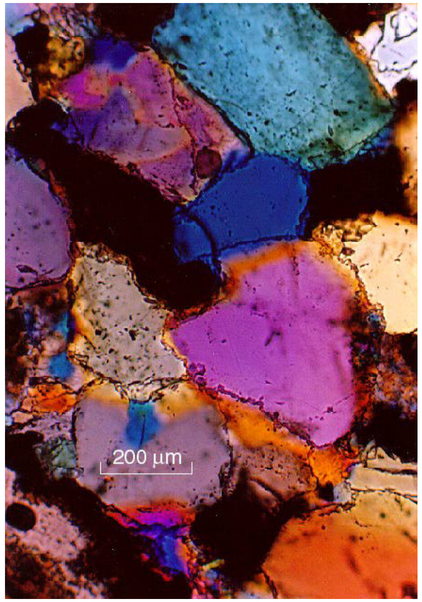
S. Marco (pers. Comm. Via Y. Ben Zion)


Time = 0.0s
Earthquake on Southernmost
San Andreas Fault
Order 10% of total slip energy radiated as seismic energy.
Barstow
Lancaster
Victorville
Santa Barbara
Oxnard
Los Angeles
San Bernardino
Riverside
Palm Springs
Long Beach
Santa Ana
Coachella
Oceanside
San Diego
Mexicali
SORD Rupture Dynamics Simulation
SCEC
an NSF+USGS center

Earthquake triggering and the role of granular media

Two types of triggering

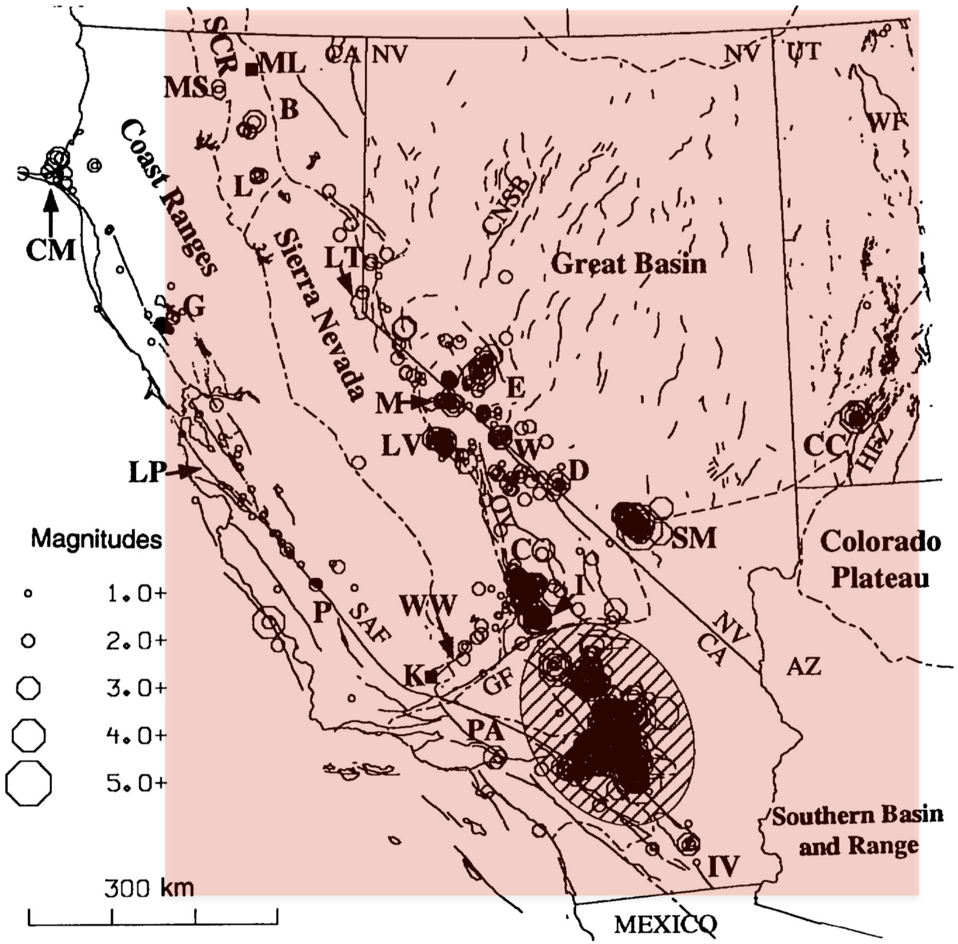
- Triggering in the region of an earthquake due to static stress changes ('aftershocks')
- Dynamic triggering locally and globally due to seismic waves



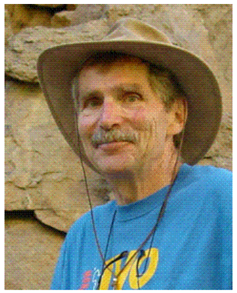

Christchurch, NZ
Earthquake Sequence
08/01/2010 - 03/13/2011
Christchurch

A tremor and earthquake triggering scenario

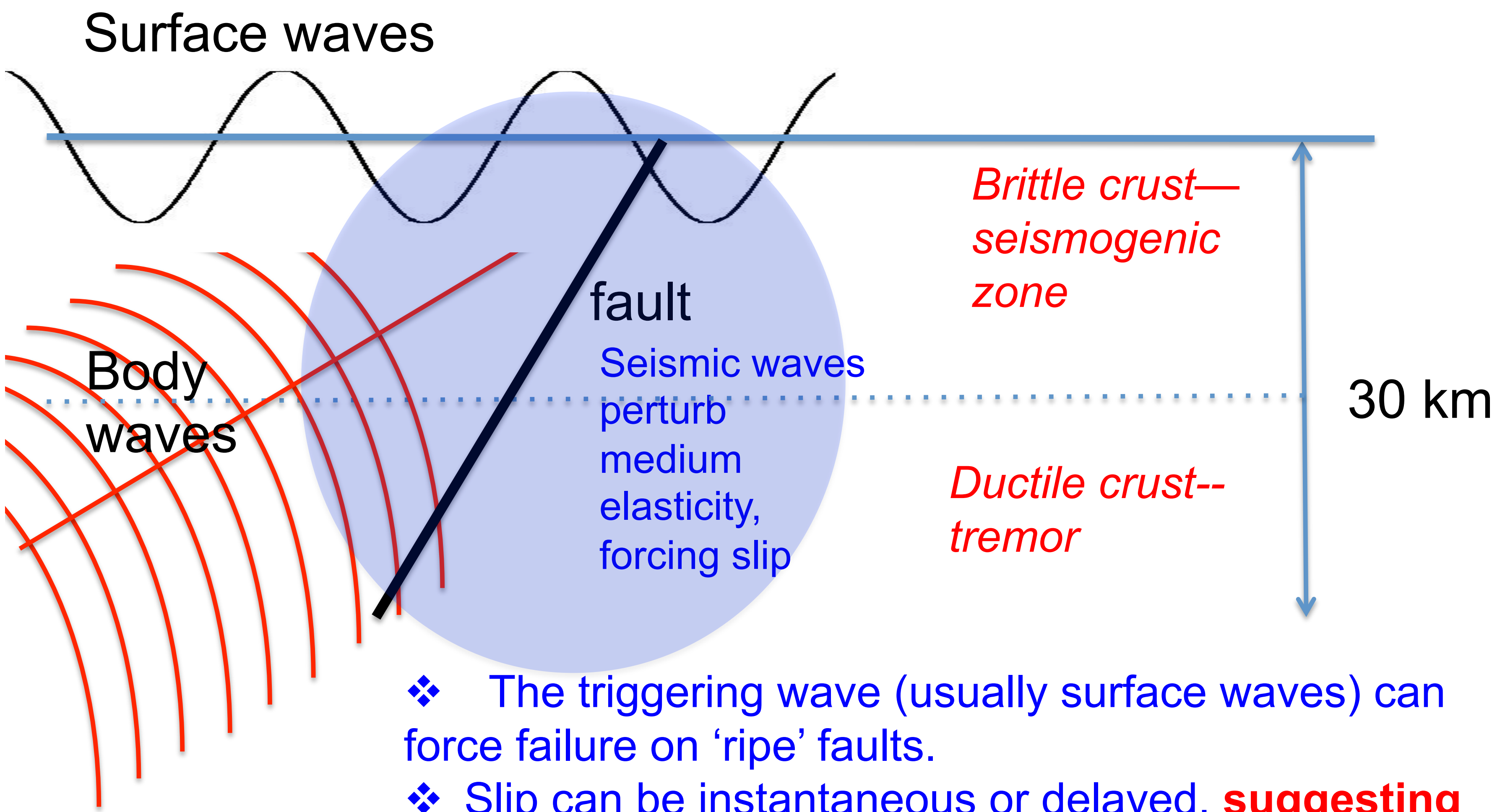
Triggering due to the 1992 M7.2 Landers earthquake



Hill et al., Science (1993)



Concept of triggered elasticity perturbation and its signatures

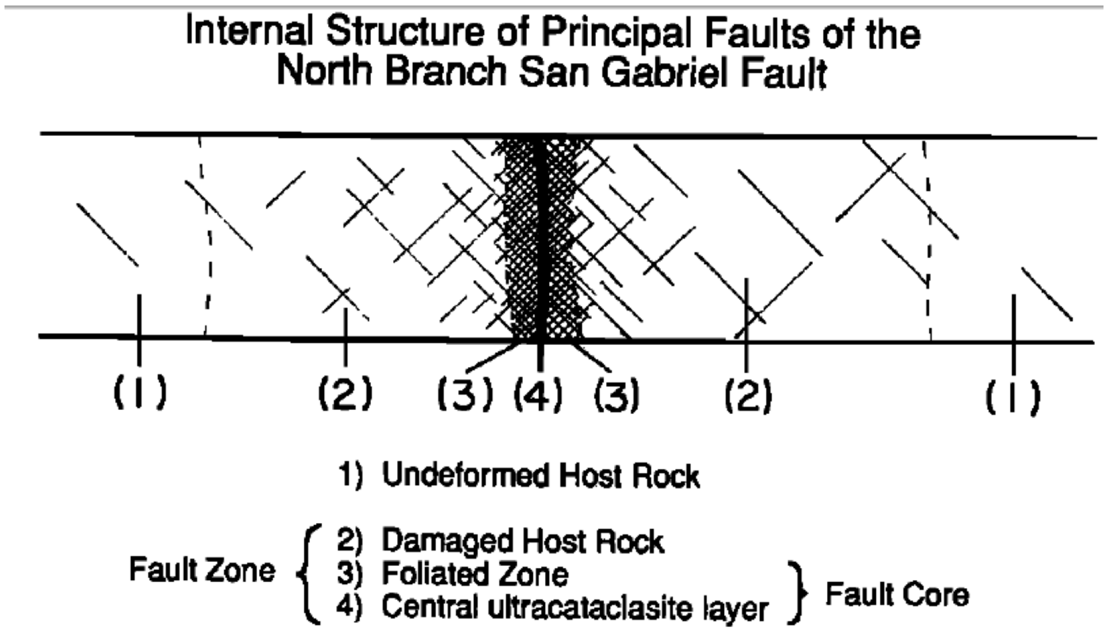


- The triggering wave (usually surface waves) can force failure on 'ripe' faults.
- Slip can be instantaneous or delayed, **suggesting an elastic perturbation that remains well after the triggering waves have passed.**

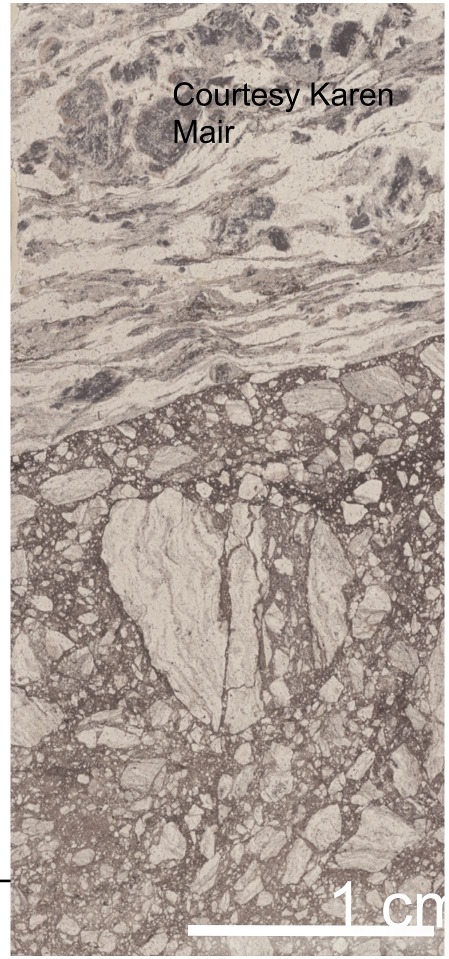
Laboratory Triggering constraints

To date, in lab studies we can only trigger in when we have fault gouge in the system*– blocks sheared face-to-face do not trigger.

We hypothesize that nonlinear granular physics is key to the triggering process.



Chester et al., *J. Geophys. Res.* (1993)

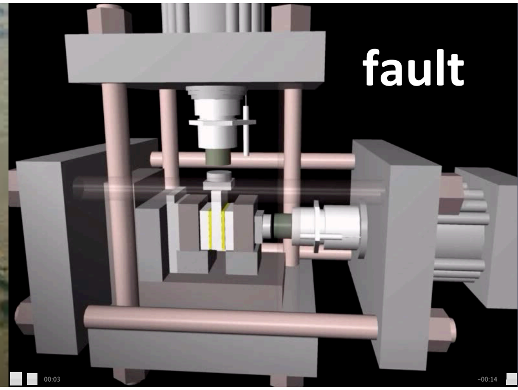


* Experiments at PSU and at INGV, Rome

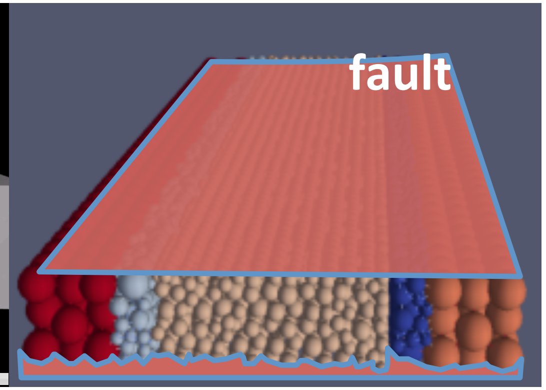
Laboratory Fault Studies

in the field

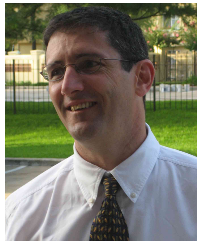
in the laboratory



numerical

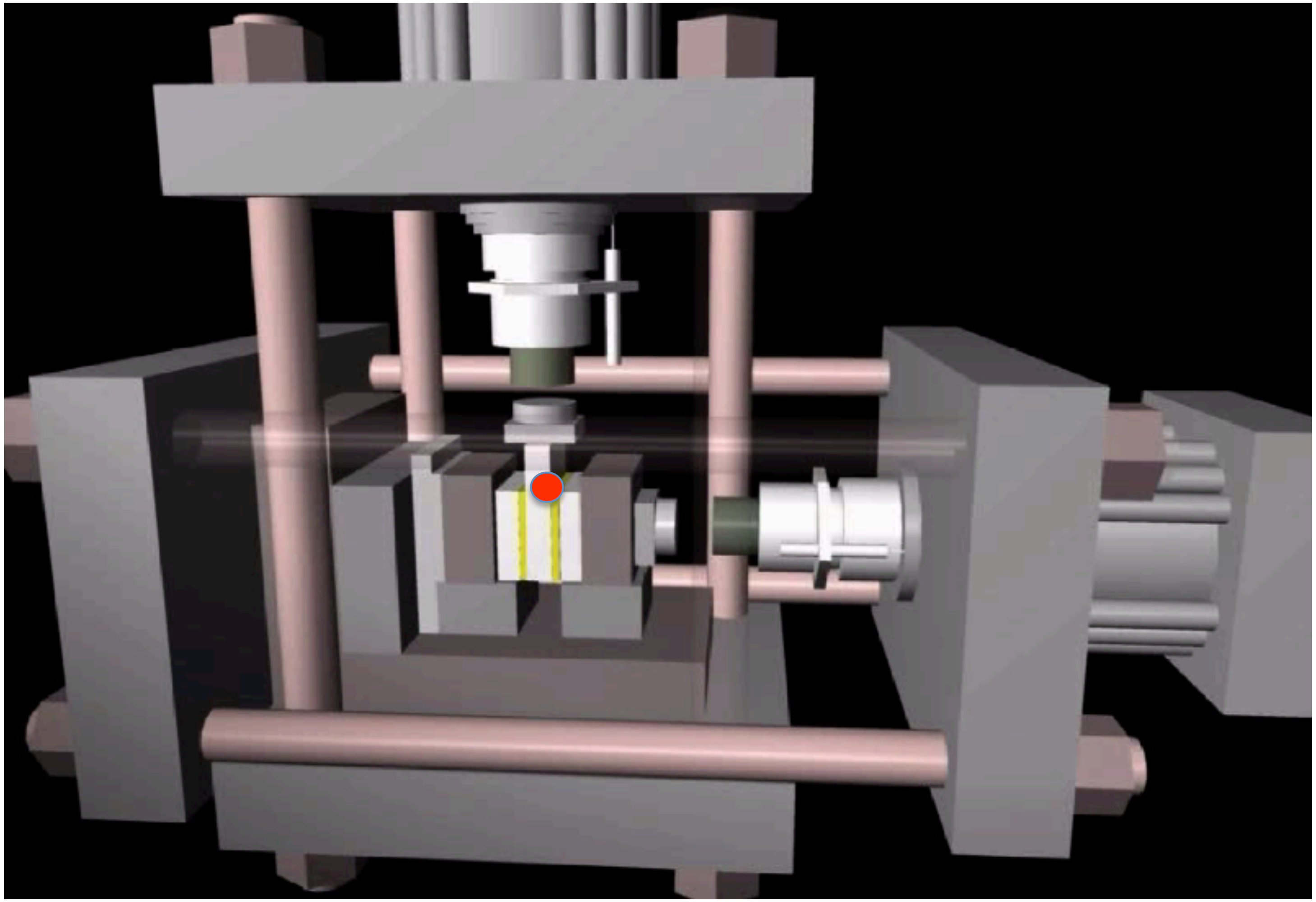


3-D slip experiments

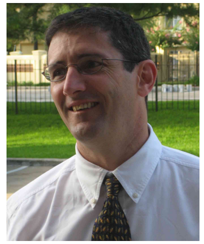


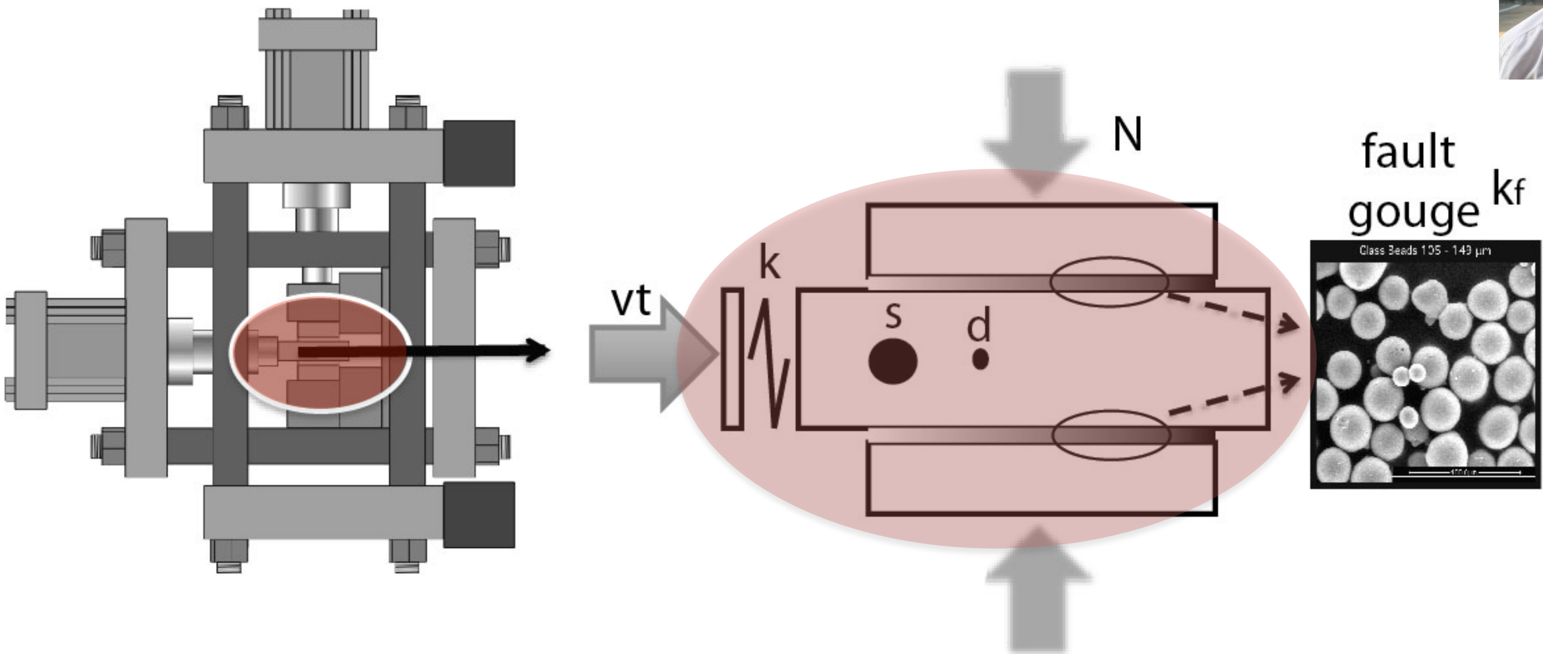
Chris Marone,
Penn State
University, USA

Experimental simulation



Earthquake machine at Pennsylvania State University

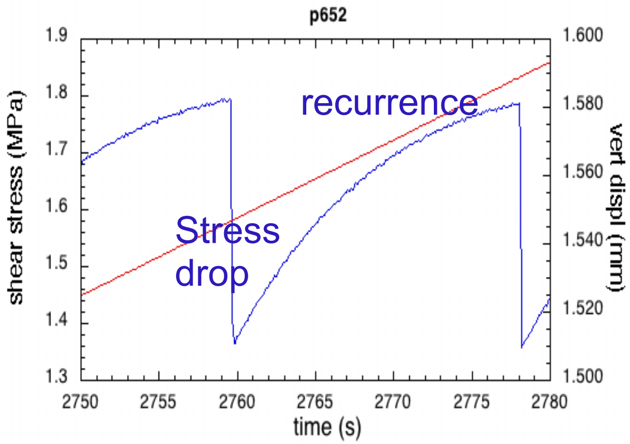


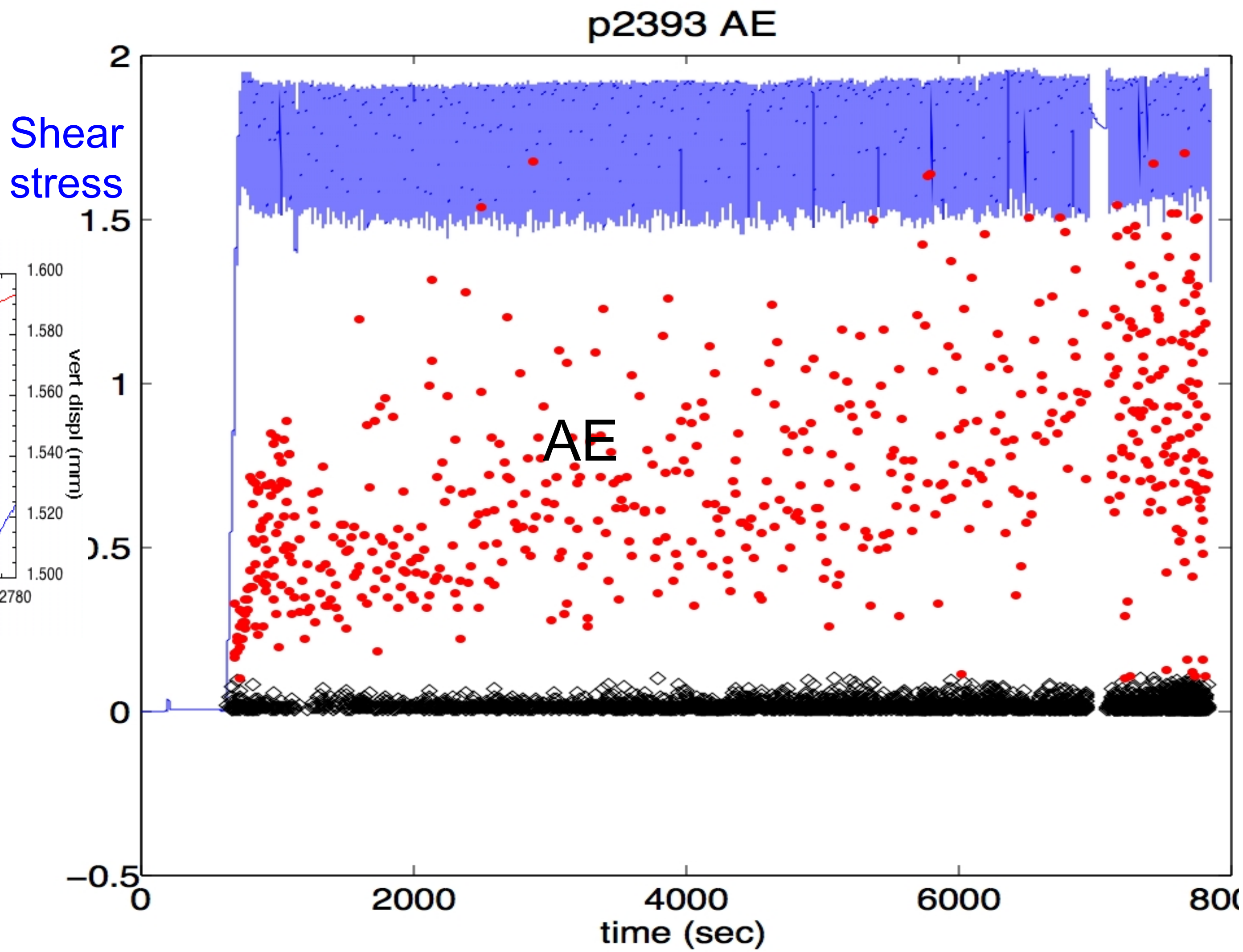


- 1-10 MPa normal stress
- background shear loading rate of 1-100 μm/sec
- 3 mm layers of soda lime beads
- 0.105-0.149 mm size distribution

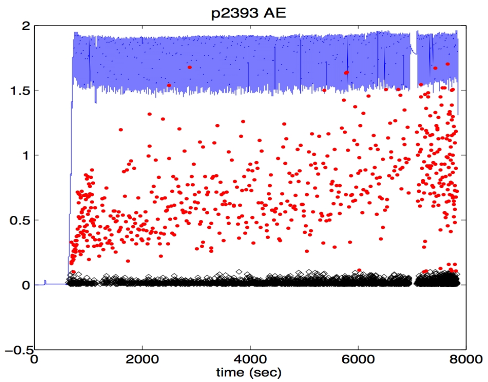
$K >> k_F$

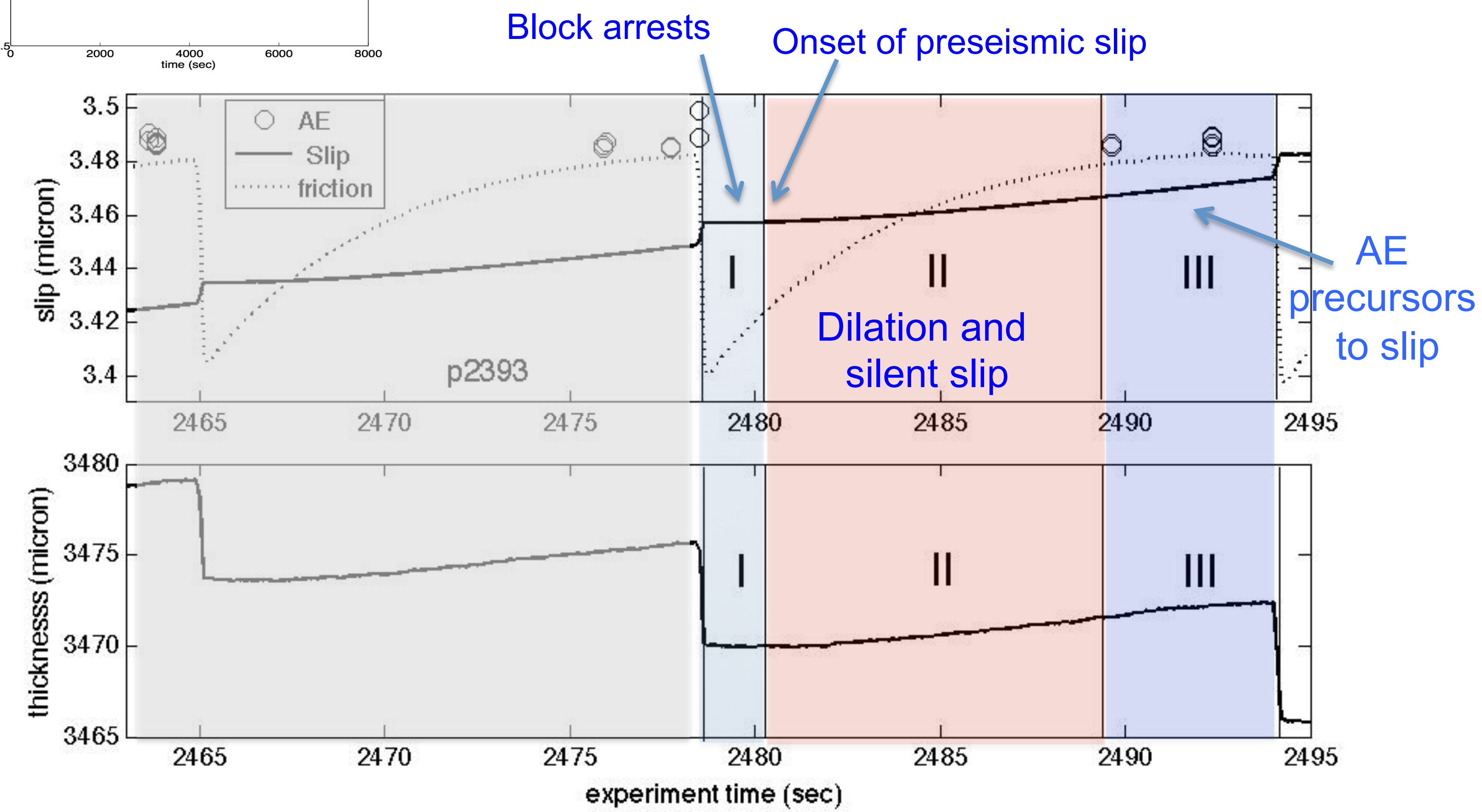
Slip events and acoustic emission in a typical experiment



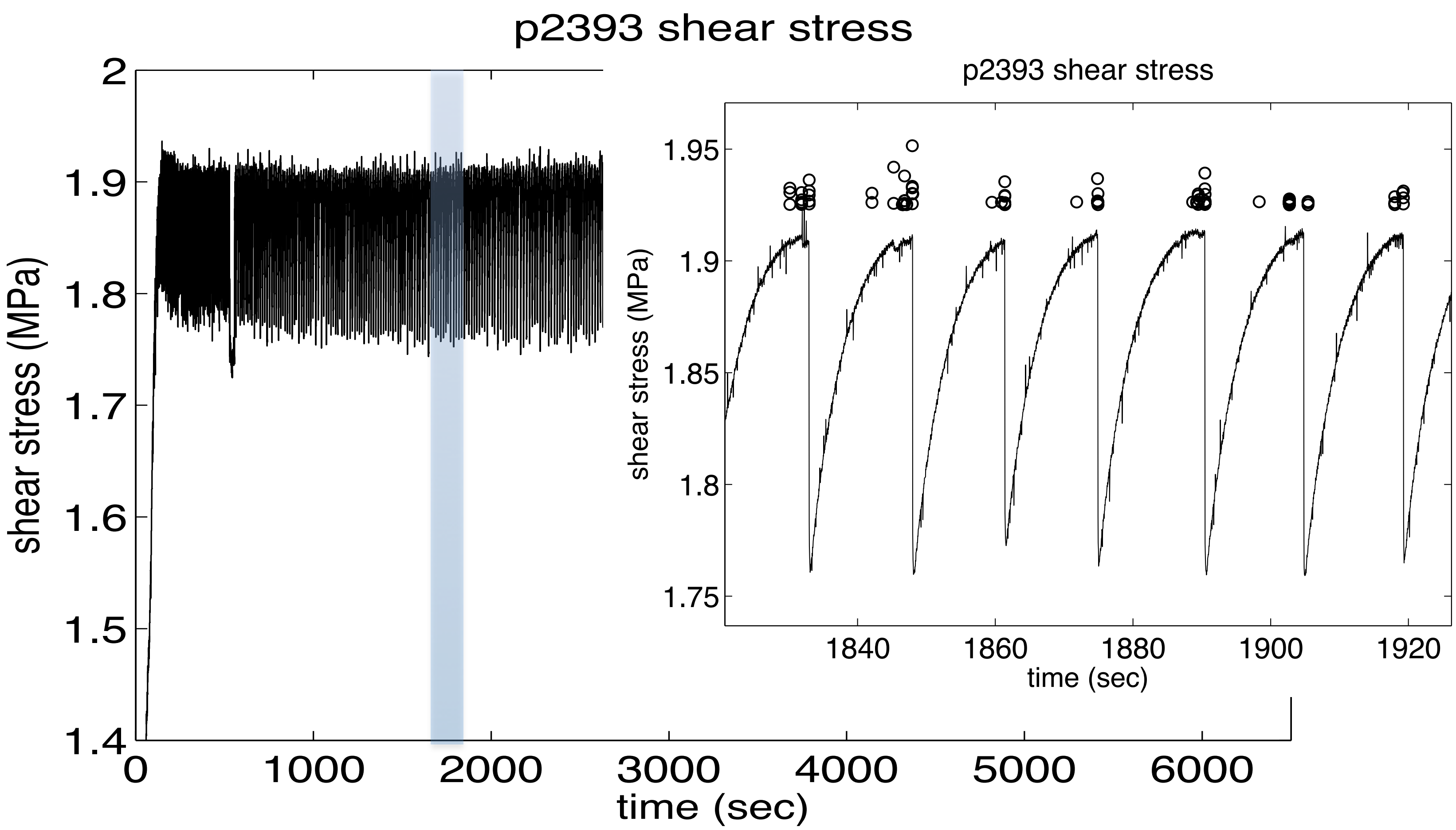


Stick-slip instabilities



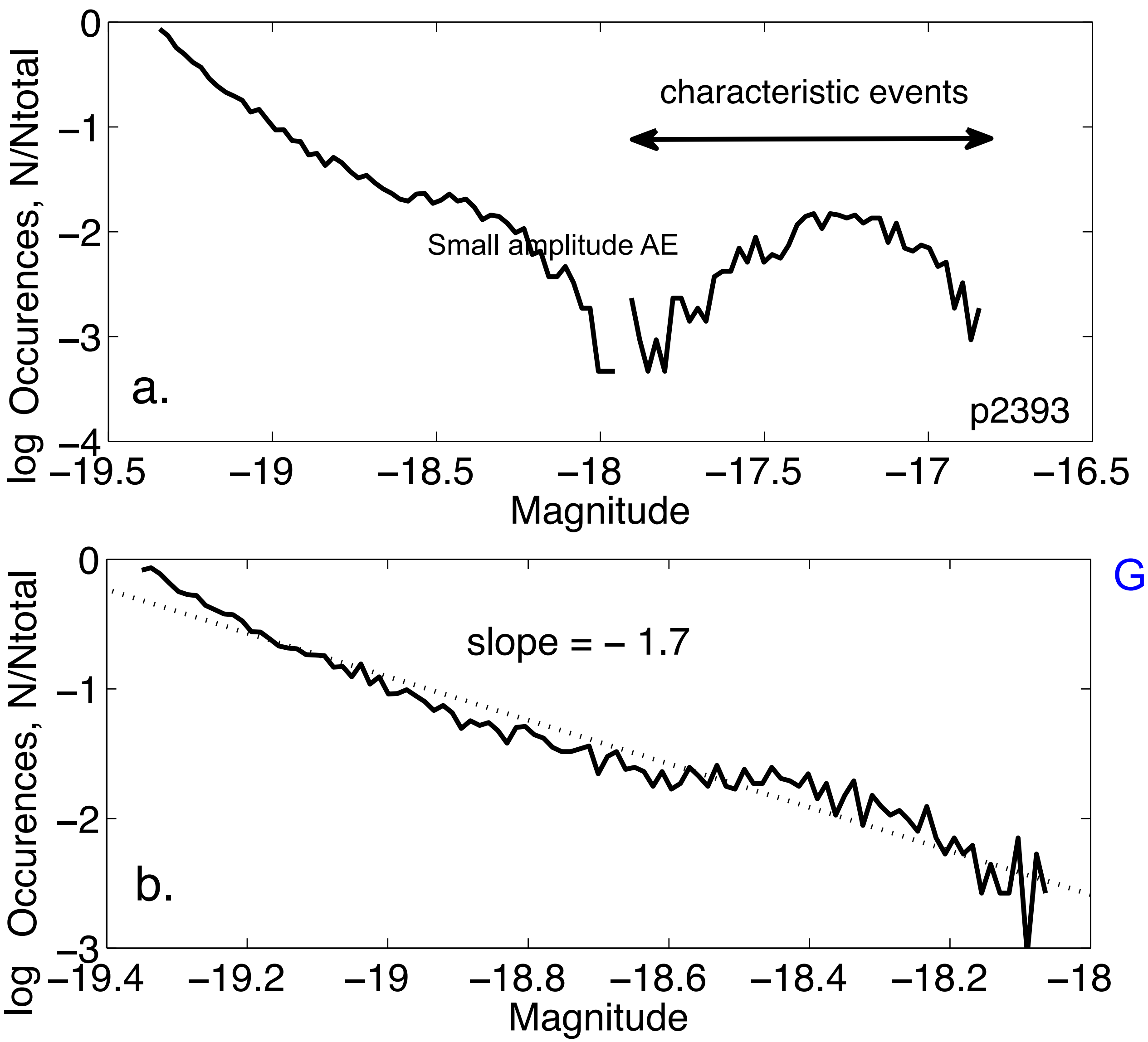


Slip events and acoustic emission in a typical experiment



Johnson et al., GRL 2014

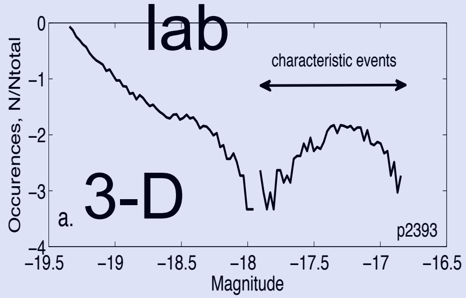
AE occurrence

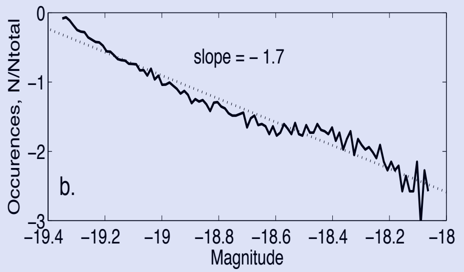


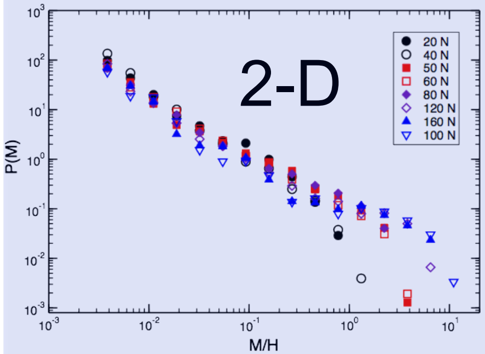
Global average of slope=1

Johnson et al., in preparation, 2013

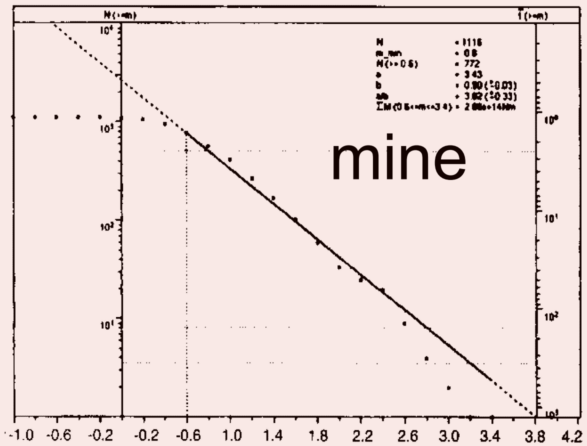
lab

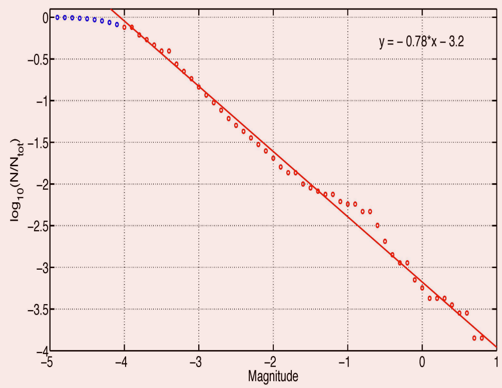






mine



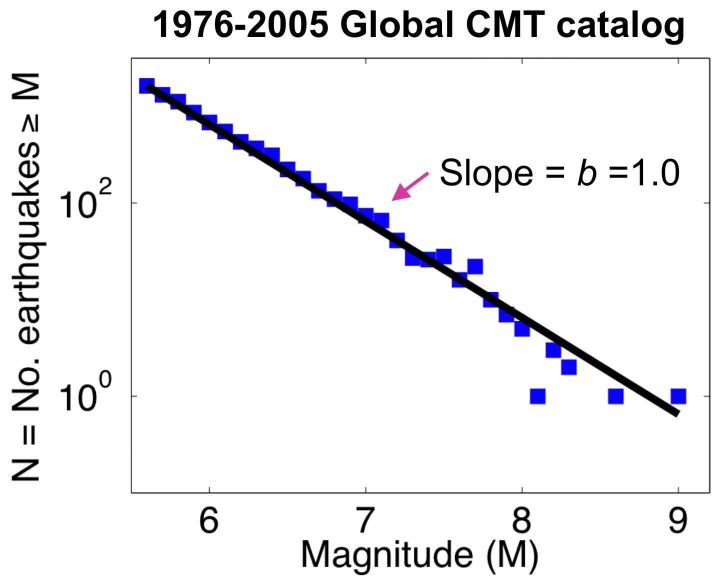


Increasing magnitude

Mine events, Mendecki, 2001

Global earth

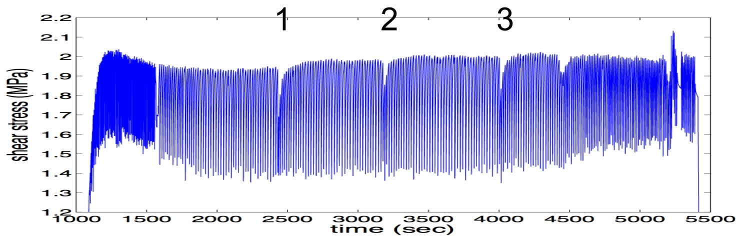
The Global Centroid-Moment-Tensor (CMT) catalog



$\log(N) = a - bM$

Feltzer, AGU Fall Meeting 2006

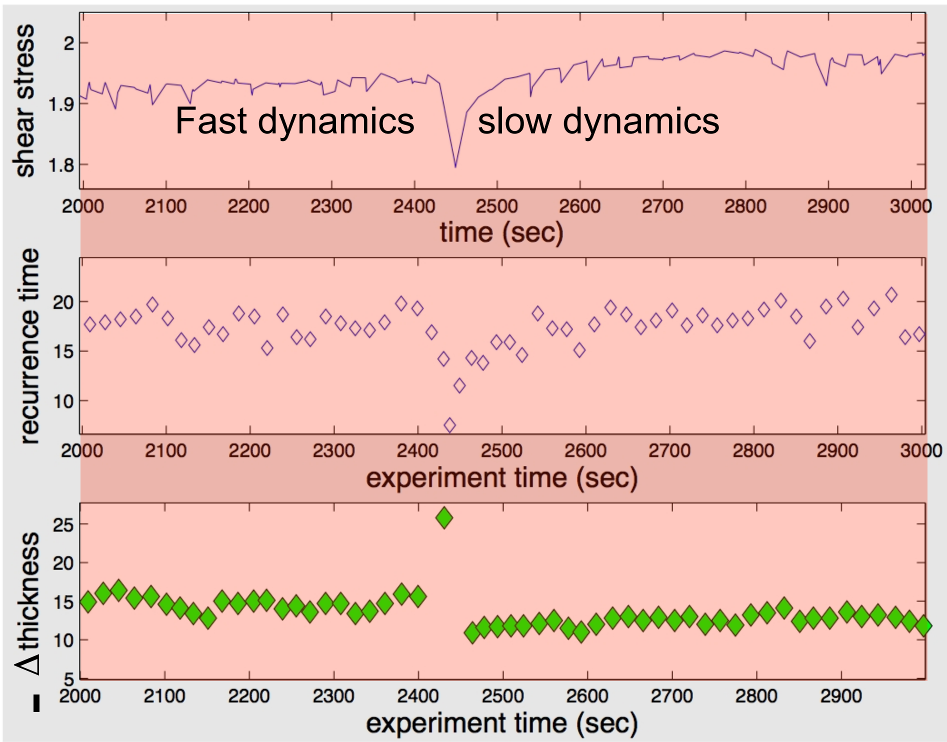
triggered slip and long recovery



p1894, 5MPa

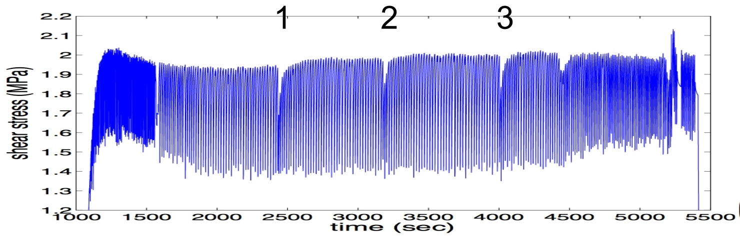
Without dynamic waves, inter-event time and thickness are ~constant

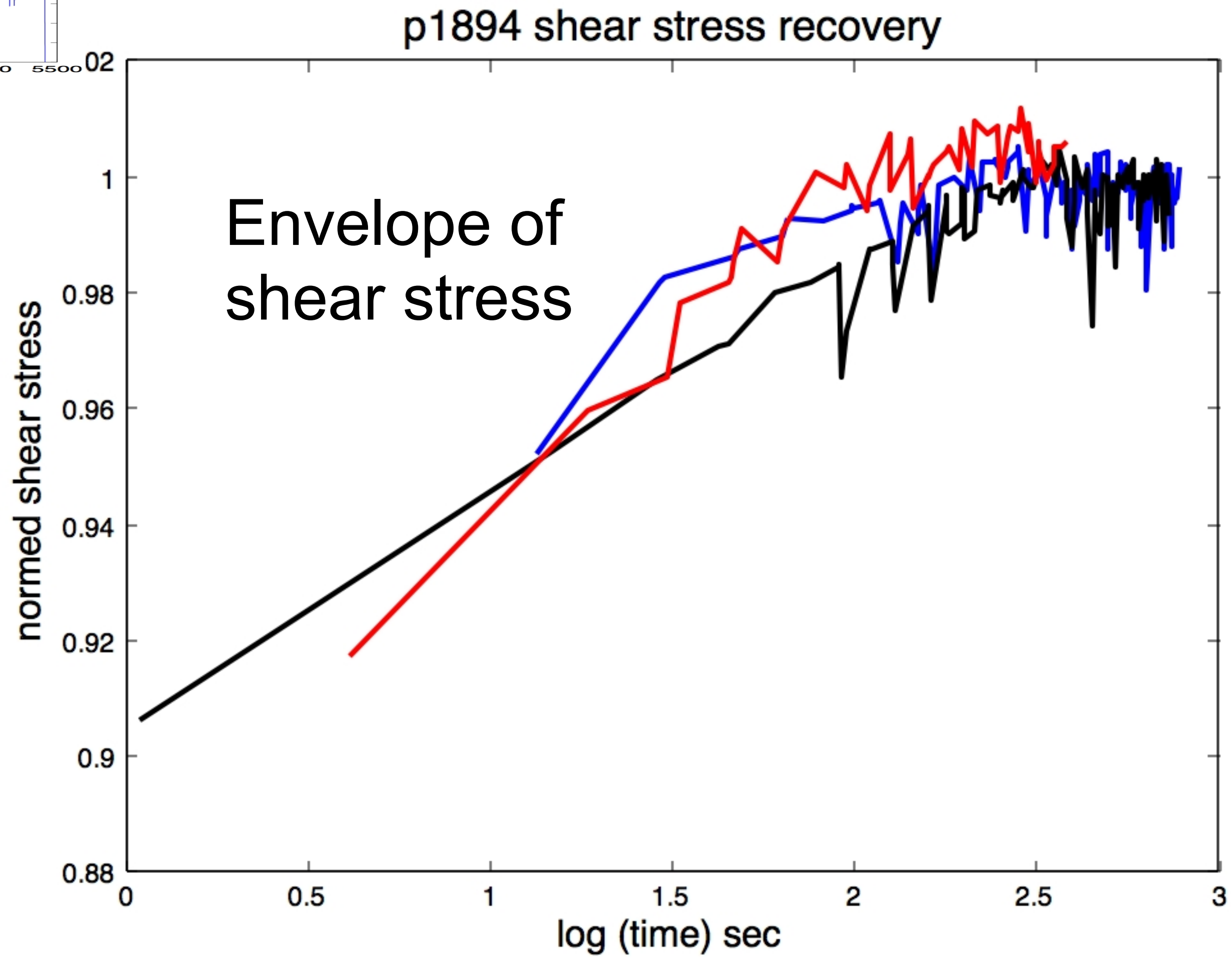
Dynamic strain ~10^{-6}



Johnson, Proc. Int. Symp NL Acoust., Tokyo, 2012

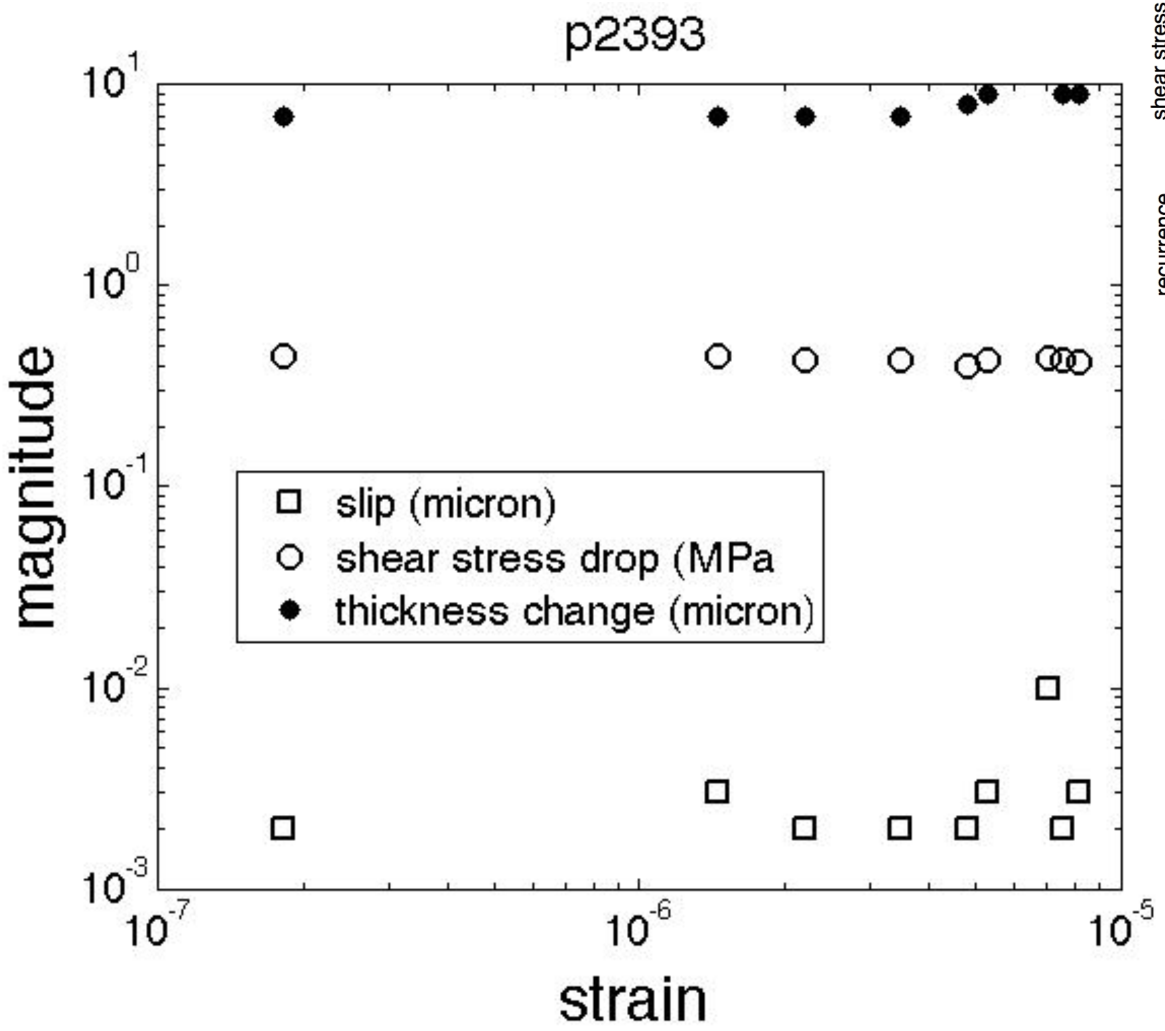
Recovery phenomena: shear stress

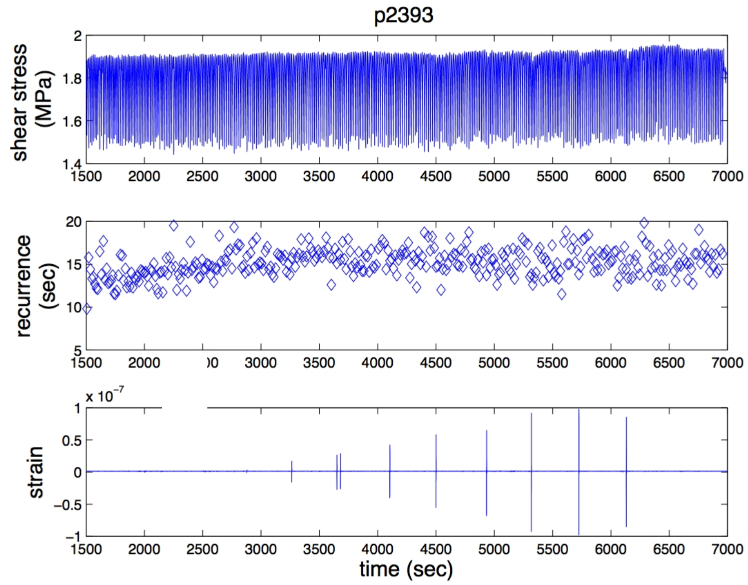




Johnson, Proc. Int. Symp NL Acoust., Tokyo, 2012

Effects of amplitude of triggering wave



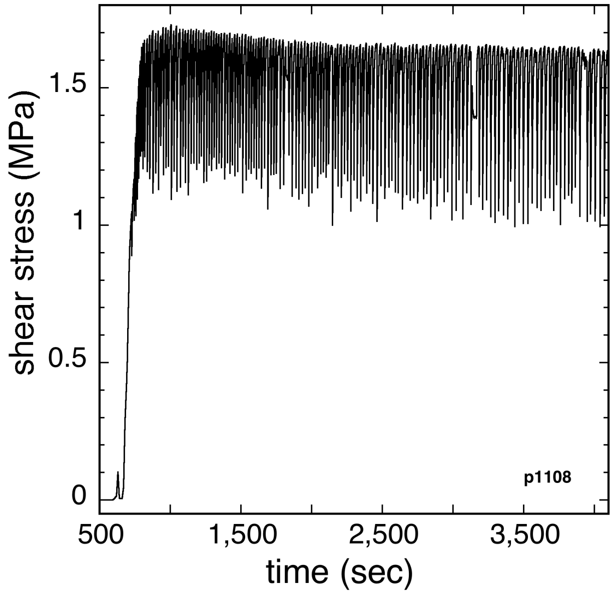


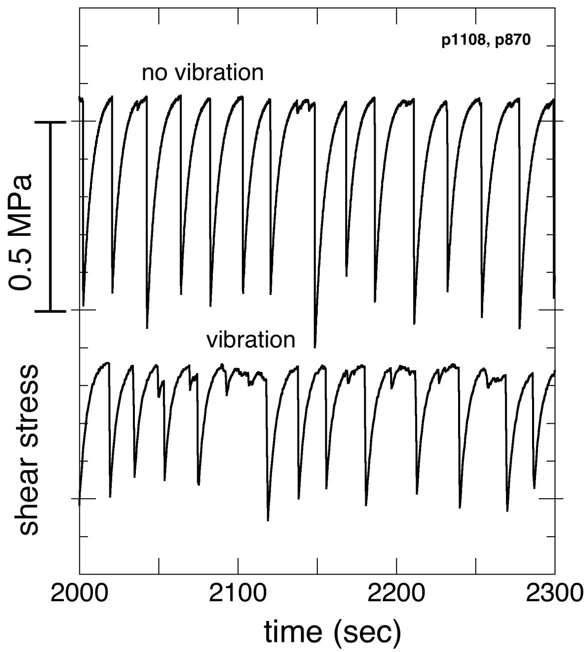
No evidence for an amplitude effect– Coulomb type failure?; however, **long lived memory effect**.

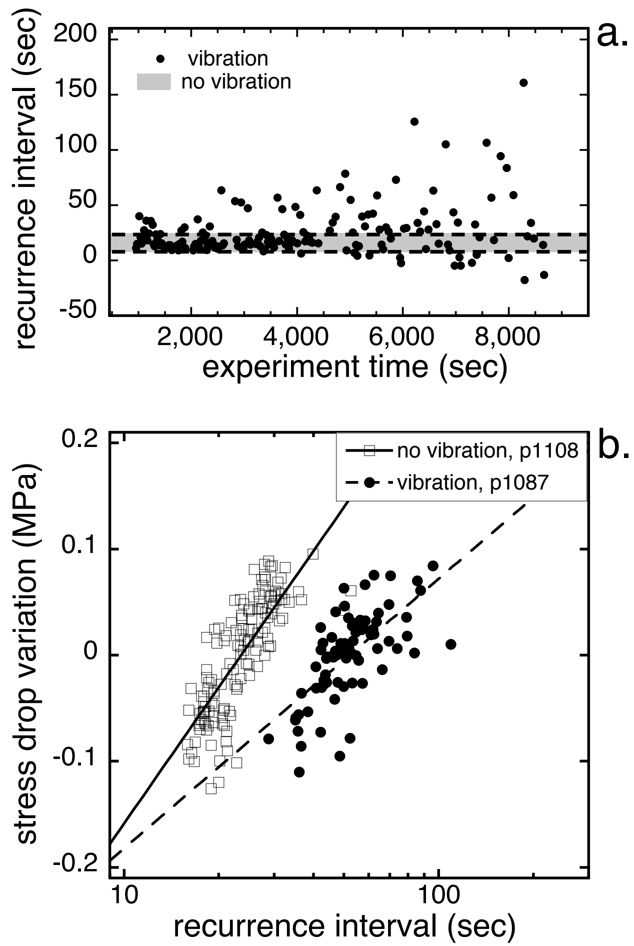
Complex mix of static shear and dynamic effects

Johnson et al., J. Geophys. Res. 2012

Many acousticial excitations





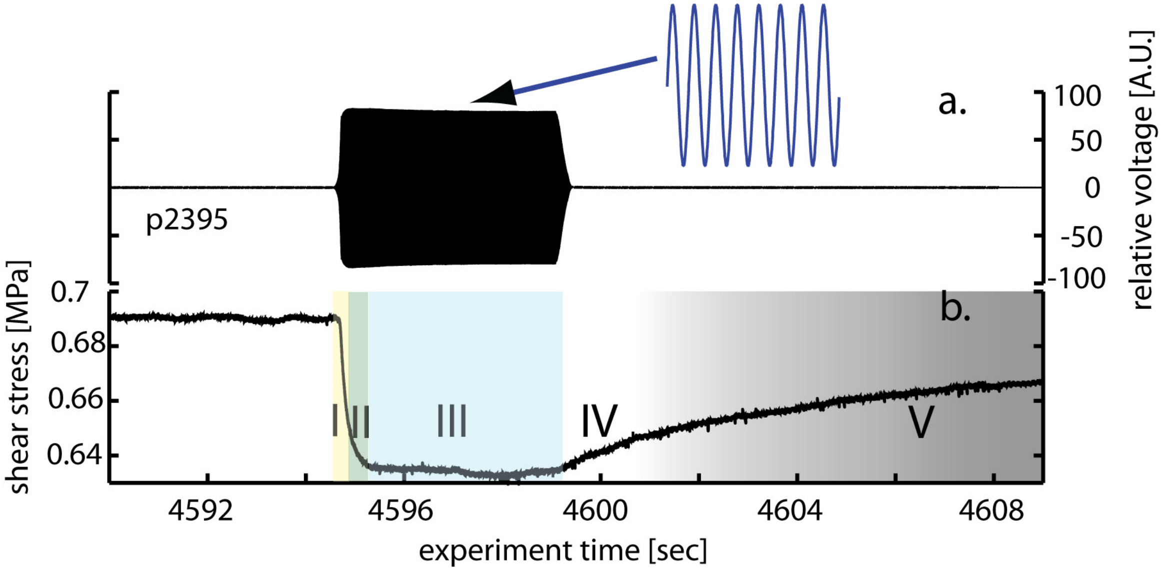


Johnson et al., Nature, 2008

2007-02-02058B Figure 4

Acoustical fluidization at smaller load: slow, slip

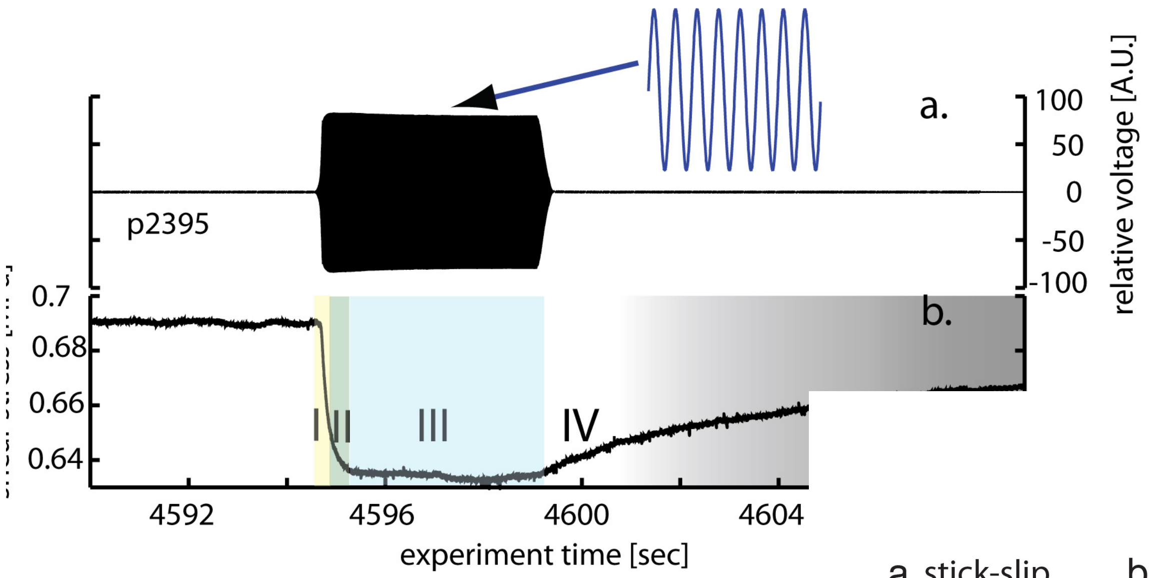
2 Mpa load

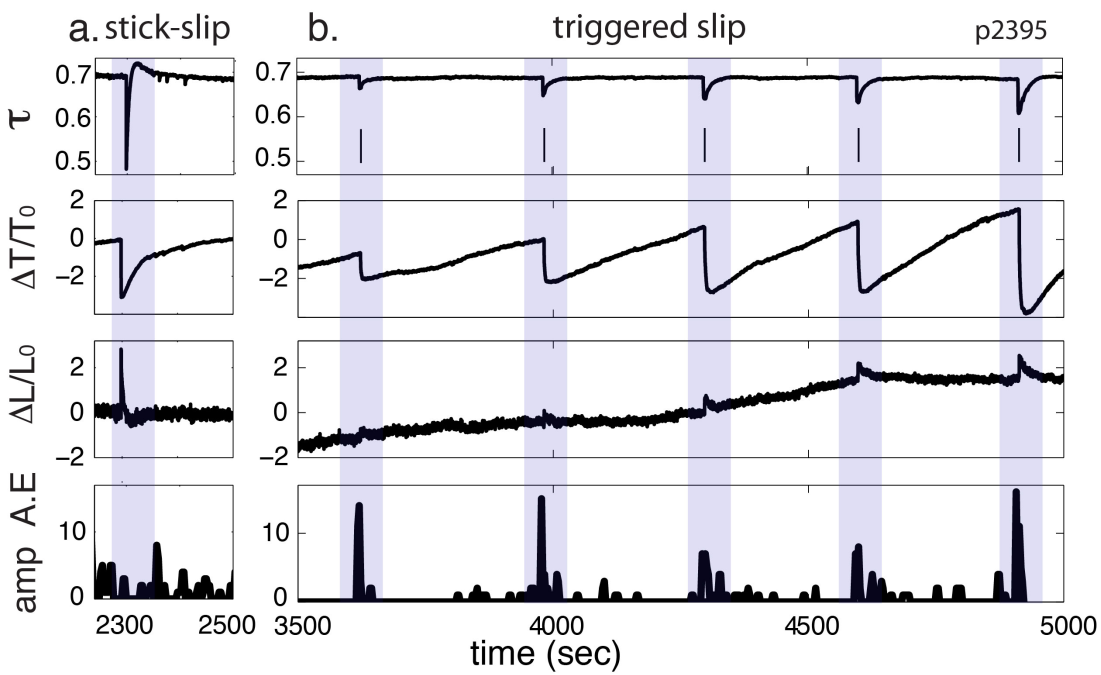


Triggering slow slip only occurs at loads <=3 Mpa; we are approaching plasticity at these pressures.

Johnson et al., Journal of Geophysical Research, 2012

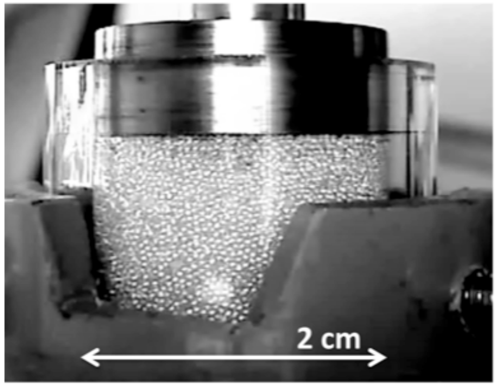
Triggered “*slow slip*”= *acoustical fluidization*

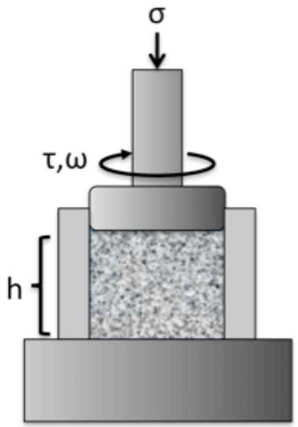


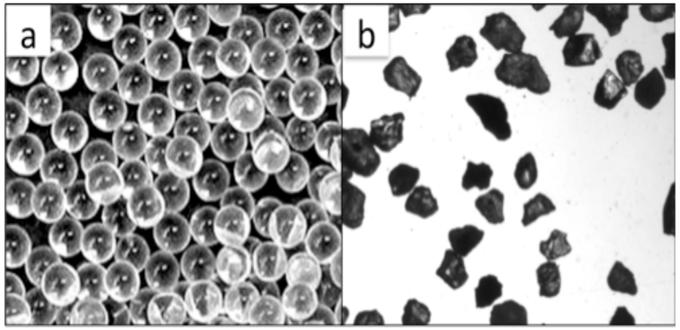


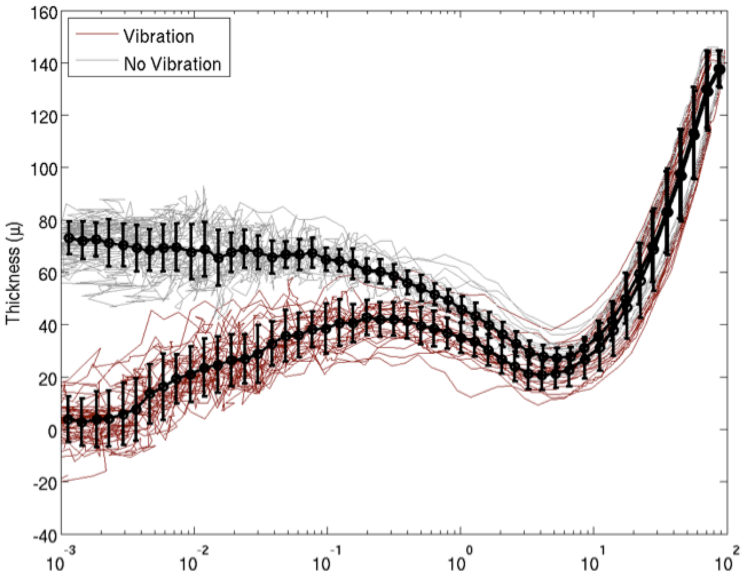
Johnson et al., Journal of Geophysical Research, 2013

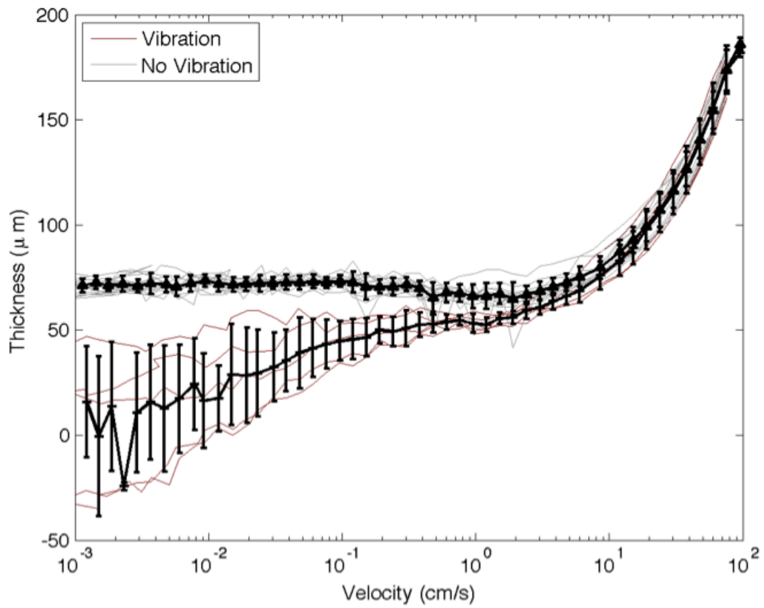
Recall J. Langer presentation:Experiment in rheometer





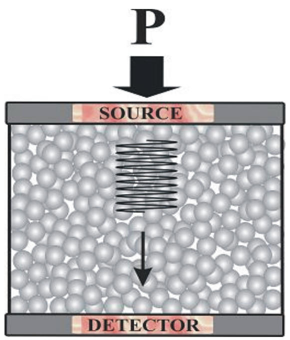


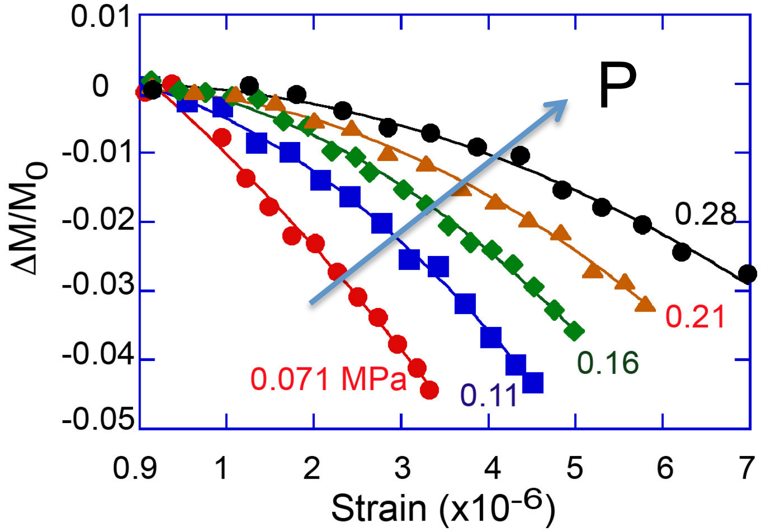




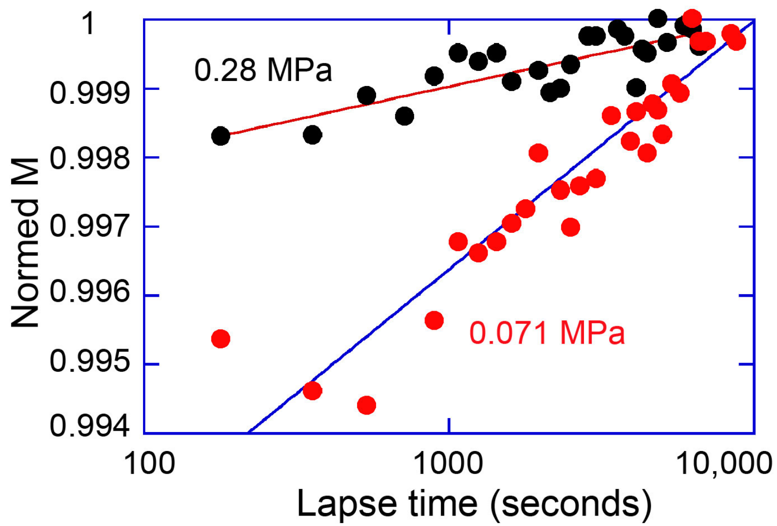
effects of elastic/plastic nonlinearity in laboratory experiments

Experiments with rock and canisters of glass beads





Decrease in modulus and increase in dissipation with wave amplitude.
We hypothesize that this may lead to softening and destabilization

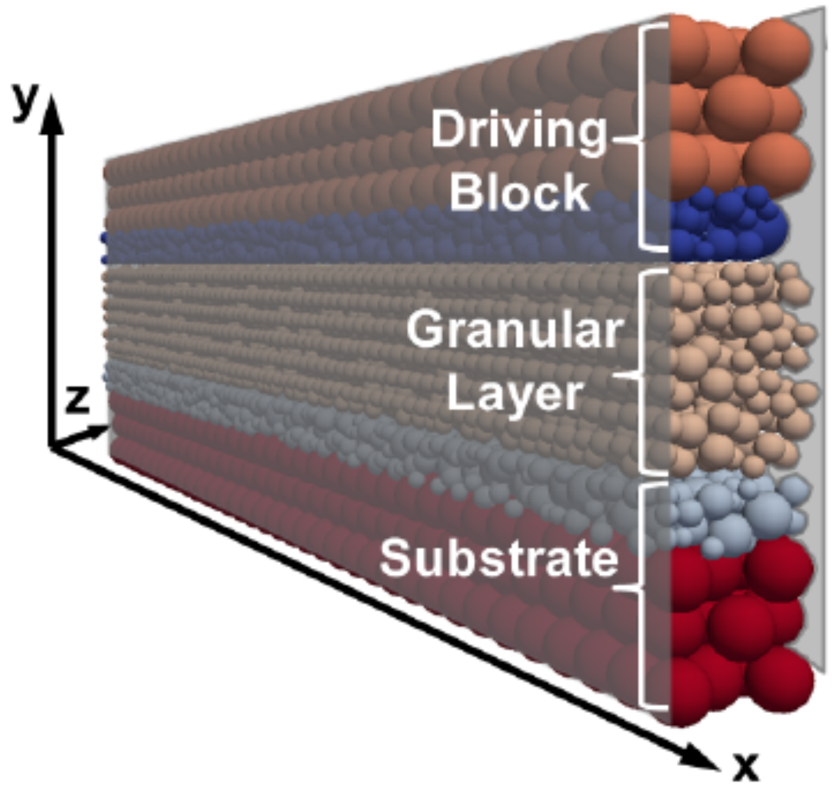


Long recovery to equilibrium (the slow dynamics)

Modified from Johnson and Jia, *Nature*, 2005

DEM simulation

DEM model of Gouge layer



Hexagonal Close Packing driving layer

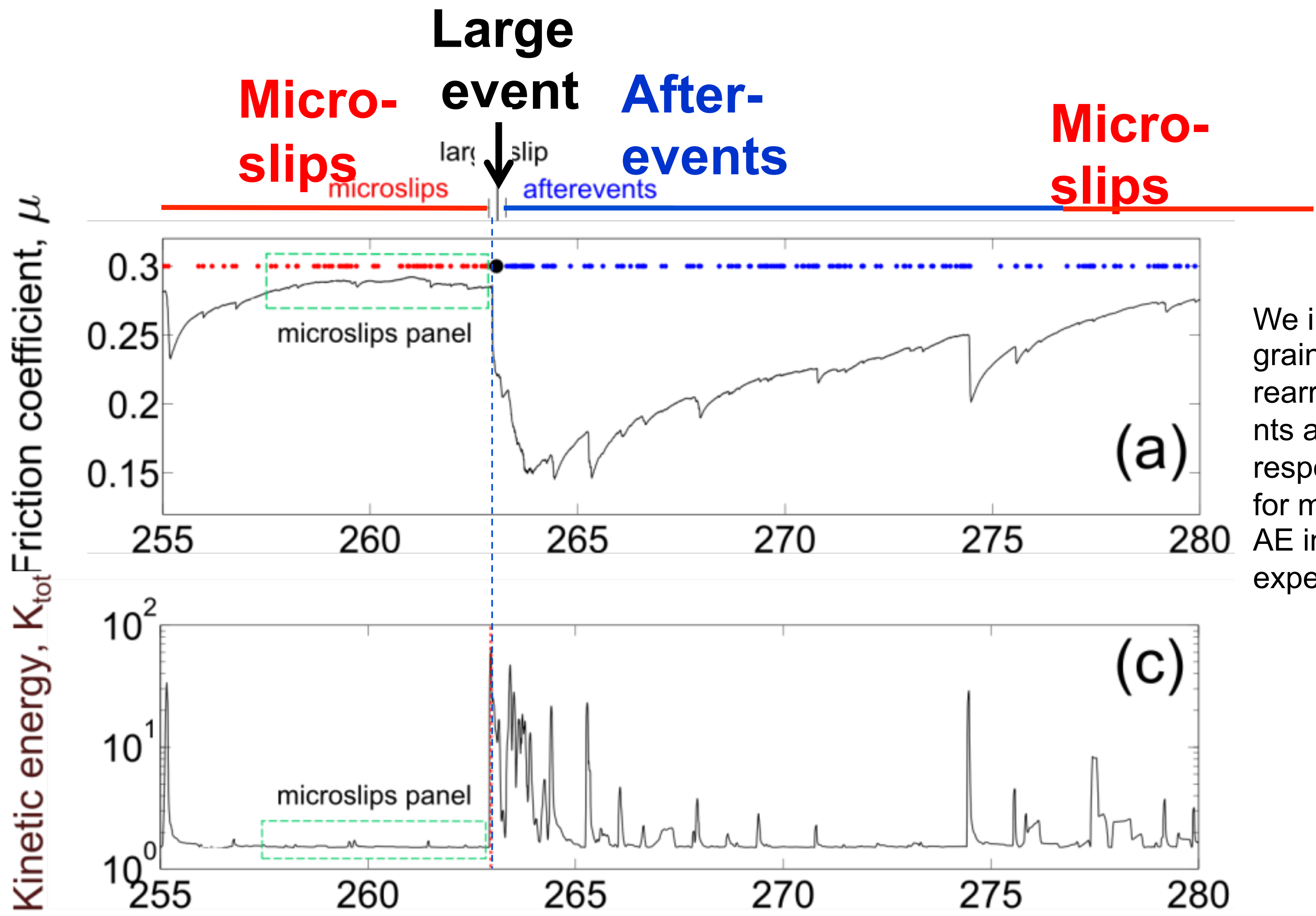
roughness layer

gouge layer unbonded particles with size distribution

100 – 150 μm

Ferdowsi et al., Geophys. Res. Lett., in review 2013

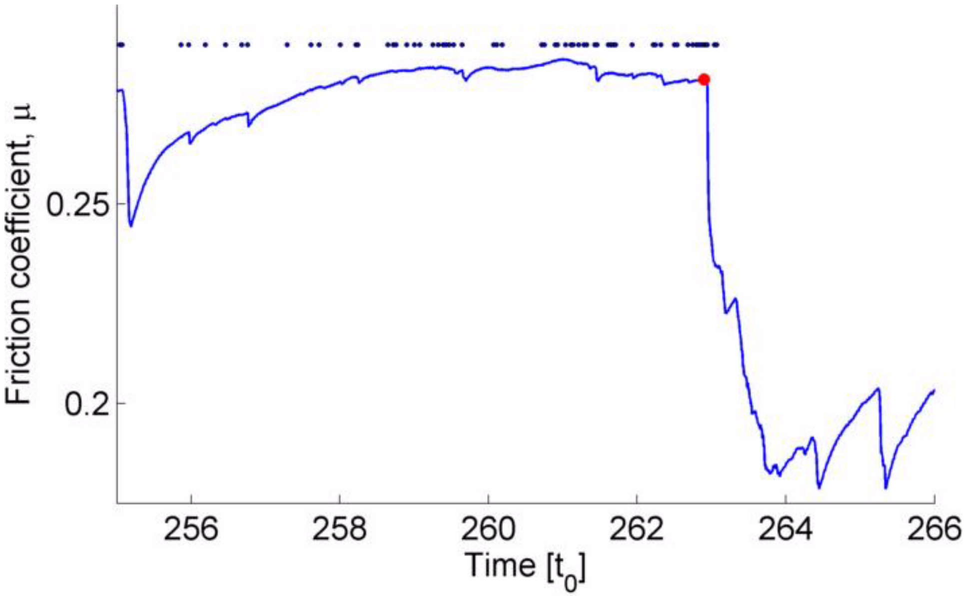
Slips associated with kinetic energy release

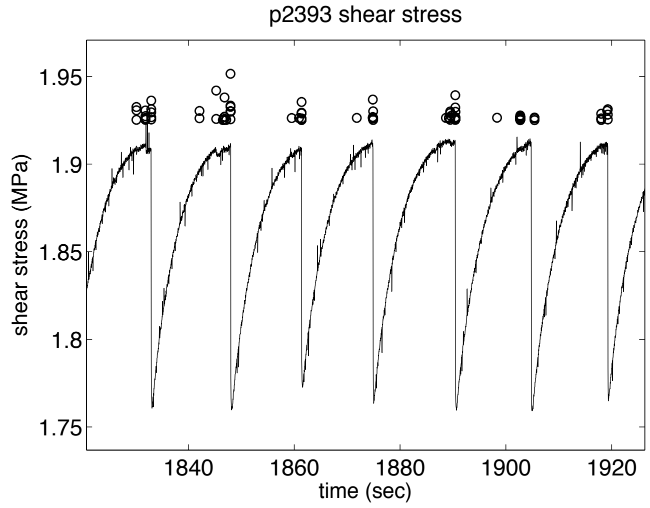


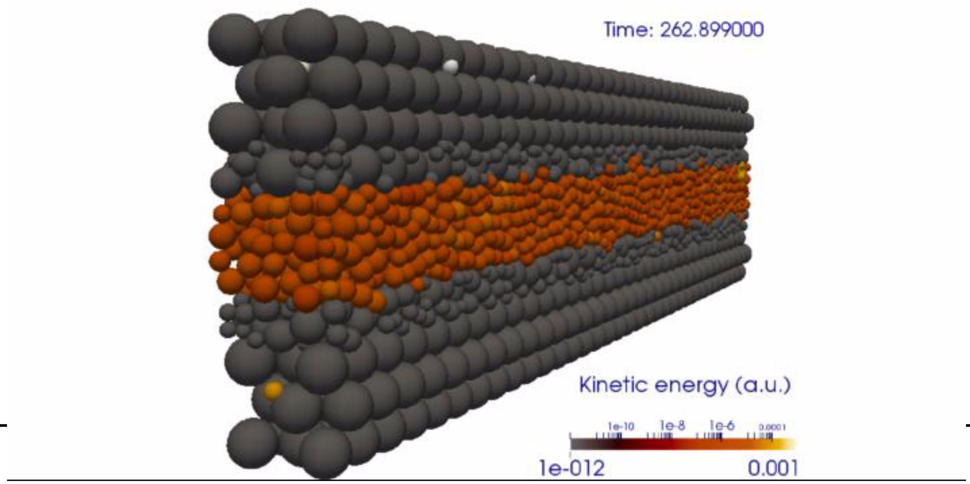
We infer that grain rearrangements are responsible for micrslips/ AE in the lab experiments

Ferdowsi et al., in review 2013

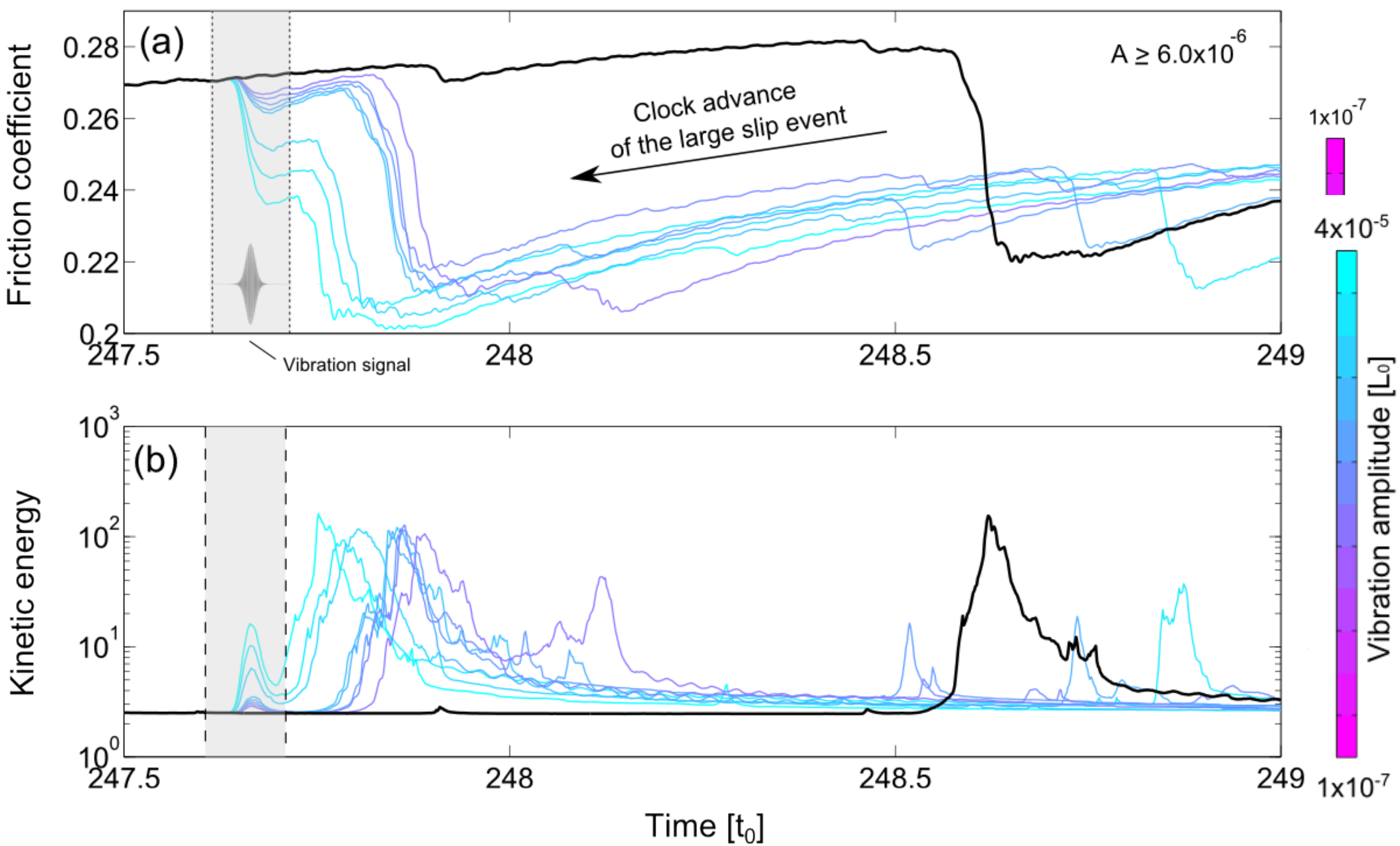
DEM: Precursors and slip event:
Energy release





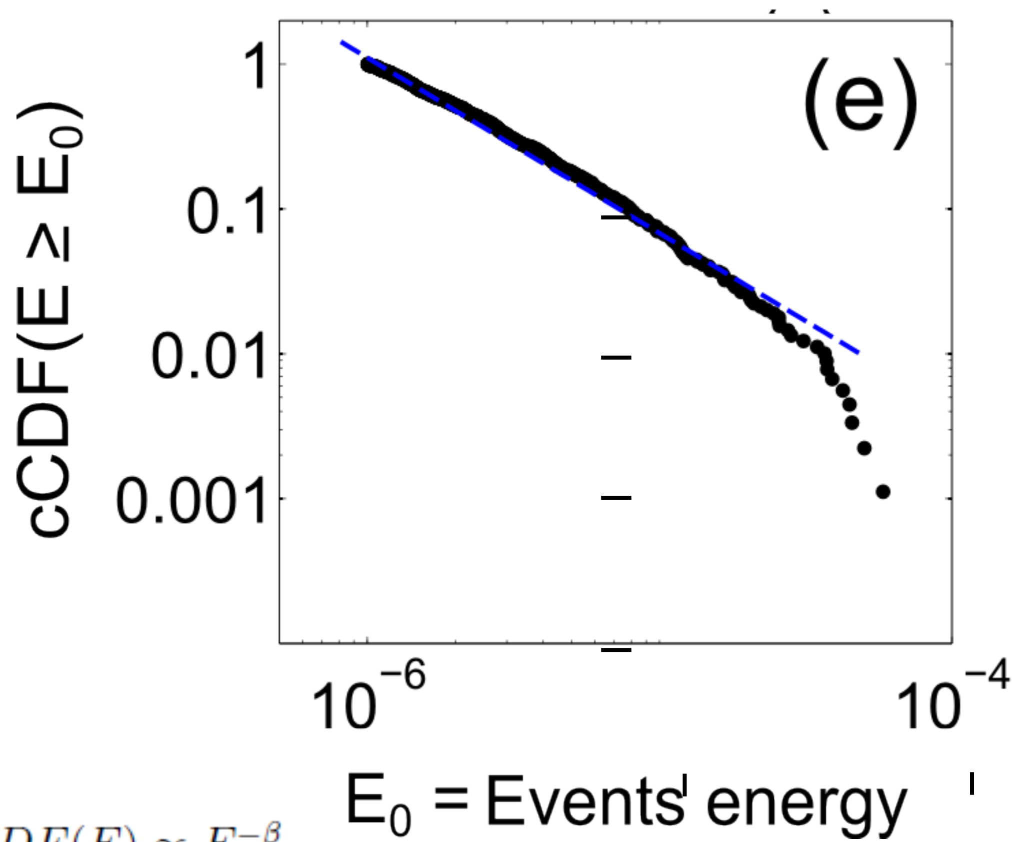


‘Clock-advance’ of slip event



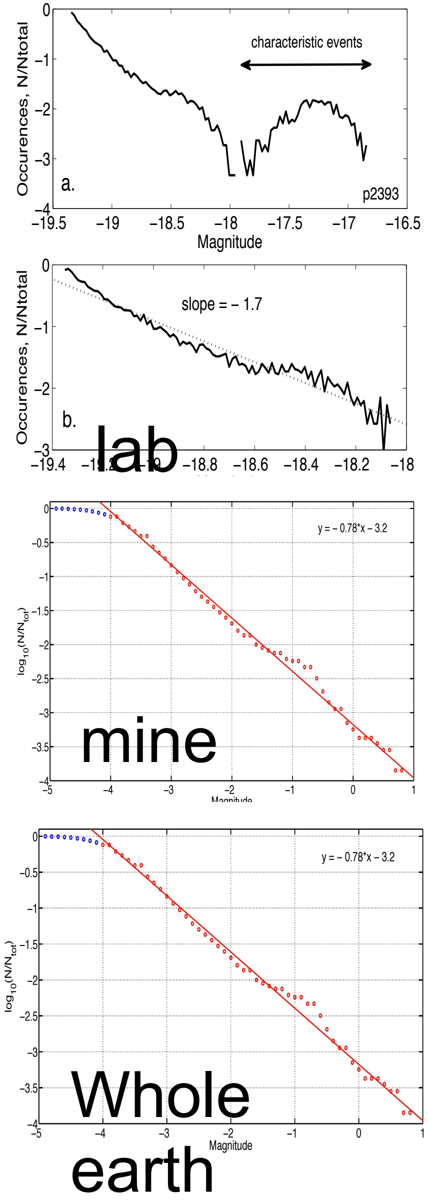
B. Ferdowsi, M. Griffa, R. A. Guyer, P. A. Johnson and J. Carmeliet. **Acta Mechanica**, 2014.

DEM Distribution of event



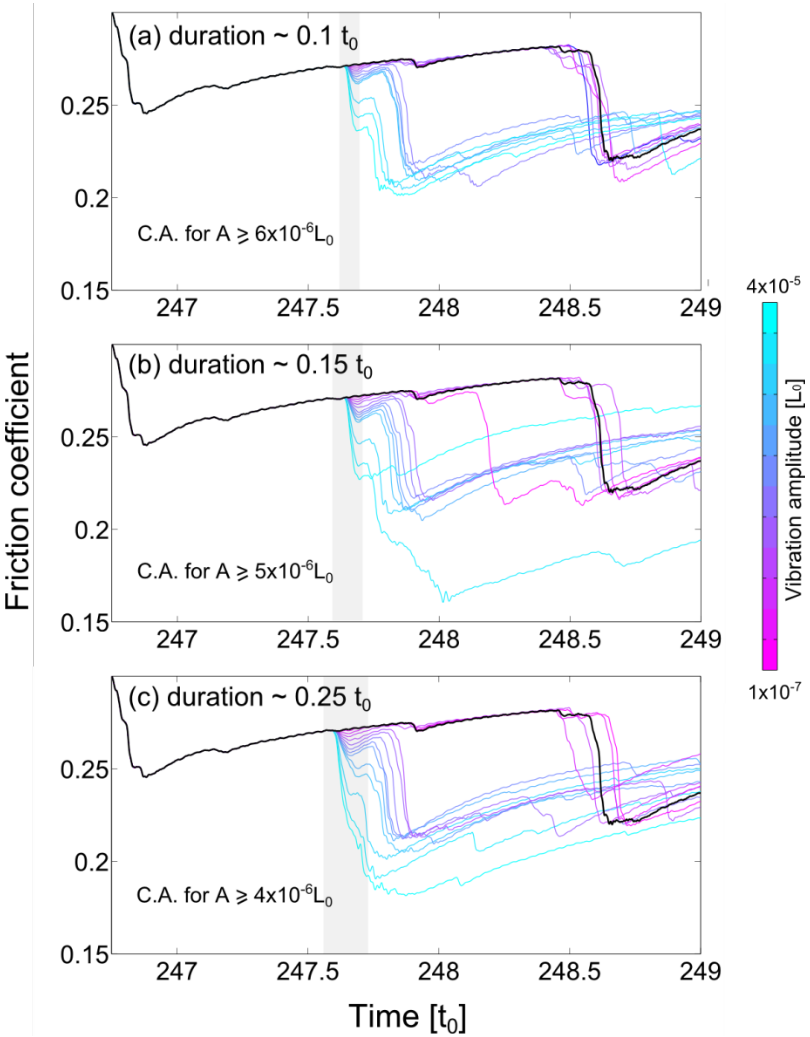
$$cCDF(E) \propto E^{-\beta}$$
$$\beta \simeq 1.23$$

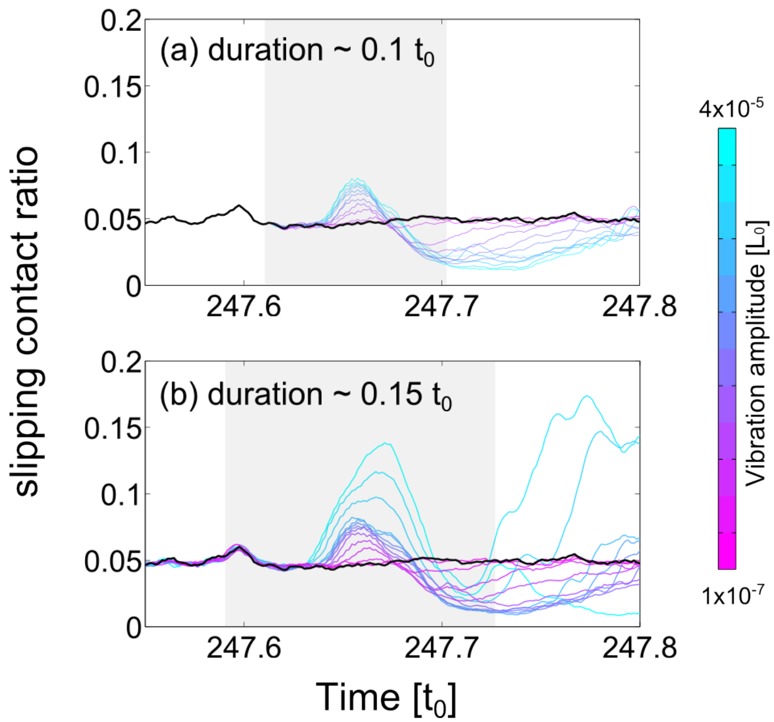
GR - type



Ferdowsi et al., in review 2013

Duration of vibration

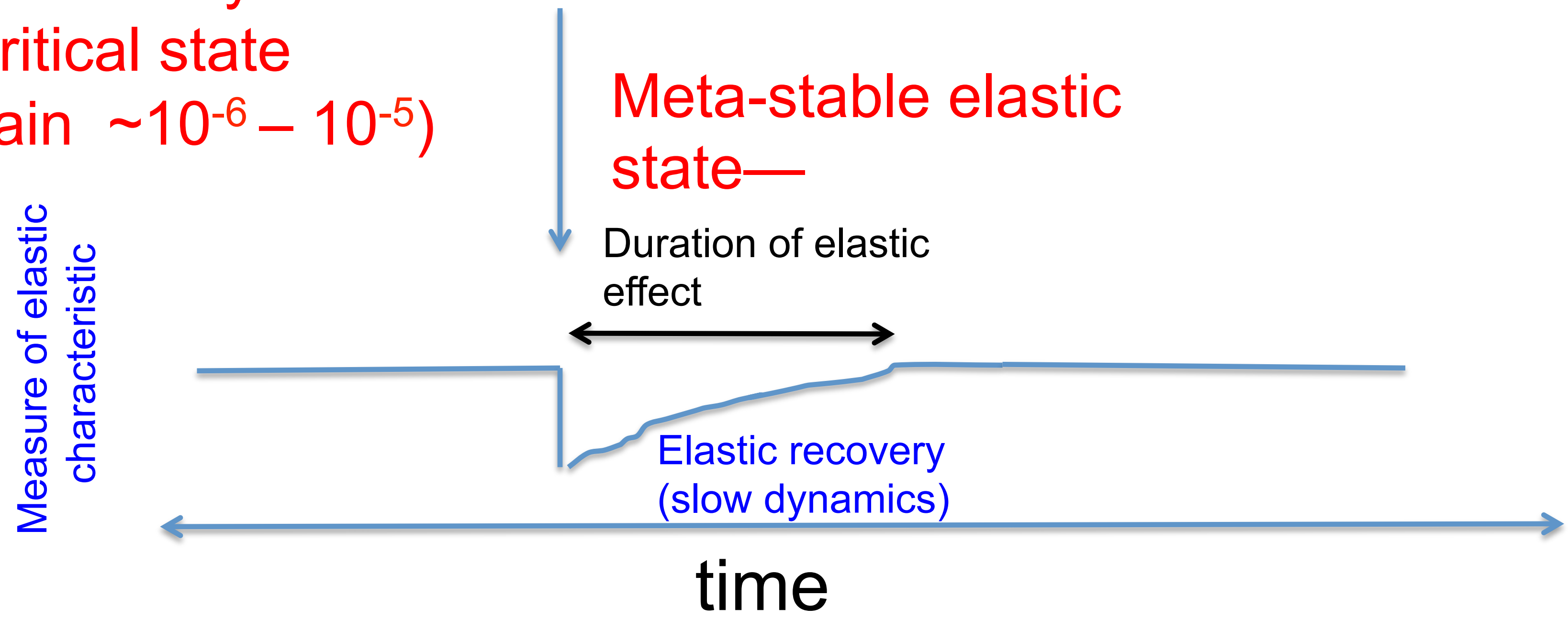




The minimum vibration amplitude for clock advance decreases with increasing duration of vibration

concept of elastic behavior in granular materials

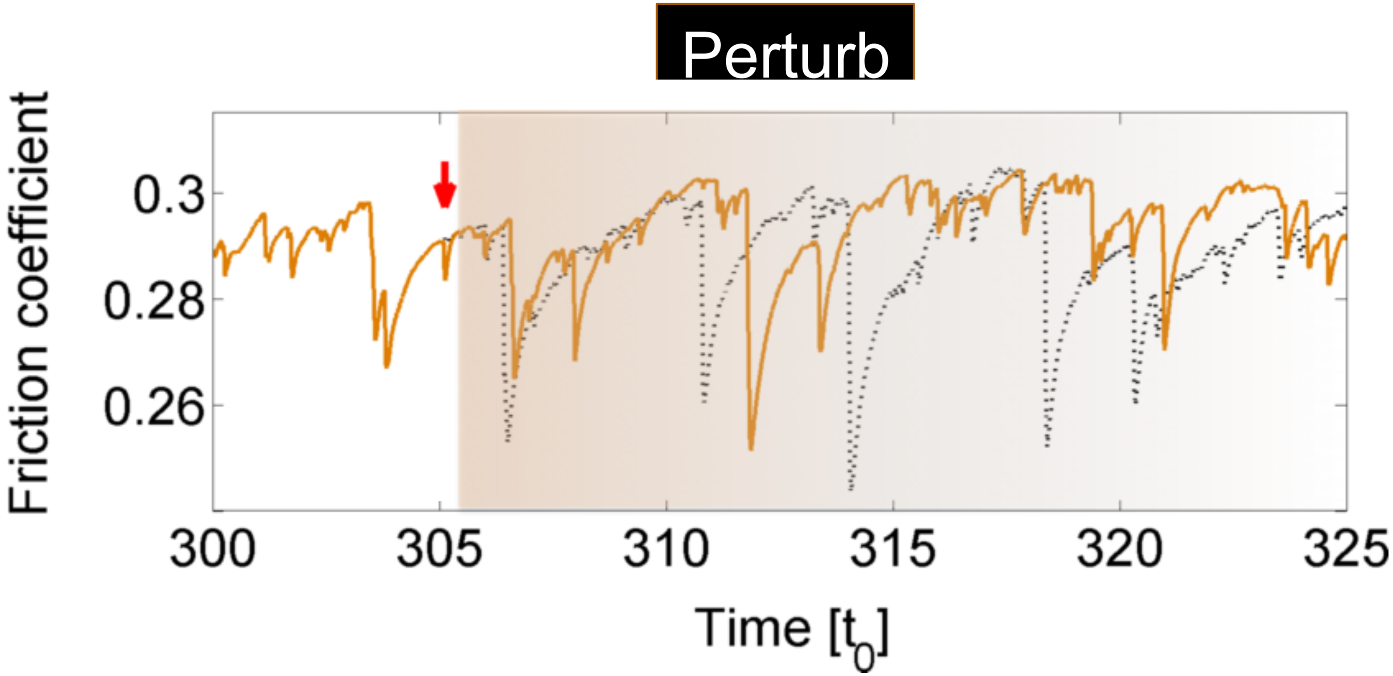
Dynamic perturbation
On elastic system
in critical state
(strain ~10^{-6} – 10^{-5})



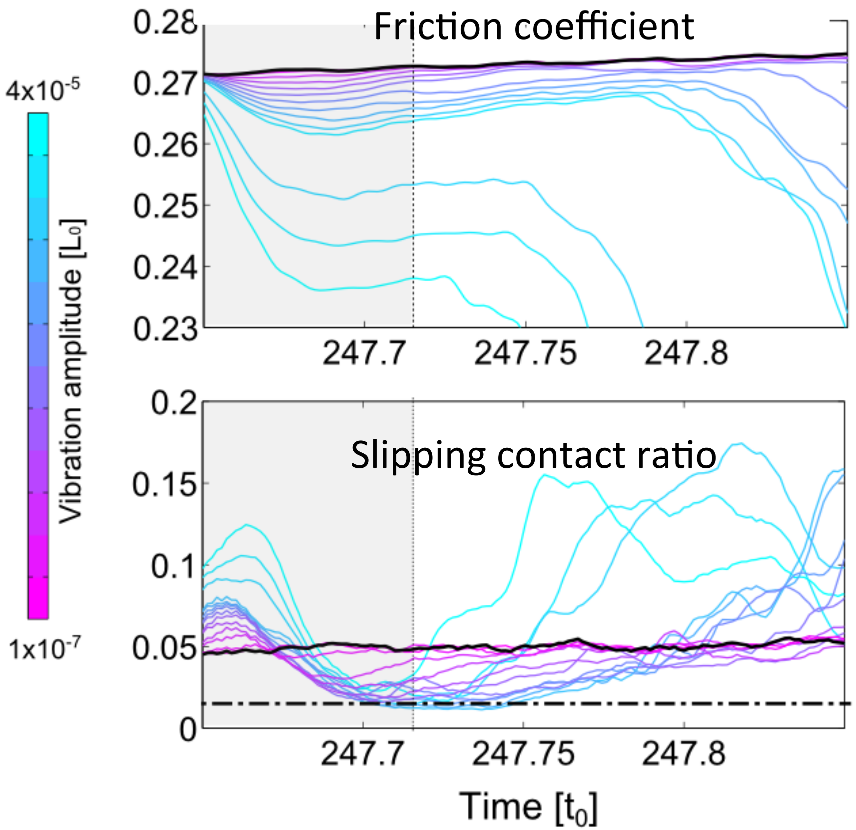
Summary/conclusions

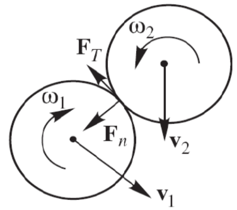
1. Earthquakes trigger earthquakes.
2. Granular physics key to triggering in laboratory
3. Mechanism of triggering in laboratory is due to granular elastic (nonlinear) dynamics

Vibration influences after the vibration interval



Clock-advance effects of triggering





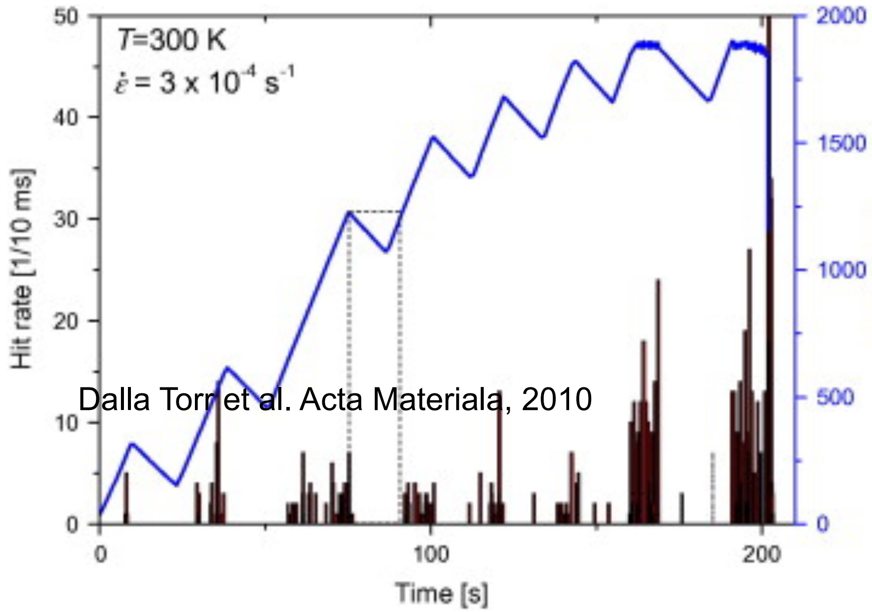
$|F_T| \leq \mu \cdot |F_N|$ $\begin{cases} \mu_S\text{: static friction} \\ \mu_D\text{: dynamic friction} \end{cases}$

Slipping Contact Ratio (SCR): ratio of the number of slipping contacts, *i.e.*, those contacts in which the tangential contact force is at the Coulomb threshold, to the total number of contacts.

B. Ferdowsi, M. Griffa, R. A. Guyer, P. A. Johnson, C. Marone and J. Carmeliet. **Physical Review E**, 89(4), pp. 042204(1-12), 2014.

Earth: an elastic system

Kaiser Effect: An effect observed in most metals, in which acoustic emissions are not observed during the reloading of a material until the stress exceeds its previous high value. Is there a global Kaiser effect due to global stress build up, release and successive build up??



Dalla Torr et al. Acta Materiala, 2010

Global catalog
cumulative energy