Los Alamos
NATIONAL LABORATORY

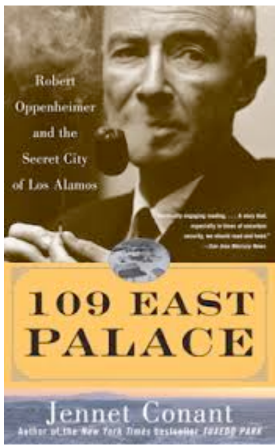
# Nonlinear elasticity: observations and implications


**Paul Johnson**

*Los Alamos*


**Ambient Noise Imaging and Monitoring Workshop, Cargese 2015**

oppenheimer




teller


Bethe

fermi

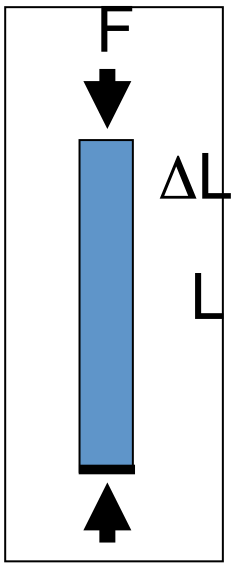

feynman

# outline

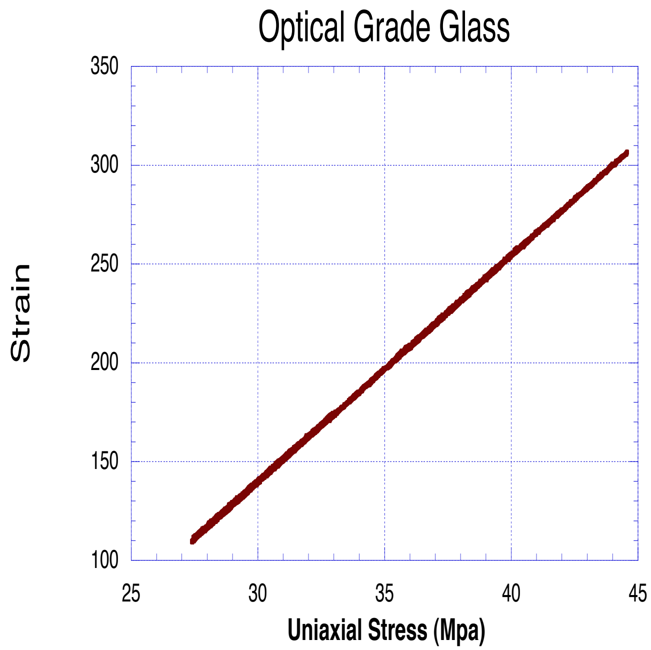
- Background on nonlinear elasticity
- Applications:
  - Slow slip laboratory, simulation
  - Slow slip Mexico
  - Widespread elastic perturbation in Japan
  - Velocity changes following the san Simeon and Parkfield earthquakes

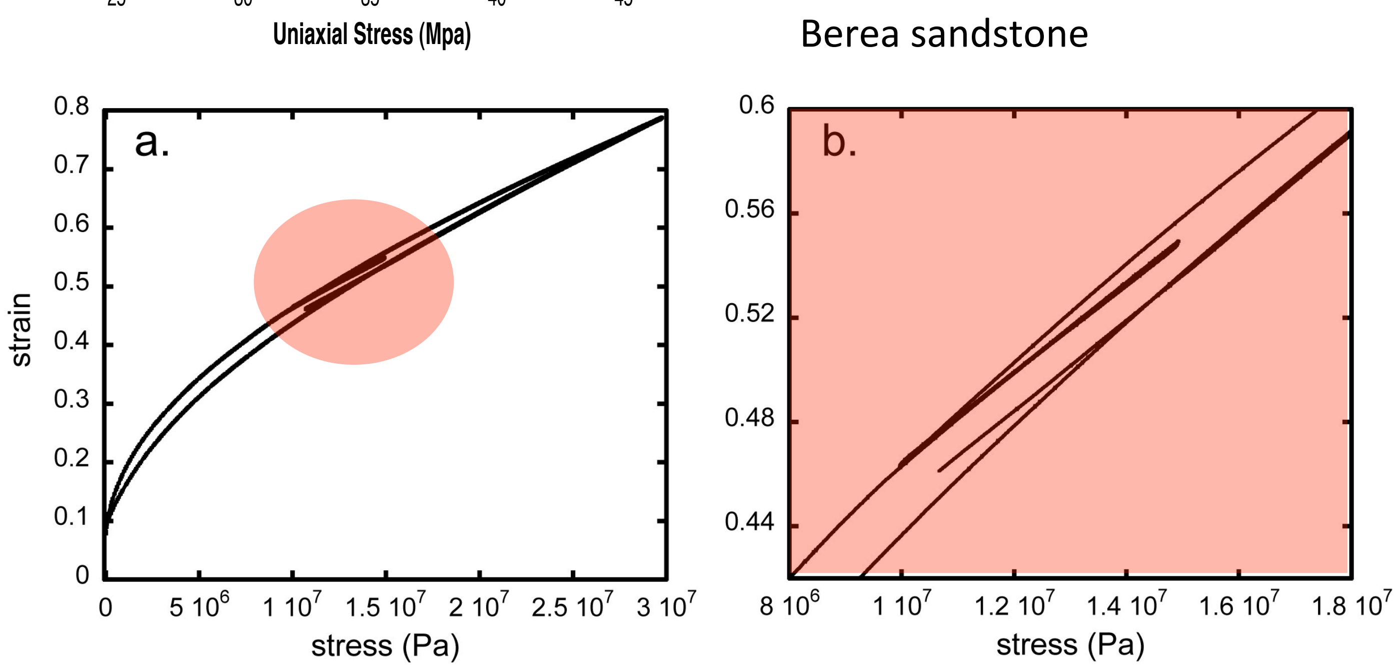
summary

# Stress-strain measurements in the lab

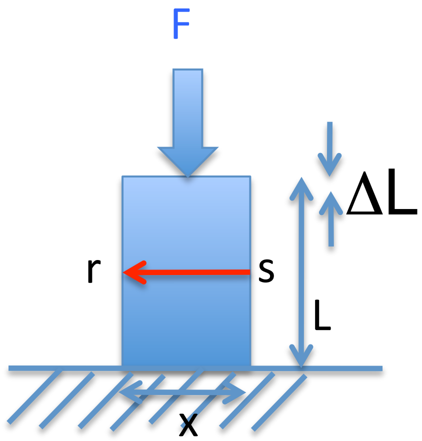


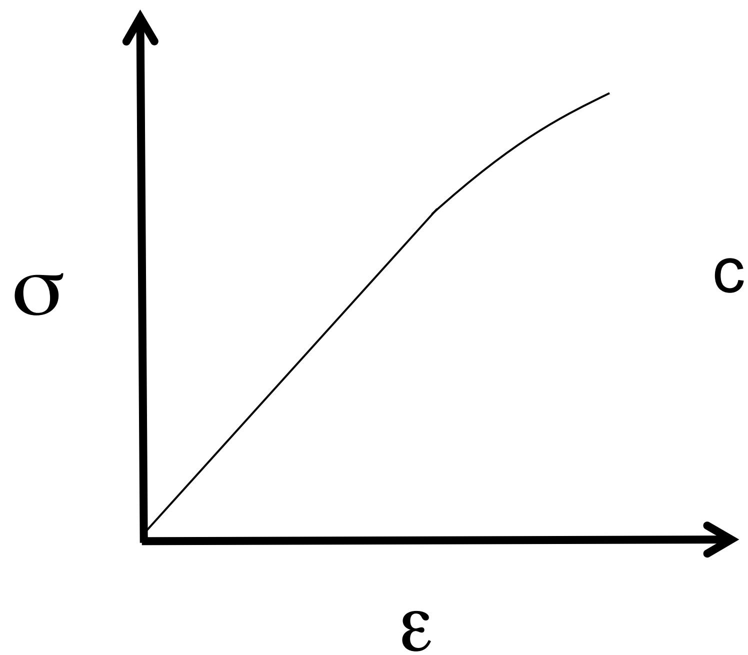

$\varepsilon = \Delta L / L$

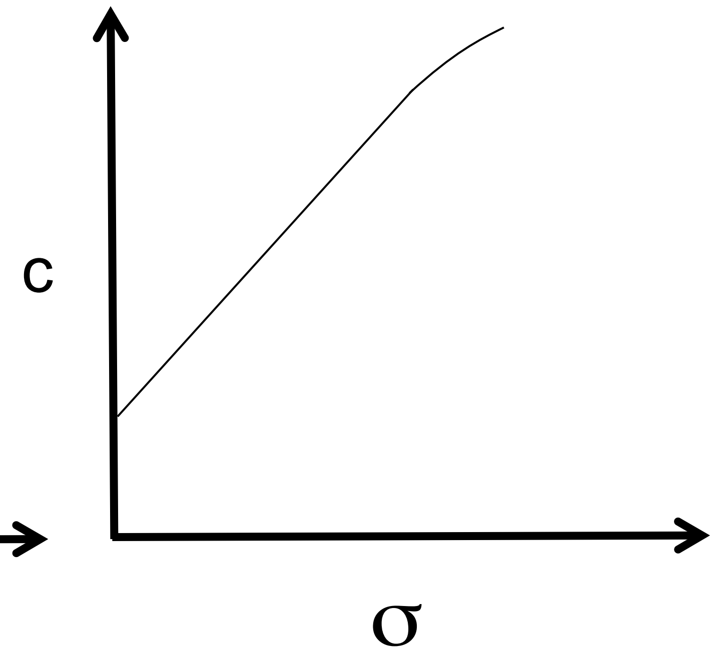


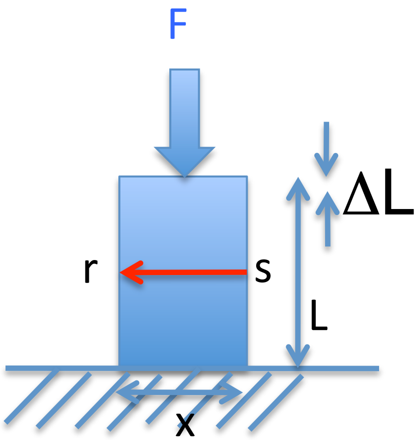
# Quasistatic and dynamic elasticity of individuals crystals and many metals

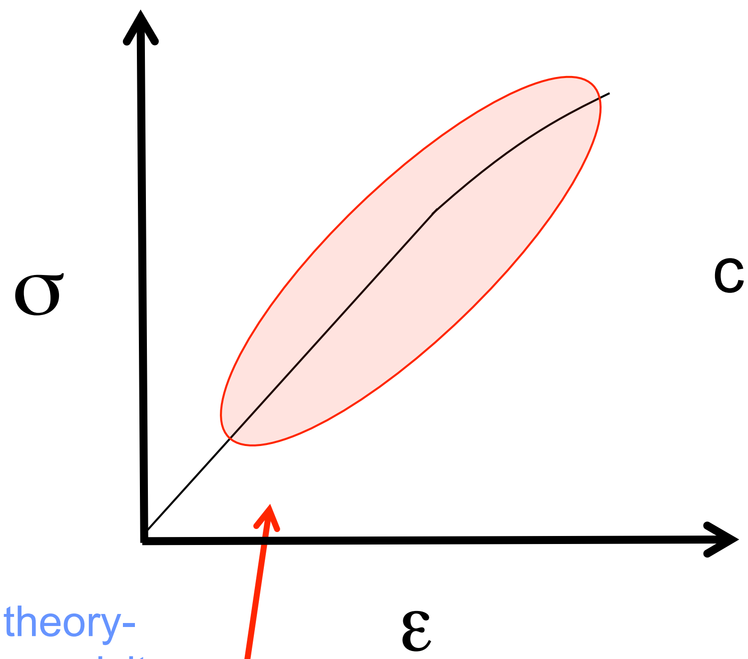


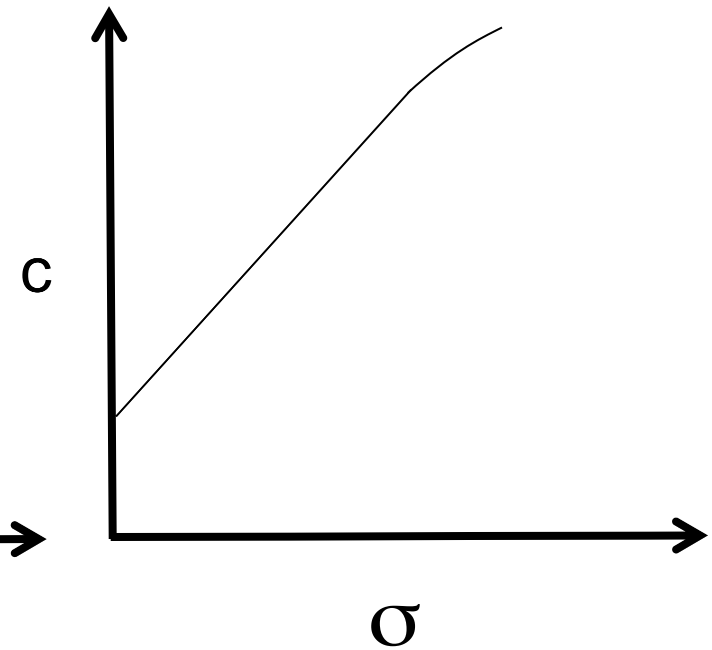



# Quasistatic and dynamic elasticity of individuals crystals and many metals



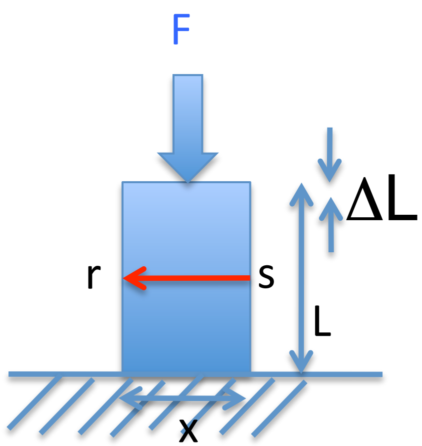

Thermodynamics based theory-
Nonlinearity due to anharmonicity in the crystalline lattice.

$$\sigma_{dyn} = M\varepsilon_{dyn}[(1+\beta\varepsilon_{dyn})]$$

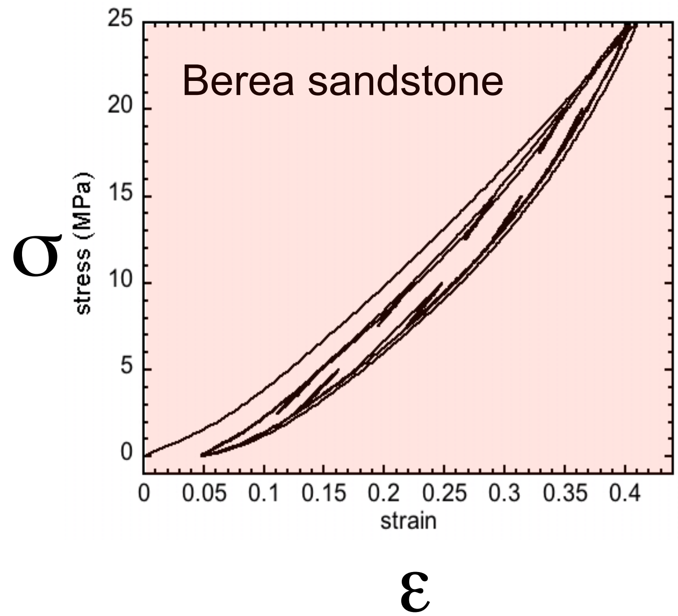
$$\beta = \frac{3}{4} + \frac{A+B+C}{2\rho c^2} = \frac{3}{2} + \frac{l+2m}{\lambda+2\upsilon}$$

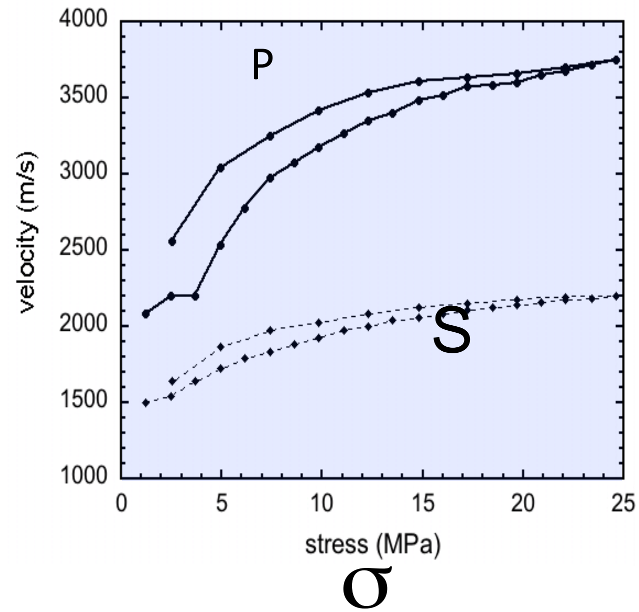
Goldberg Murnaghan

# Quasistatic elasticity of rock and 'damaged' materials



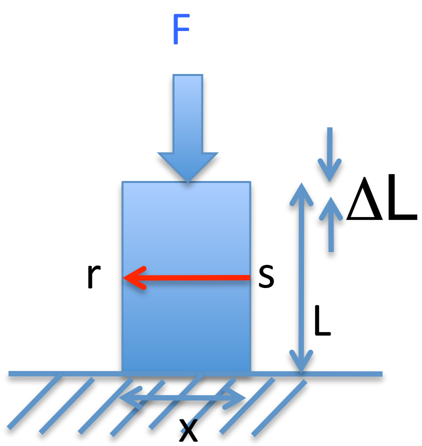

Nonlinearity much larger than metals and single cyrstals…..

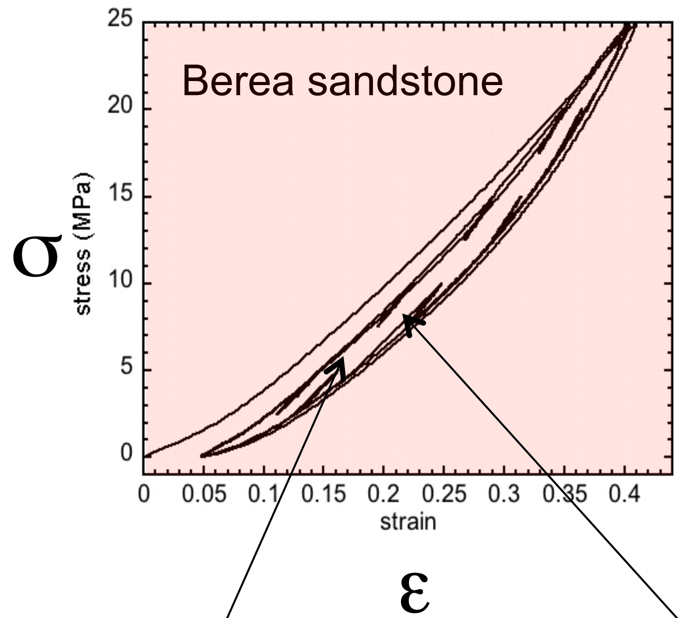


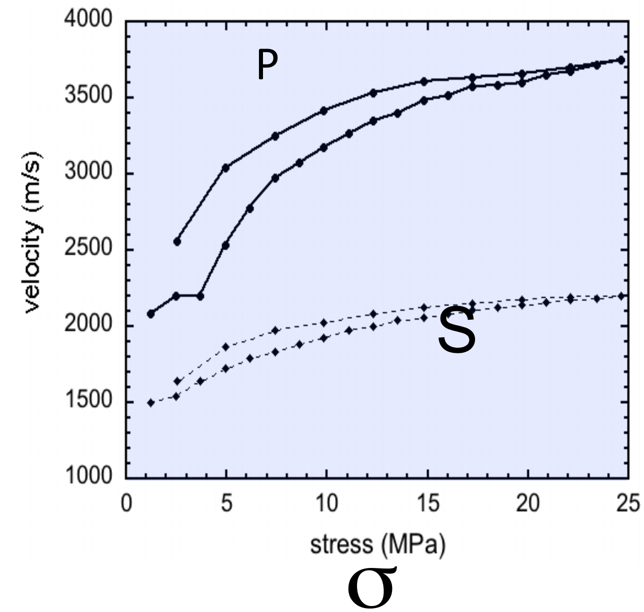



# Elasticity of individuals rock and damaged materials

Nonlinearity much larger than metals and single cyrstals…..



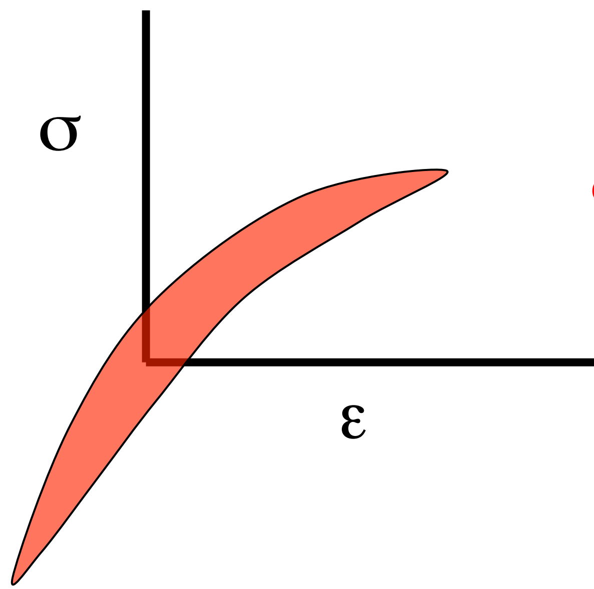




Phenomenological model of nonlinearity and hysteresis (Preisach-Mayergoyz)

$$\sigma_{dyn} = M\varepsilon_{dyn}[(1+\beta\varepsilon_{dyn}+\delta\varepsilon_{dyn}^{2}+\ldots)+(\varepsilon-\alpha[(\Delta\varepsilon_{dyn})\varepsilon \pm \frac{1}{2}(\varepsilon_{dyn}{}^{2}-\Delta\varepsilon_{dyn})^{2}]$$

# Wave dynamics in rock and other earth materials



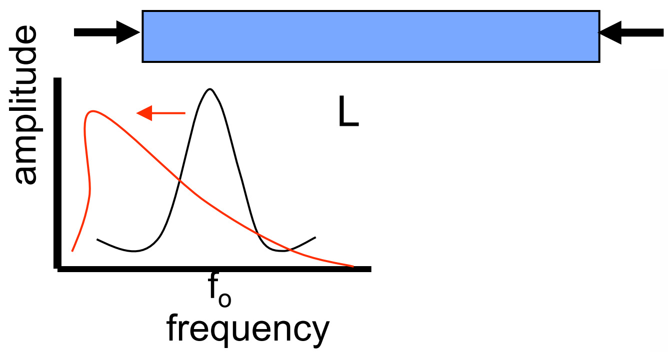

σ = stress

ε = strain

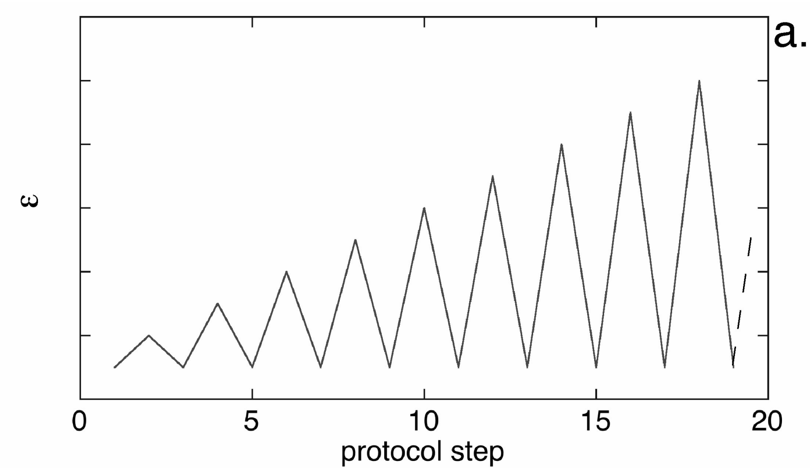
Elastic nonlinearity and hysteresis are present in dynamics when strains exceed ~$5\times10^{-7}$ - $10^{-6}$ [*at low effective pressure*].

*Material dependent*

# ‘Memory’ of wave excitation (‘conditioning’)



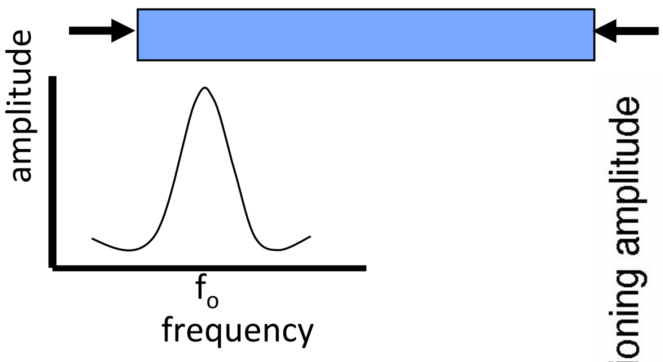

Young’s mode experiments in a bar



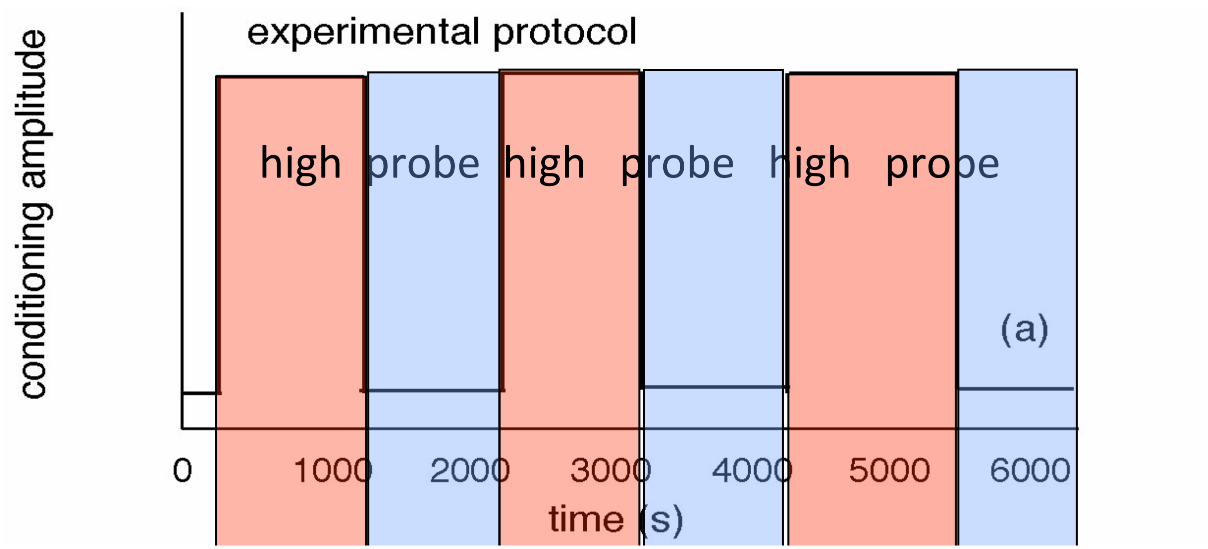

Experimental Protocol

*From Pasqualini et al., Jour. Geophys. Res. 2007*

# Regime iii: nonequilibrium slow dynamics



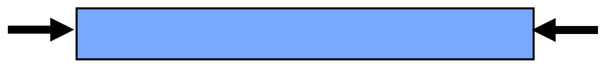

Young's mode experiments in a bar




Slow dynamics– a type of creep

Modified from TenCate and Shankland, GRL 1997

# Modulus ‘softening’ and recovery (the ‘slow dynamics’)

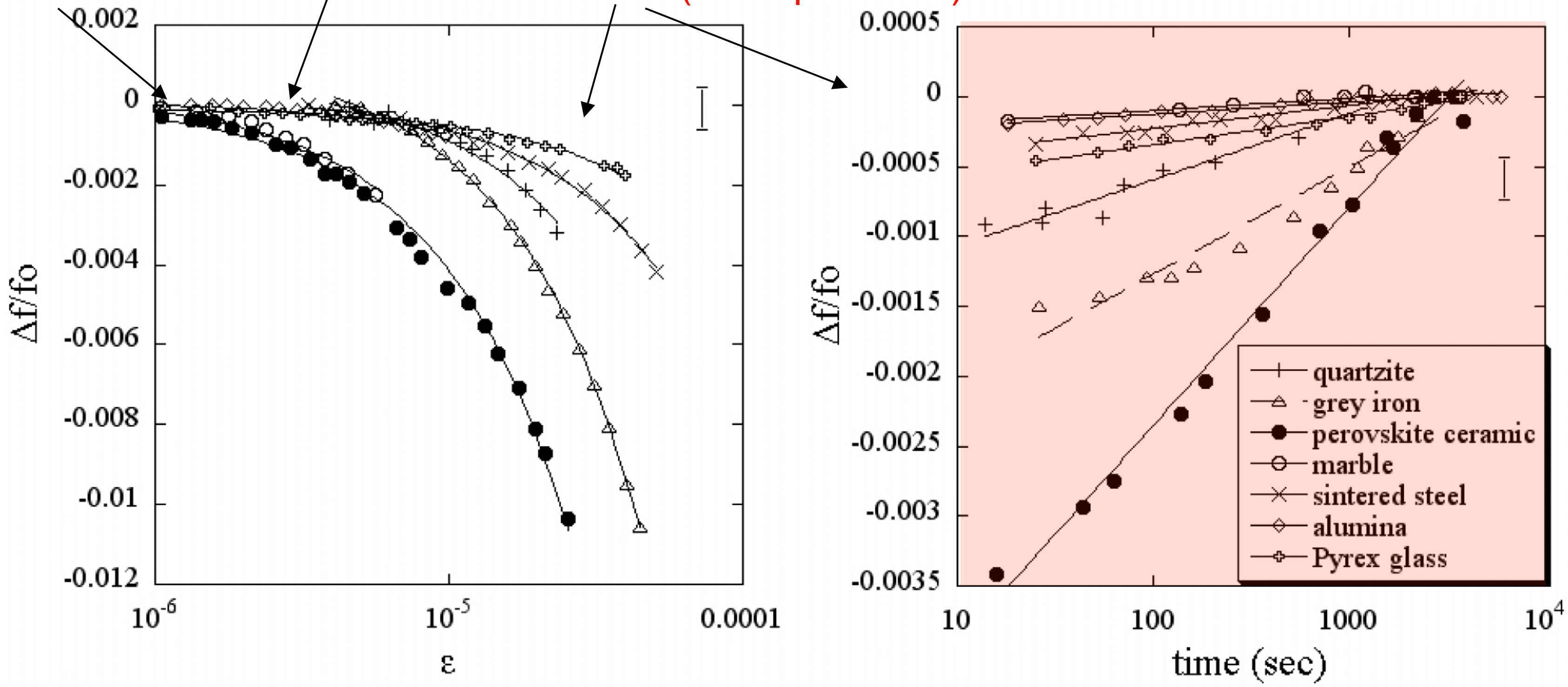


Young’s mode experiments

Classical NL behavior

Linear elastic

Nonclassical (nonequilibrium) behavior



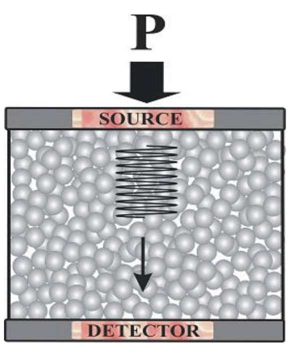

Fast dynamics/conditioning

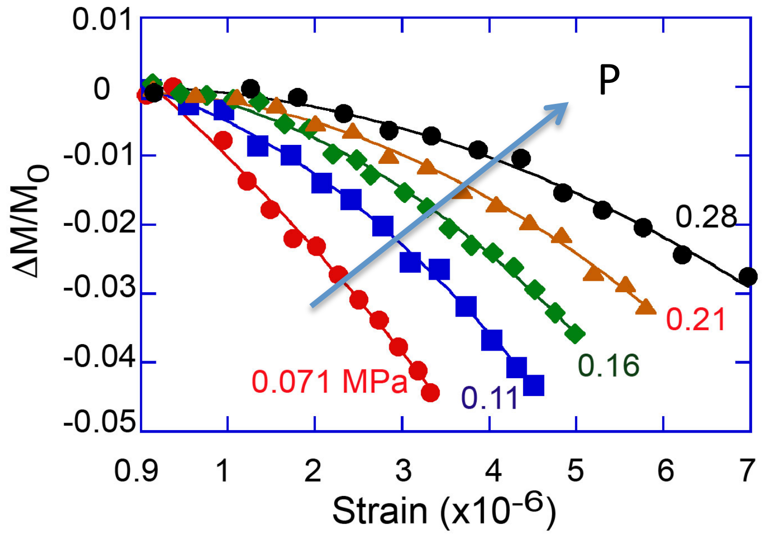
Slow dynamics

*From Johnson and Sutin, JASA 2005*

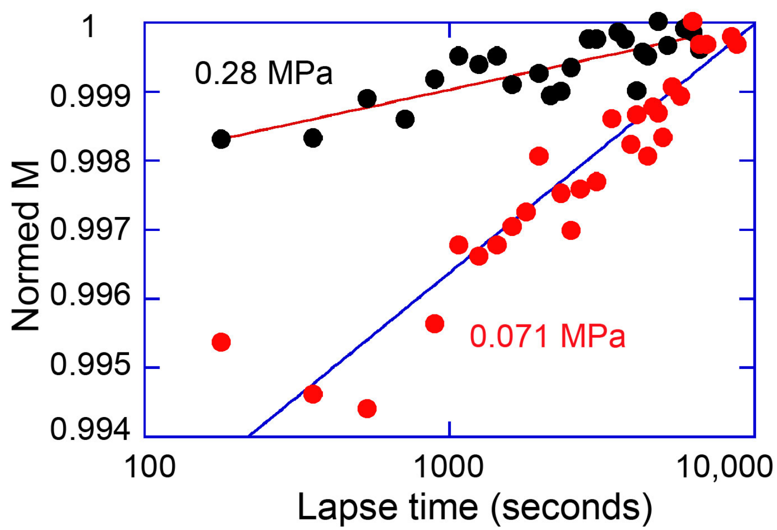
# Modulus 'softening' and recovery (the 'slow dynamics') in glass beads

Experiments with rock and canisters of glass beads



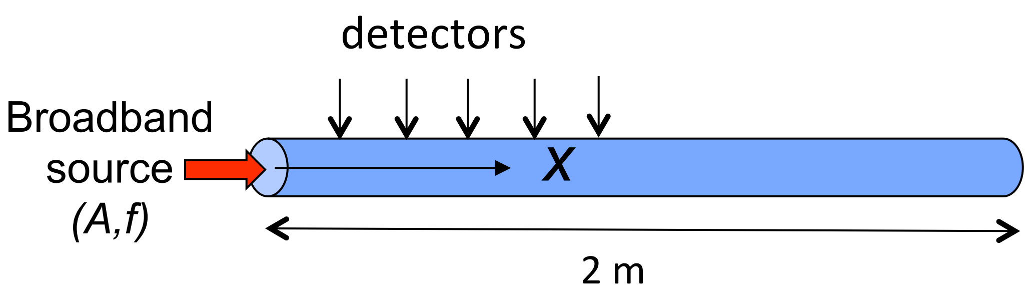

Decrease in modulus and increase in dissipation with wave amplitude.

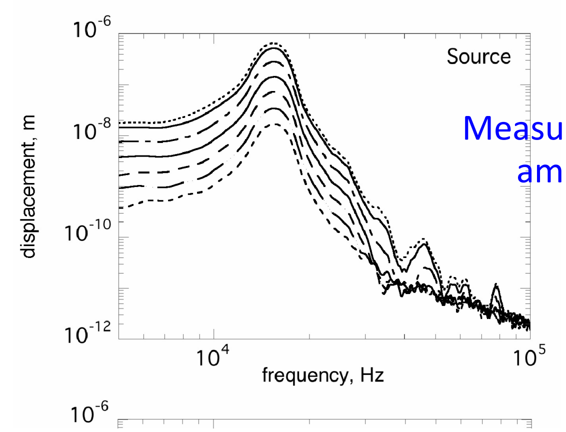



Long recovery to equilibrium (the slow dynamics)

Modified from Johnson and Jia, *Nature*, 2005

# Nonlinear dynamical experiments: NL ‘path’ effects

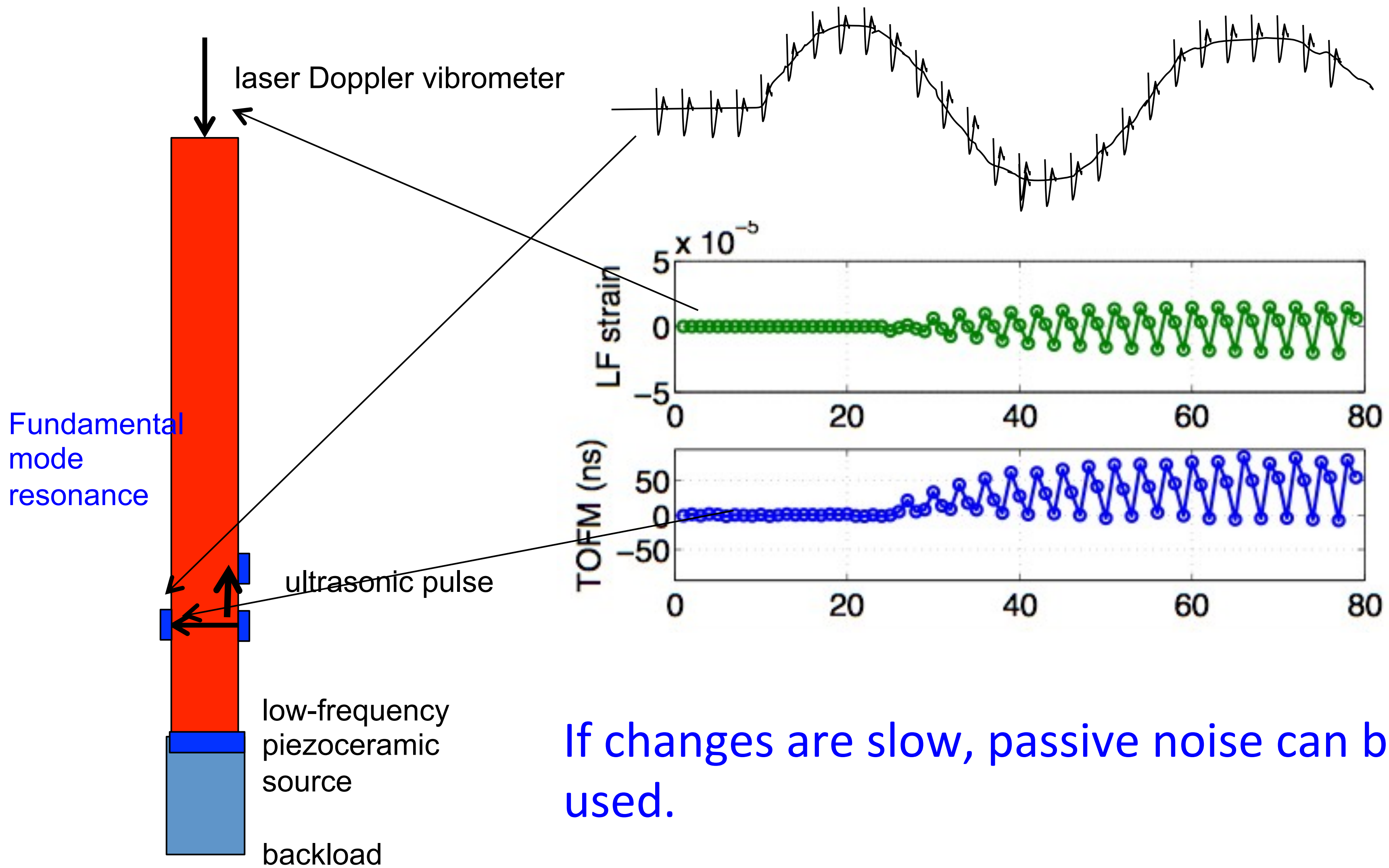



Measured source amplitude

Johnson and McCall, GRL 1994

# Dynamic acousto-elasticity (DAE)

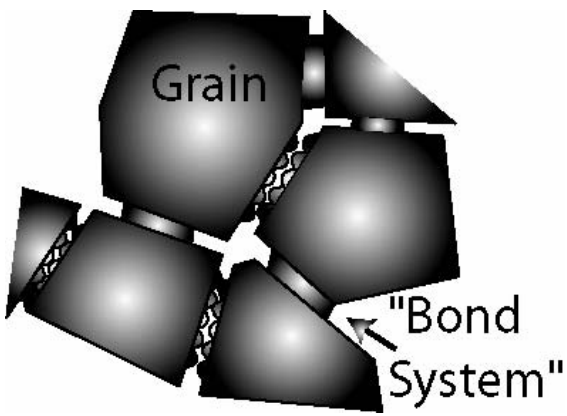



If changes are slow, passive noise can be used.

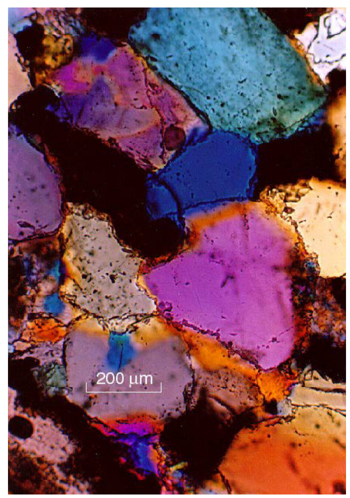
G. Renaud, J. Riviere , others.

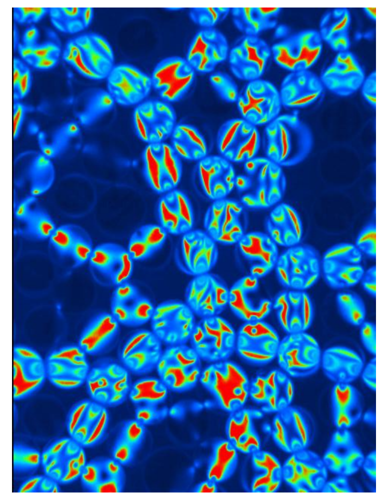
# Physical origin of behavior

## Dominant contribution is material 'damage'

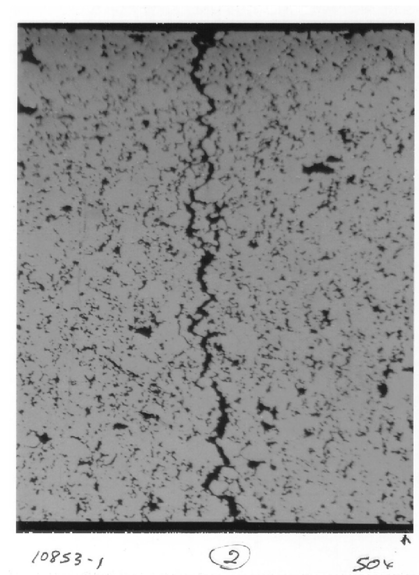



"Distributed"



"Localized"

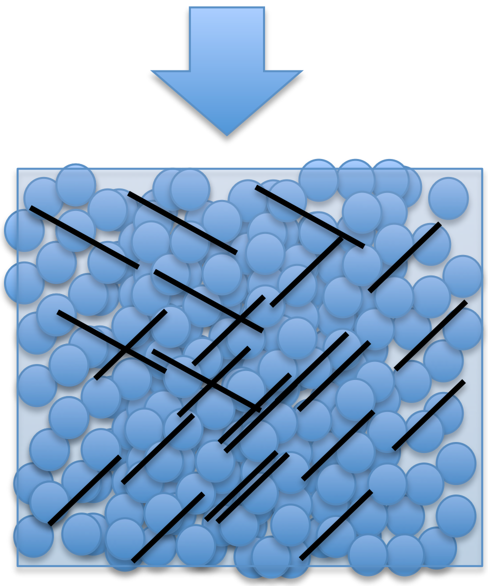


The grains or material around damaged region remain rigid.
The bond system is soft.

# Why does this happen?

Velocity increase, length decrease

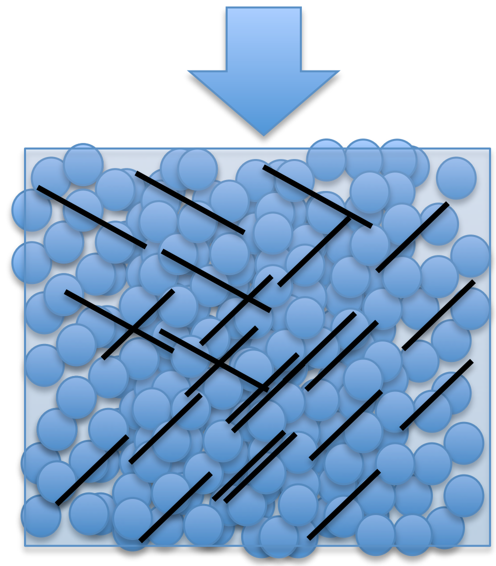
F



Stress transferred by skeleton. Little activation of damage features.

Velocity decrease, length decrease

F cos ($\omega t$-kx)



Stress activation of damage features, primarily by shearing

# Applications: Slow slip.....

# Seismic evidence of tremors and slow-slip events

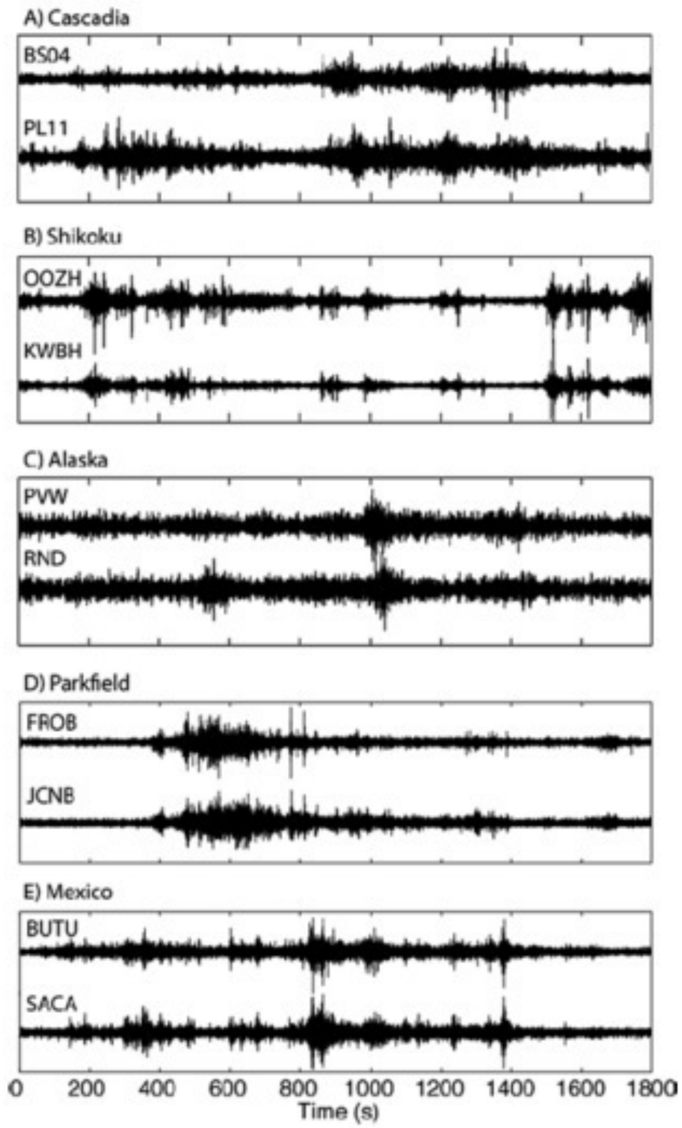
Long duration

Low Amplitude

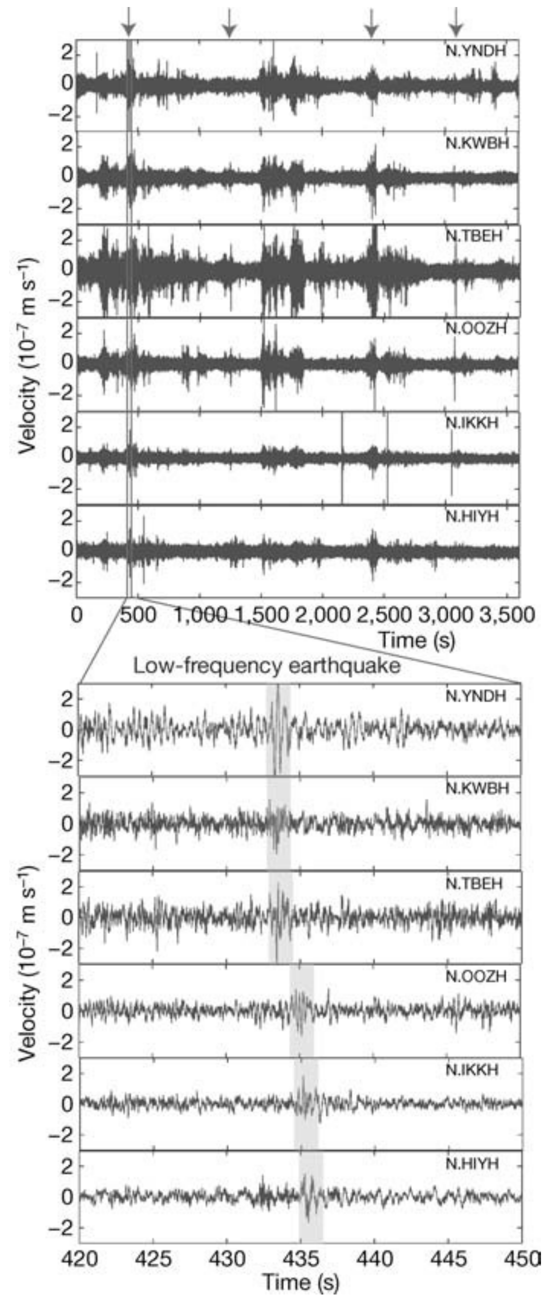
Non-impulsive seismic radiation

usually in the 1-10Hz frequency band

very difficult to distinguish from the ambient noise.

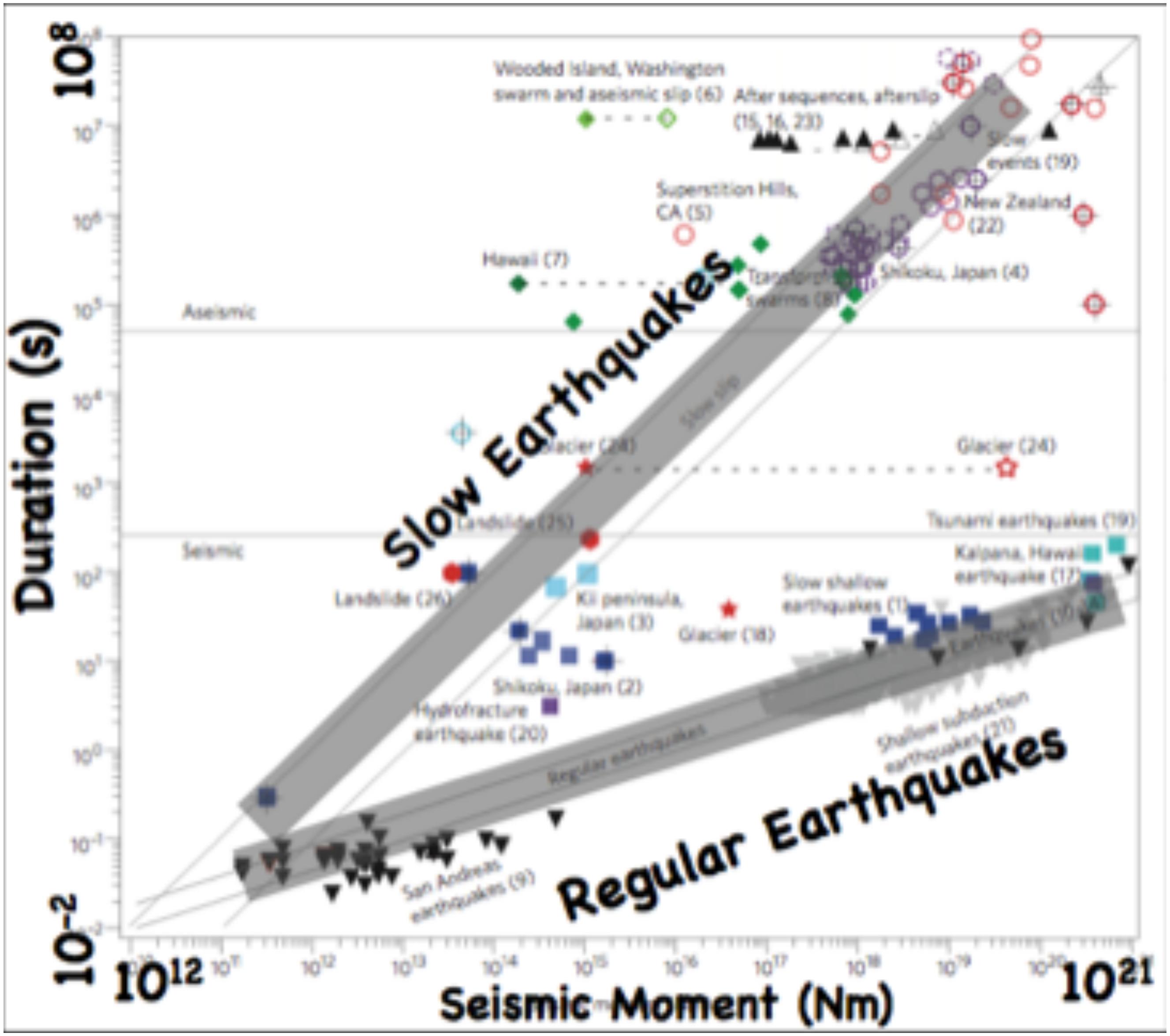



Shikoku, Japan




Rubinstein et al., 2012; Shelly et al., 2006 Nature

# The spectrum of fault slip behavior

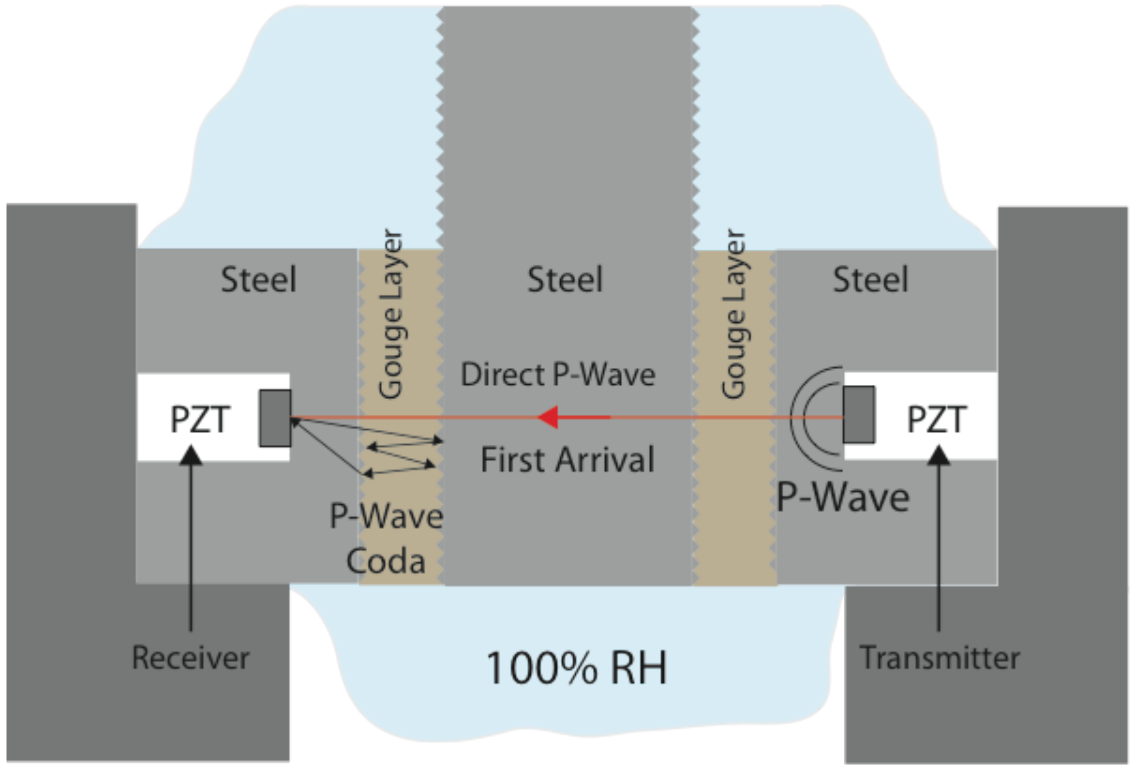



Quasi dynamic processes

Regular earthquakes

after Ide et al., 2007 Nature

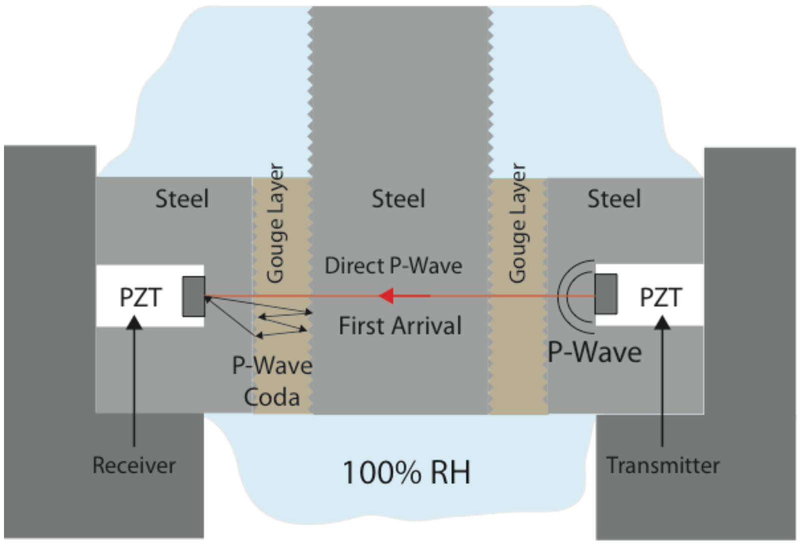
# Scuderi et al: Ultrasonic wave speed measurements




From the transmitter P-Waves are sent at a rate of 10 Hz.
The receiver records the first 140 µs of the waveform
at a frequency of 50 MHz.

During the experiment, waveforms are accurately synchronized with mechanical data.

# Ultrasonic wave speed measurements

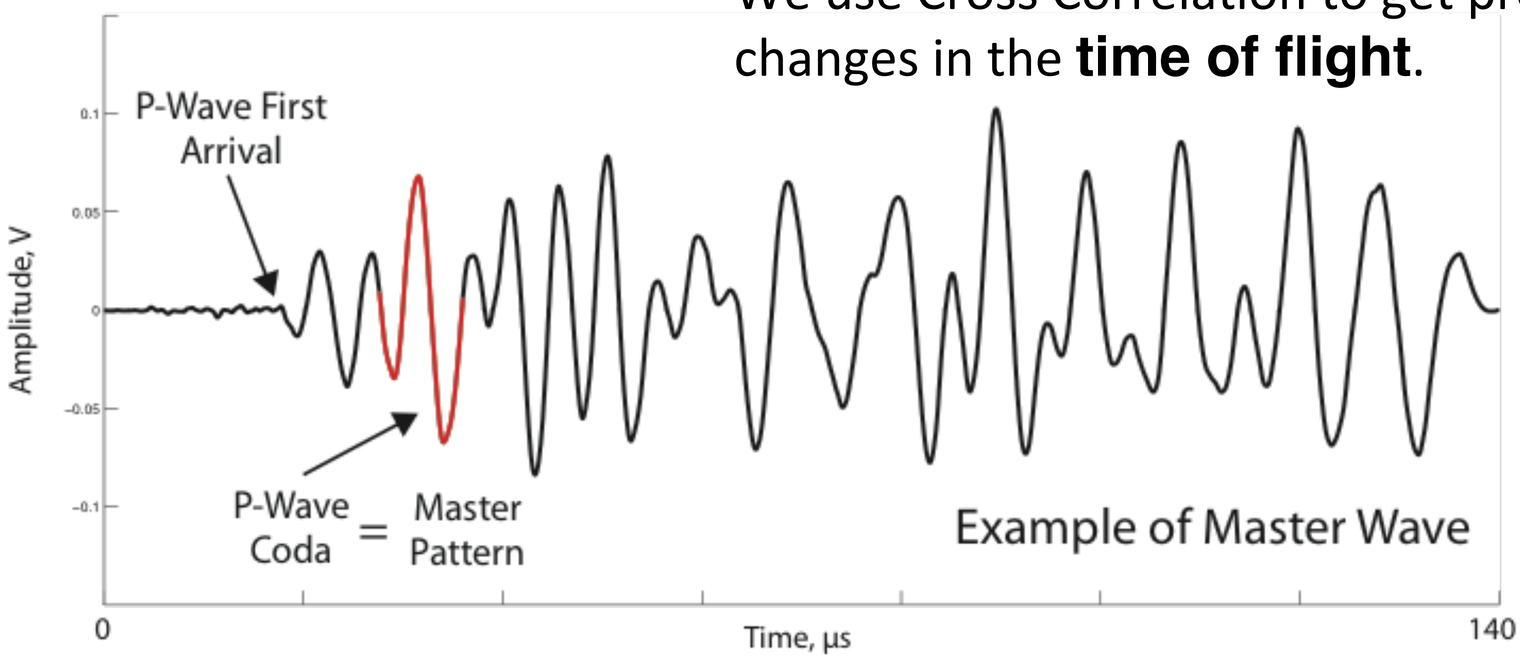



## Waveform Analysis

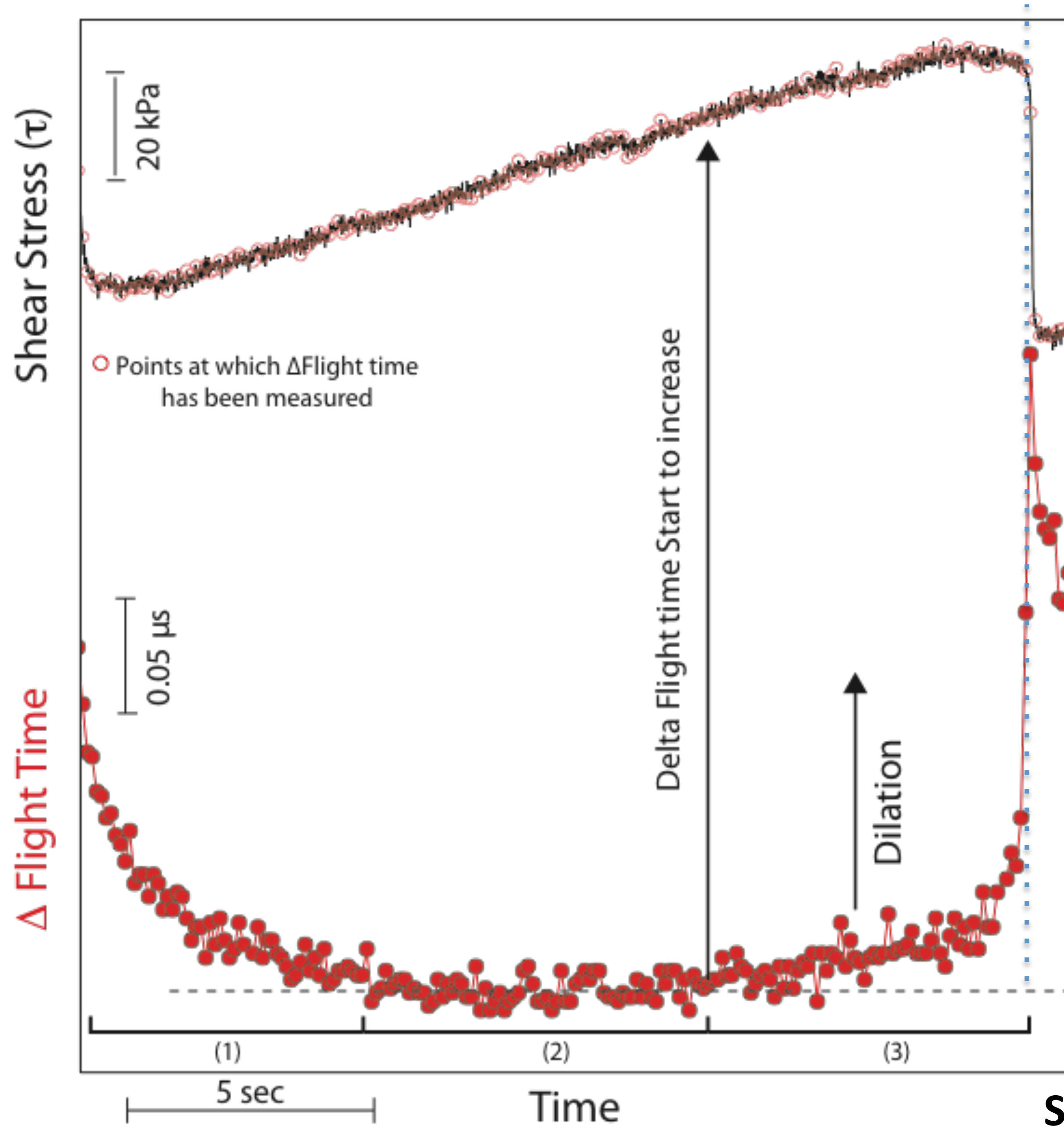
We select a <u>master wave</u> from a stable period of the experiment prior to the events of interest

We focus on the P-Wave coda and choose a <u>master pattern</u>

We use Cross Correlation to get precise changes in the **time of flight**.



# Scuderi: Details of a slow-slip and its acoustic signature




Time of flight evolves during a slow-slip cycle, showing:

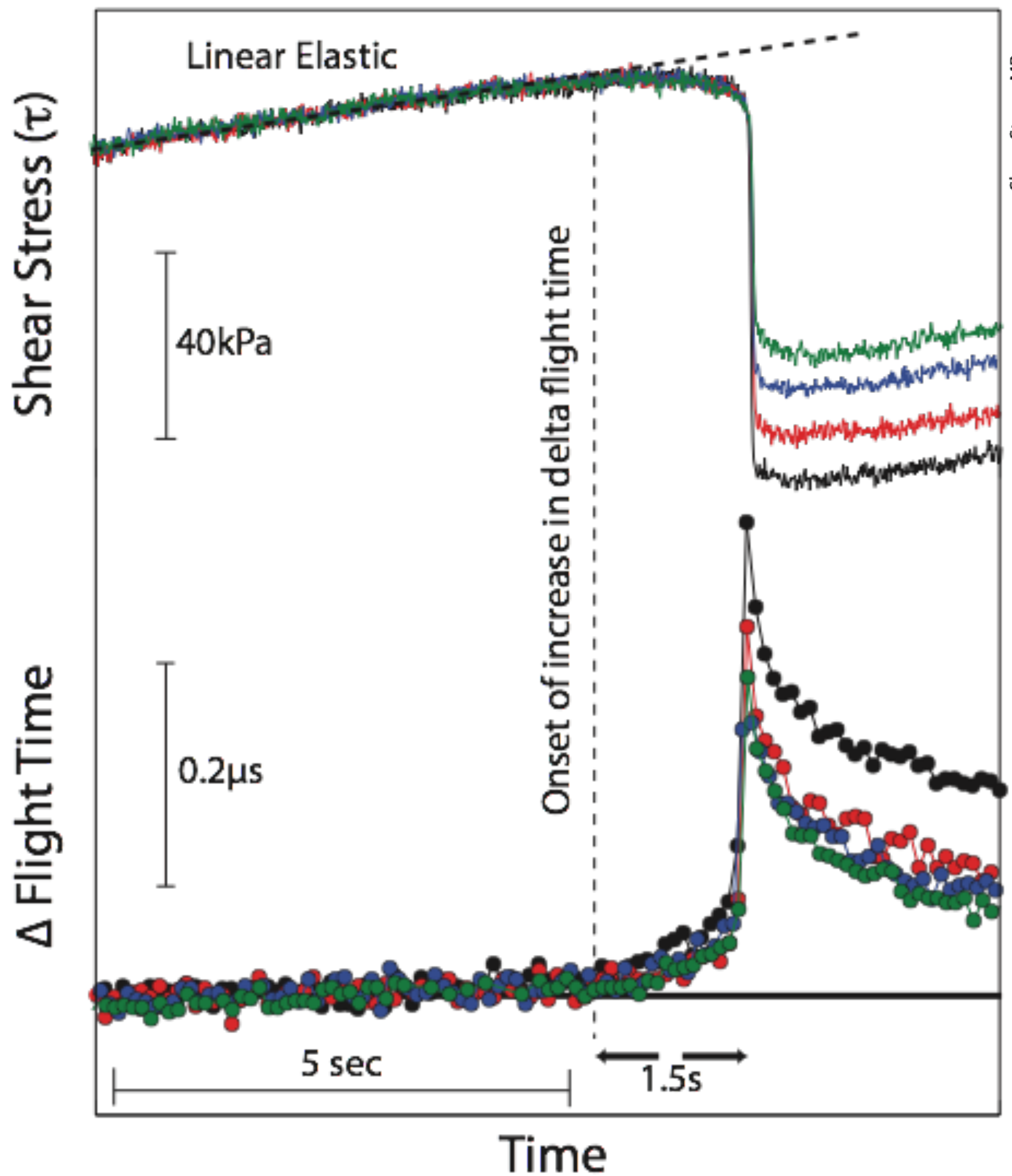
**(1)** First stage of decrease (possibly due to layer compaction).

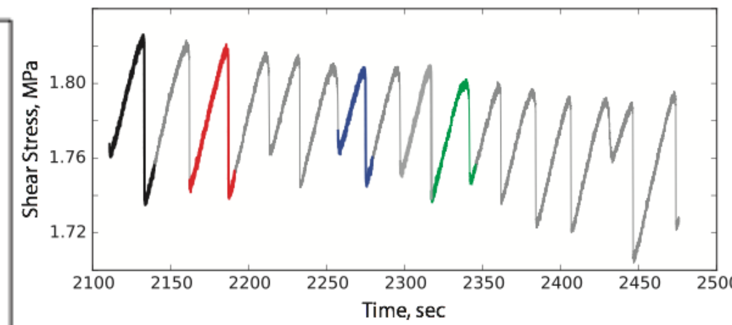
**(2)** Stabilization to constant values.

**(3)** A gradual increase preceding the failure event and stress drop

**Scuderi et al. in prep.**

# Comparison between different events

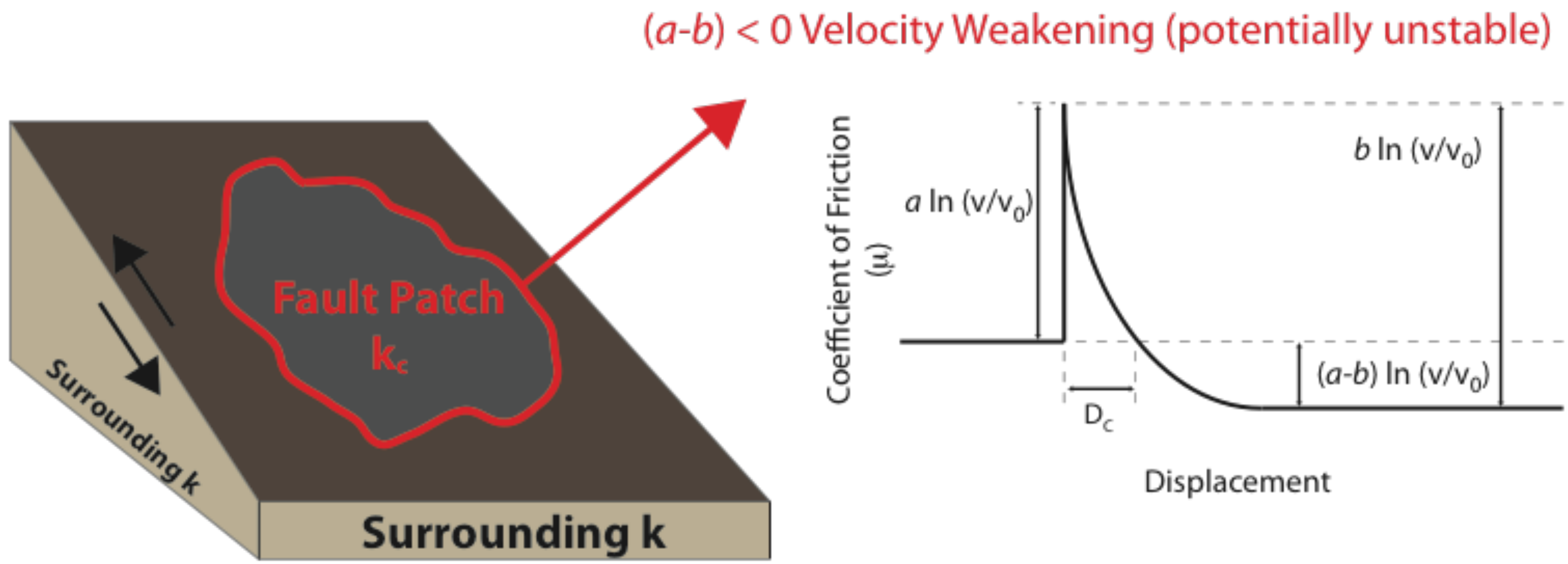



Flight time always starts to increase before the maximum strength is reached and continues during the stress drop.

**Scuderi et al. in prep.**

# Frictional stability along faults



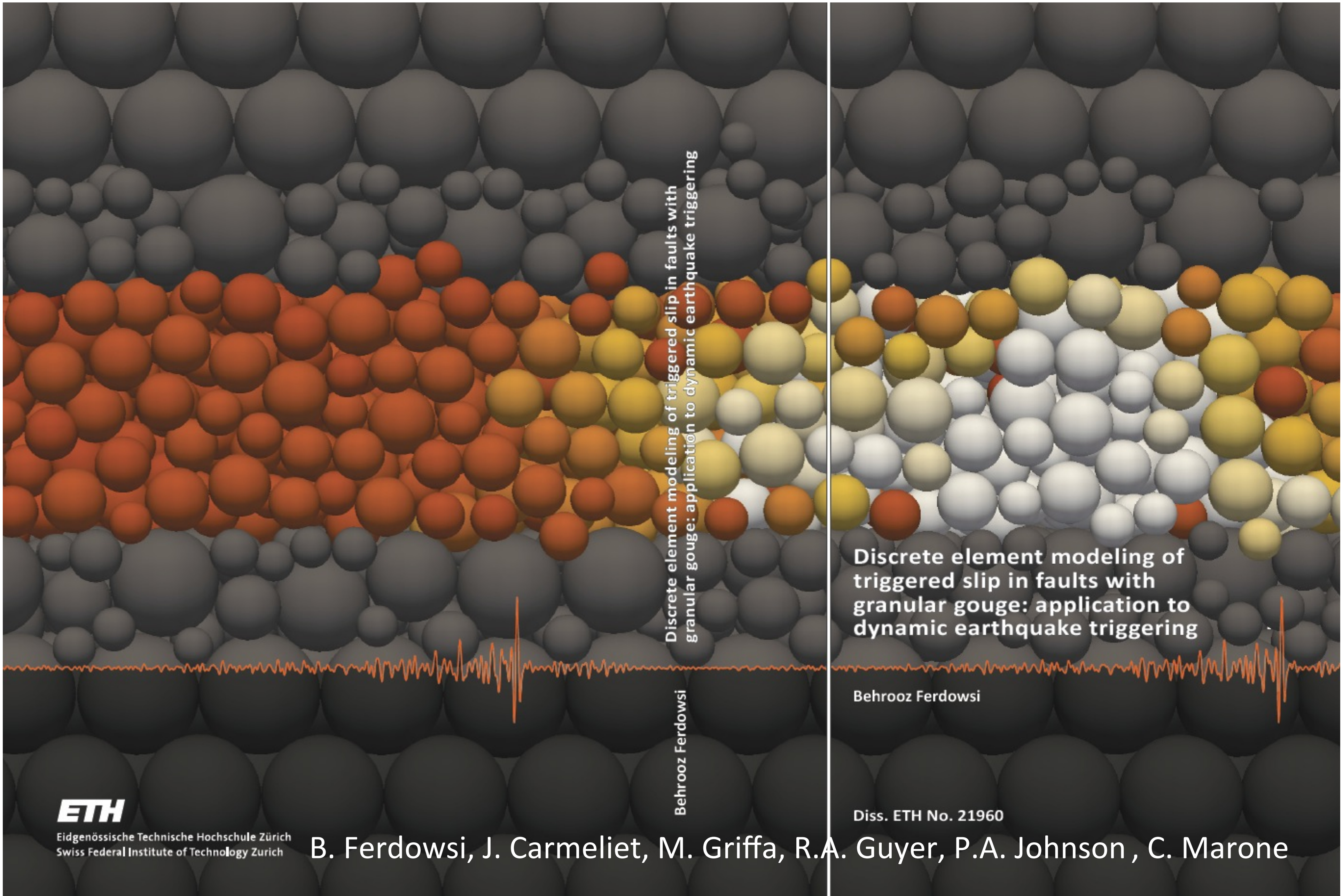

**Criterion for fault Stability**

defined by the critical stiffness (kc)

$$k_c = (\sigma_n - P_f)(b-a) / D_c$$

- $k > k_c$ — *Stable*
- $k \sim k_c$ — *Conditional Stability*
- $k < k_c$ — *Unstable*

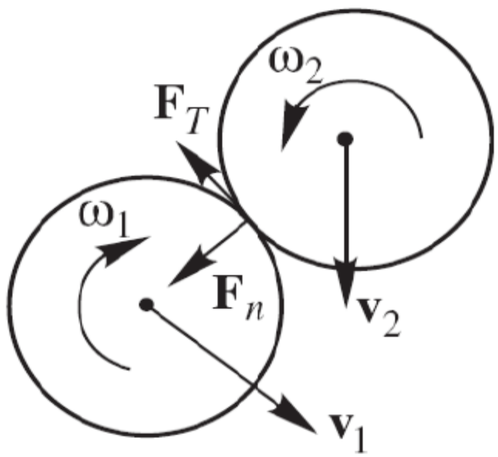
**Scuderi et al. in prep.**

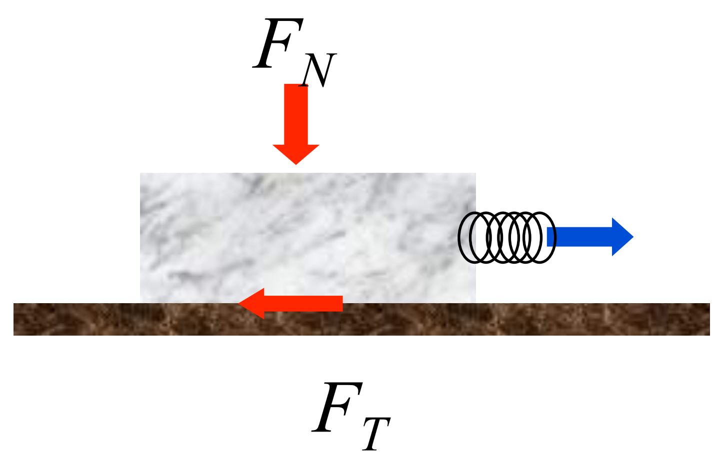



B. Ferdowsi, J. Carmeliet, M. Griffa, R.A. Guyer, P.A. Johnson , C. Marone

# DEM modeling

## Motion of particles solving Newton´s equations




- ❑ Normal contact force

- ❑ Tangential contact force

  Coulomb friction law $|F_T| \leq \mu \cdot |F_N|$

  $\mu_S$: static friction

  $\mu_D$: dynamic friction

Ferdowsi et al., in review 2013

# Particle kinetic energy

$$K_{lin}{}^{i} \equiv \frac{1}{2} \cdot m_i \cdot \left\|\dot{\vec{u_i}}\right\|^2$$

translational kinetic energy

$$K_{rot}{}^{i} \equiv \frac{1}{2} \cdot I_i \cdot \omega_i{}^2$$

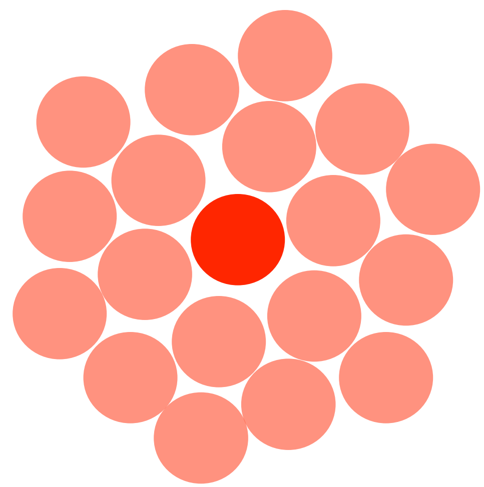
rotational kinetic energy

$m_i \equiv$ mass

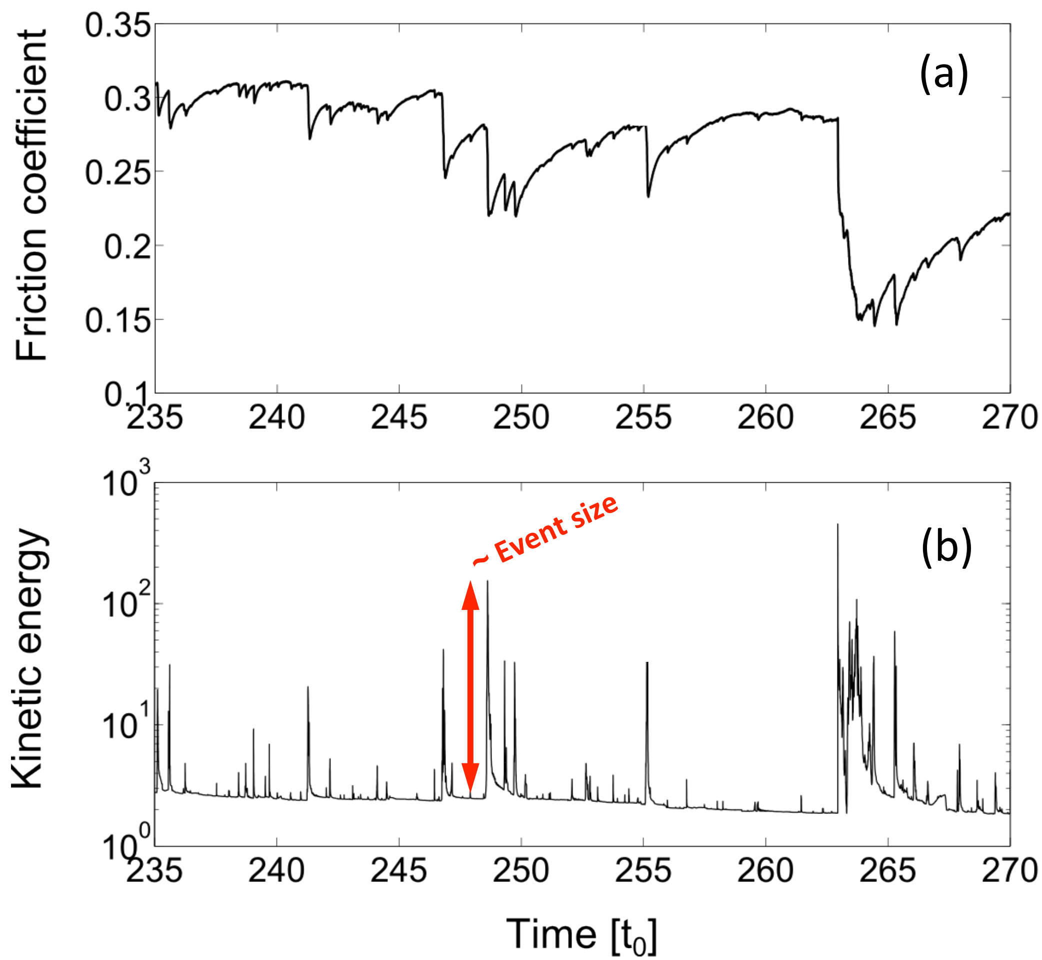
$\vec{u_i} \equiv$ displacement vector

$I_i \equiv$ moment of inertia

$\omega_i \equiv$ angular velocity



# Similarities in Stick-slip dynamics in DEM

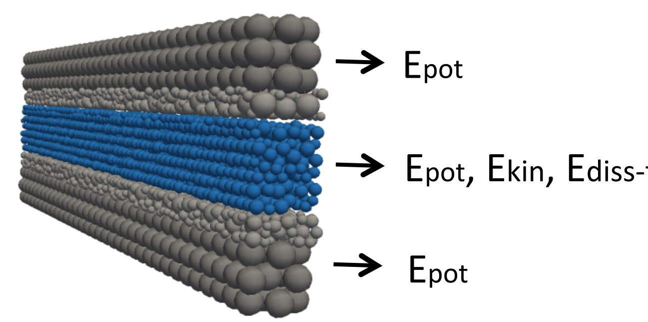



Stick-slip energy budget:

$E_{pot} = E_{kin}$ ~ 10%

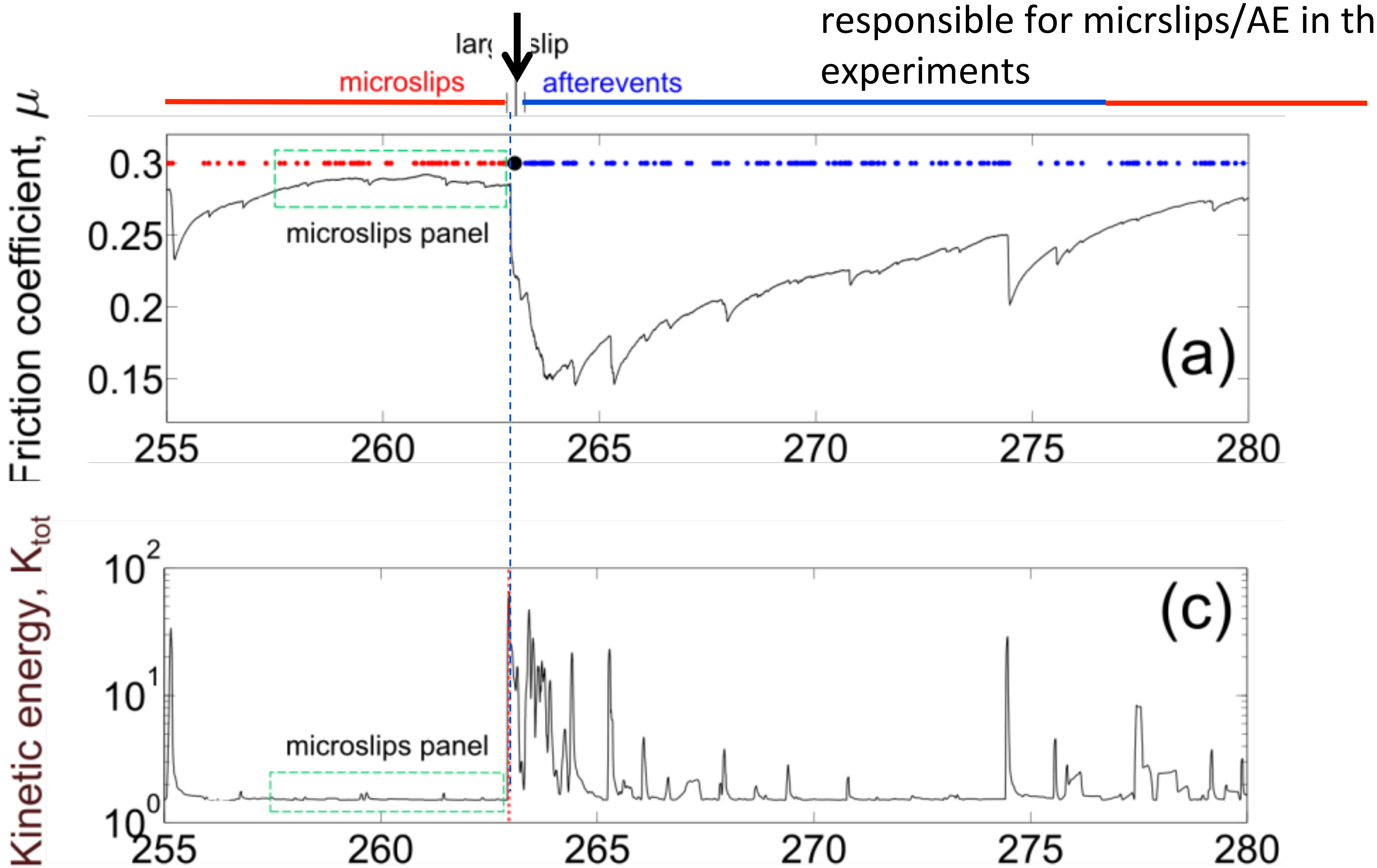
$+ E_{diss\text{-}friction}$ ~ 80%

$+ E_{diss\text{-}viscous}$



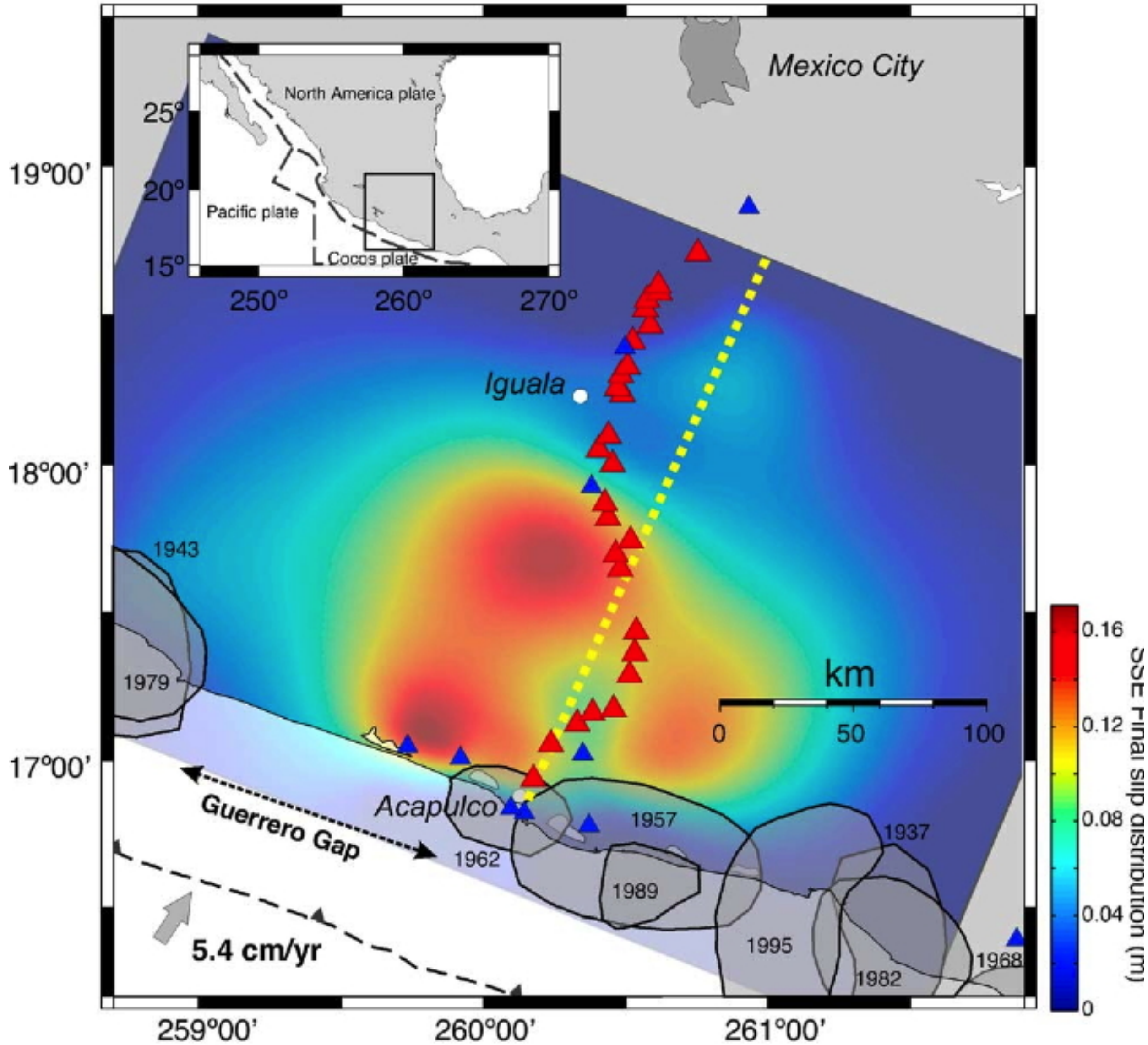
# Slips associated with kinetic energy release

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



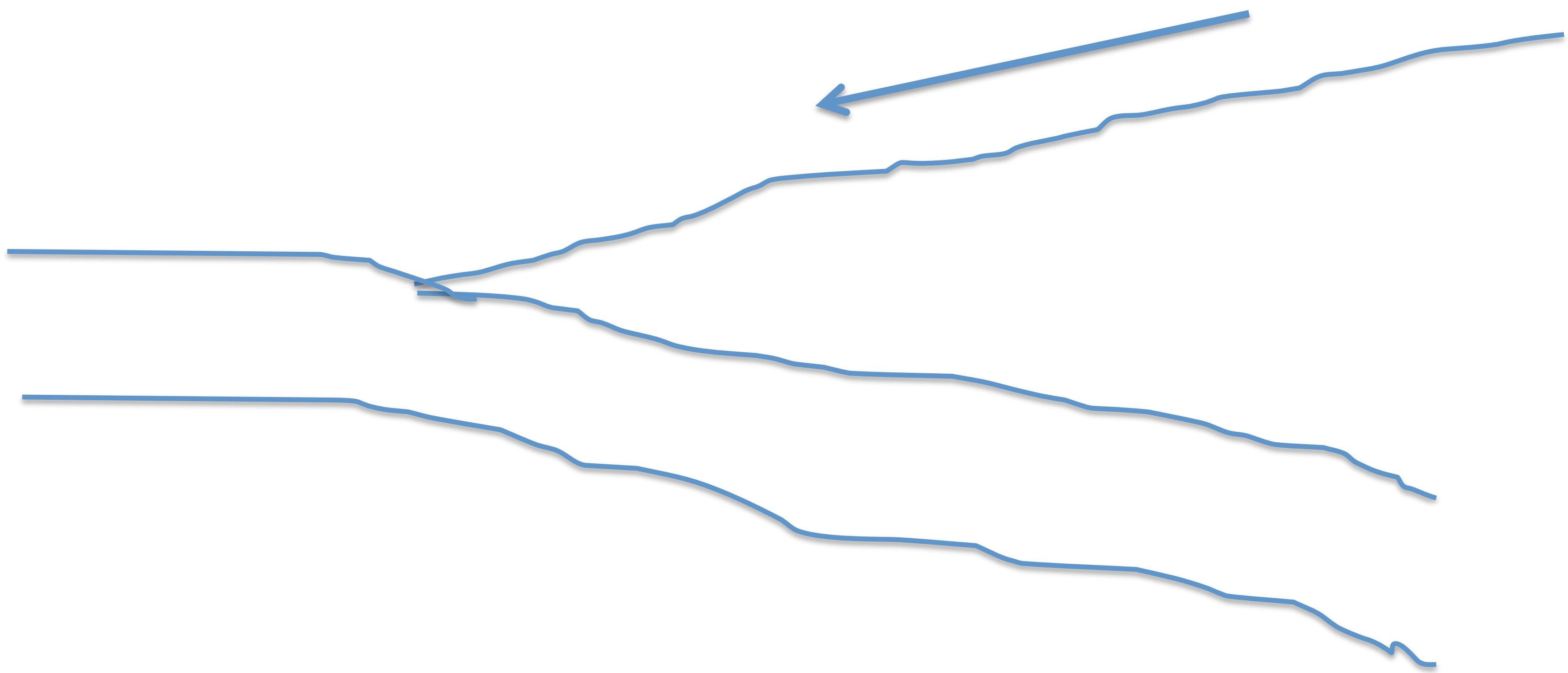

Ferdowsi et al., 2014

# Slow slip at Guererro, Mexico

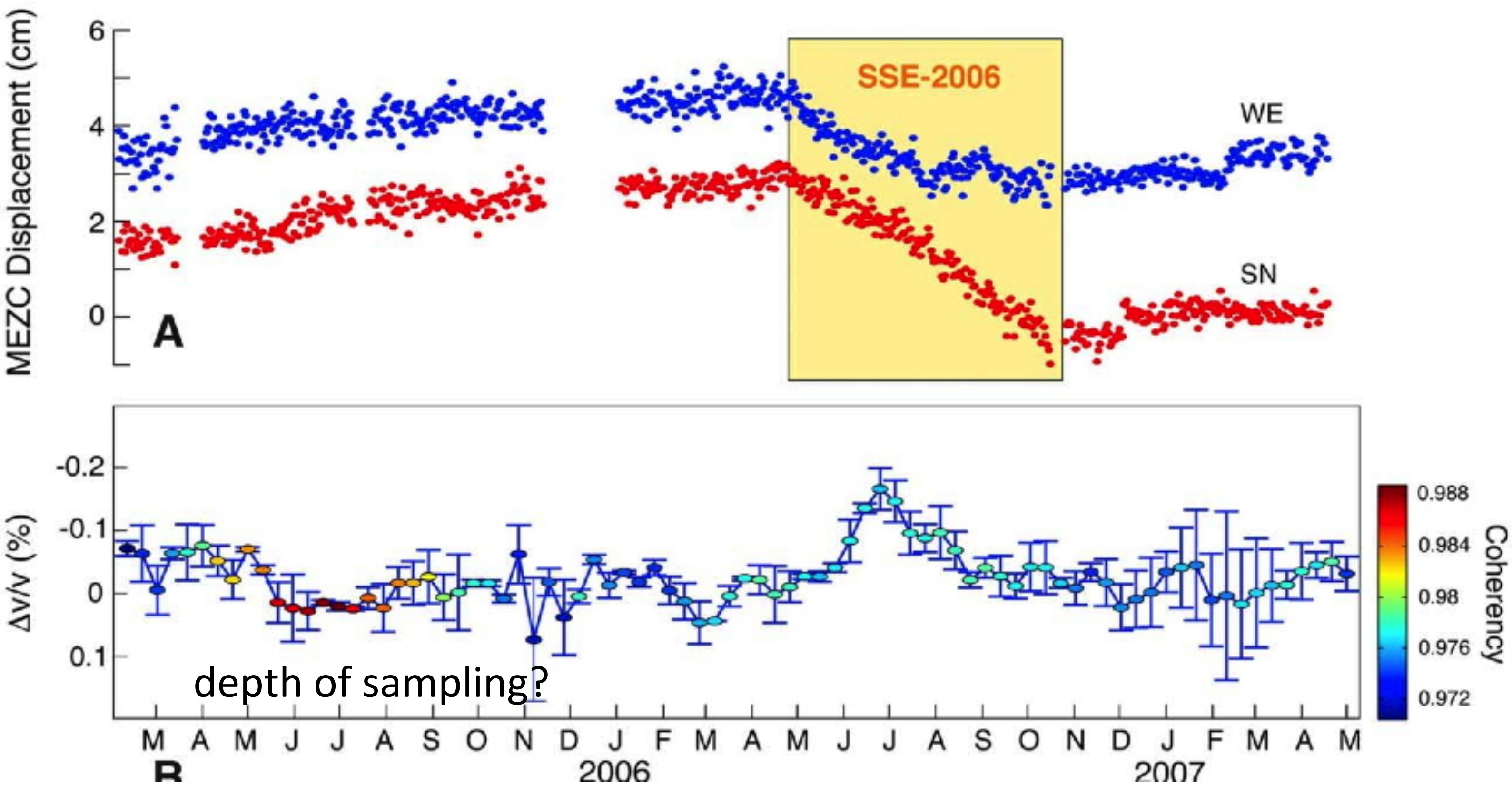



Rivet et al. GRL 2011

# Slow slip



# Guererro



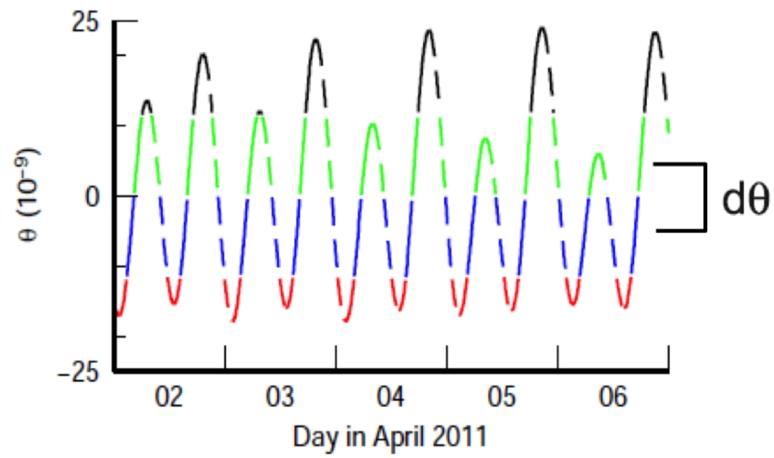

Rivet, et al., GRL 2011

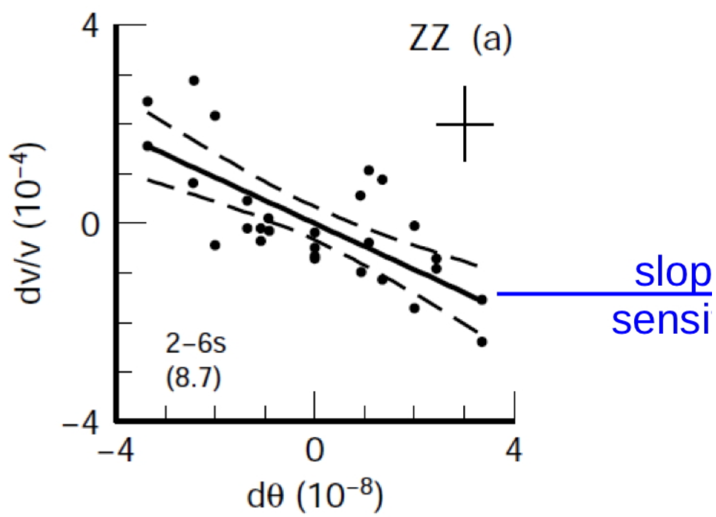
# Guerrero vs. Lab

- Lab experiment in the granular layer
- Guerrero measurement in bulk material that may be highly fractured.

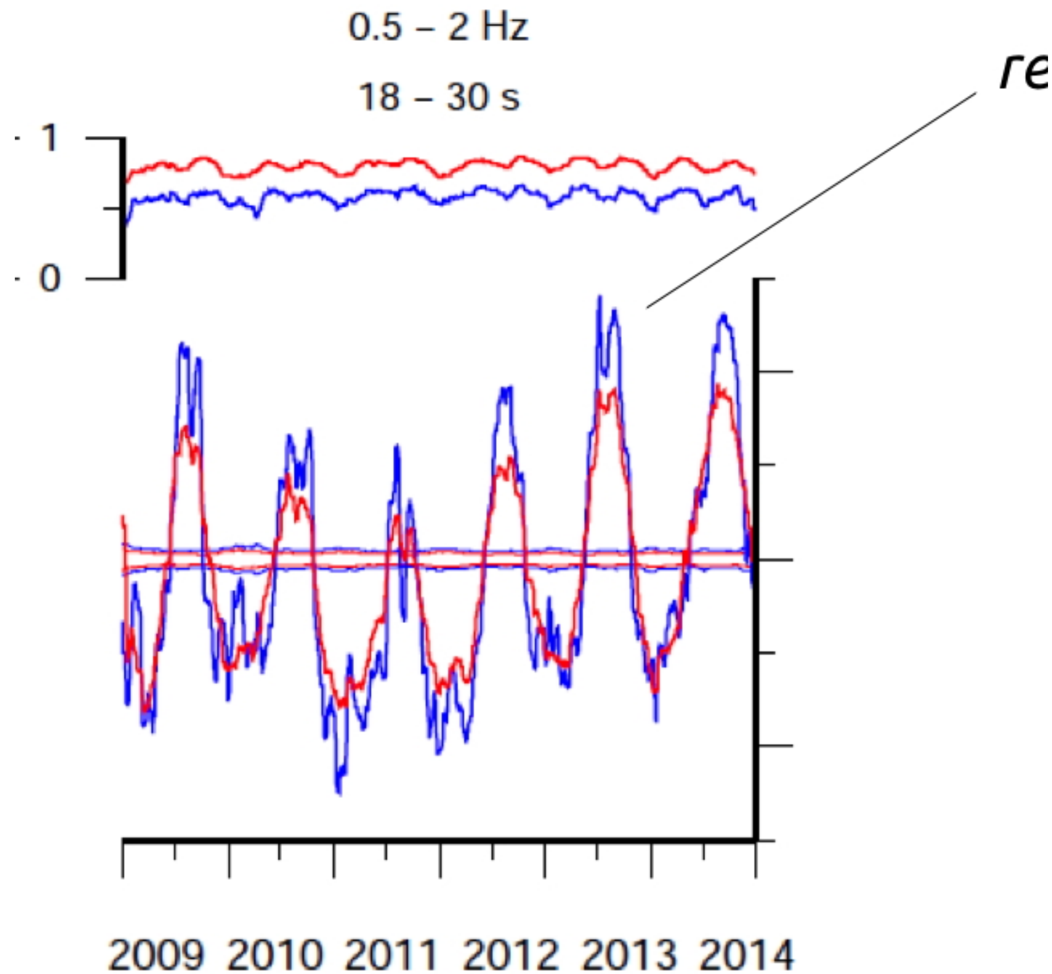
Similar mechanism?

# Hillers- probing earth tide elasticity



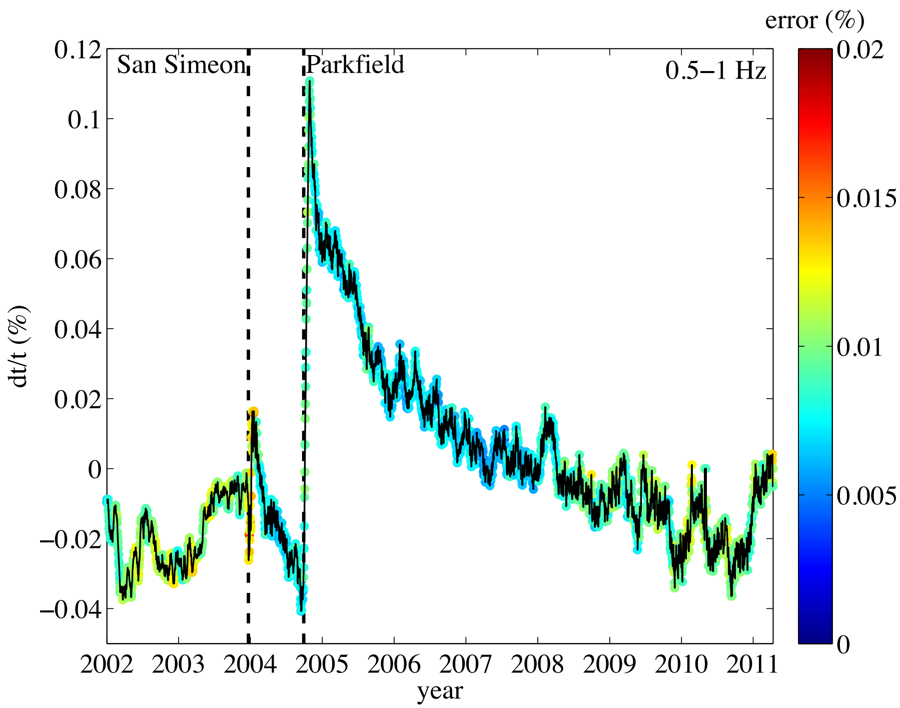
# Hillers – earth tides



## Next:  Parkfield Earthquake recovery study

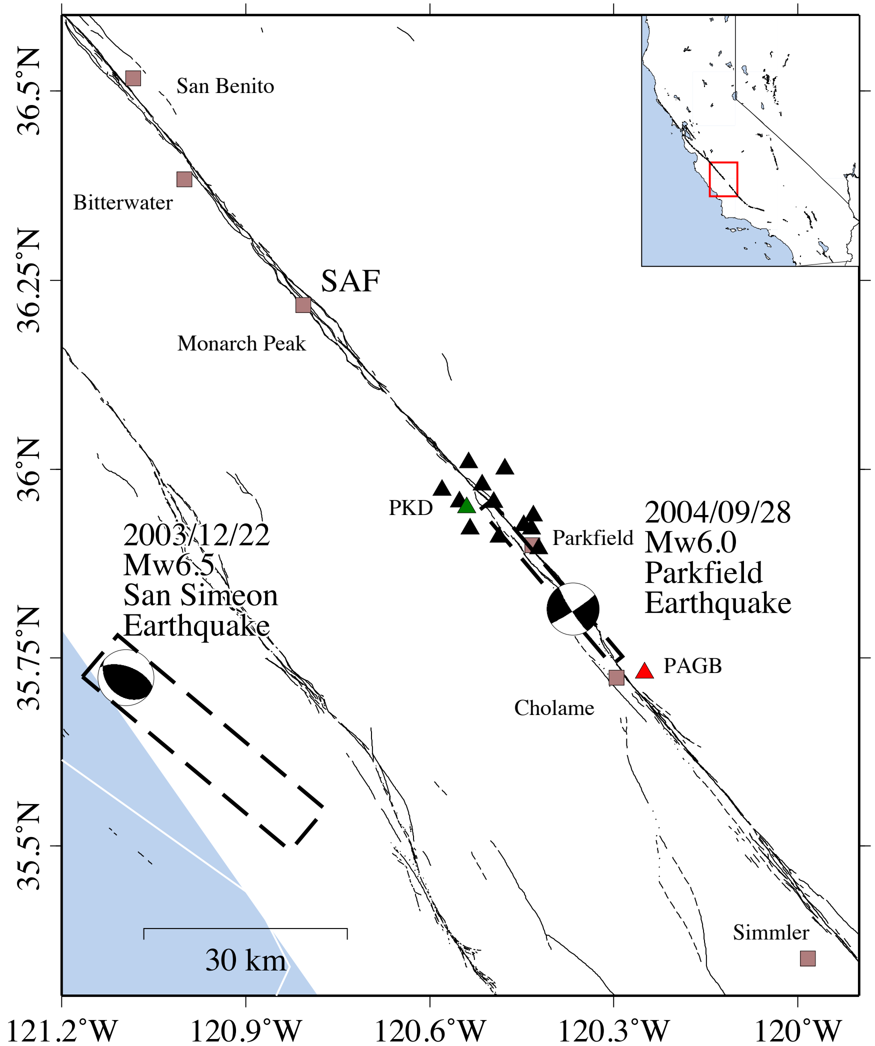
Wu et al., in preparation 2015

# Temporal Changes in Seismic Velocity



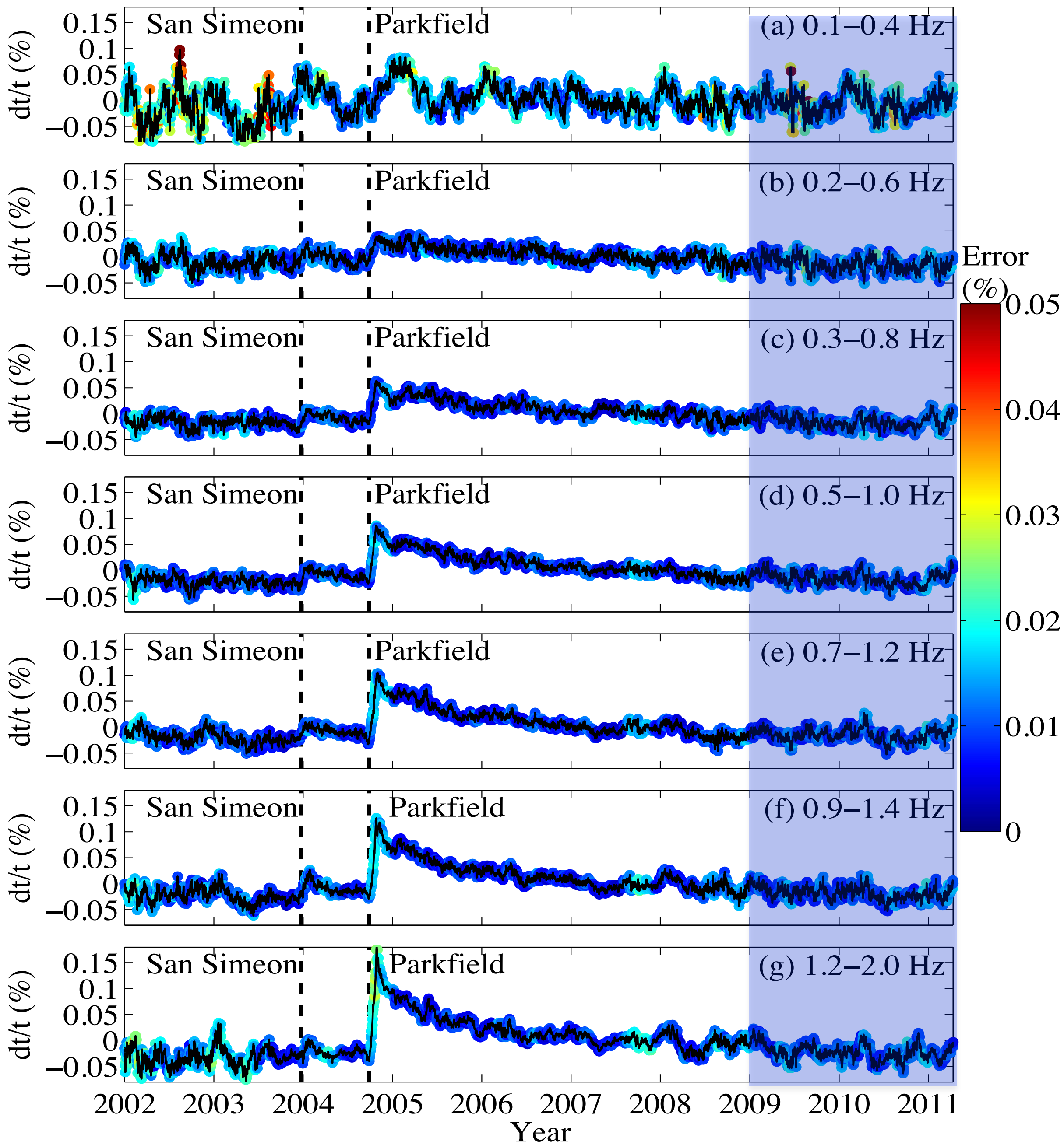

- Passive Noise Imaging
- Tracks changes in empirical Green's functions over time
- Strong shaking causes an increase in travel times due to a weakening of contacts in cracks and faults.

# How deep are the changes?




We apply passive noise in different frequency bands to find out....

Wu et al., in preparation 2015

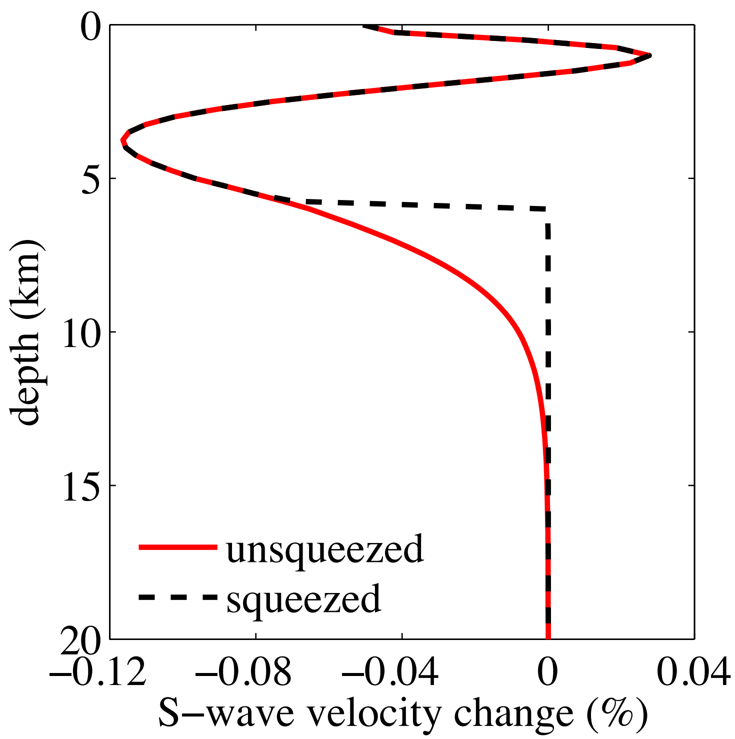



Wu et al., in preparation 2015

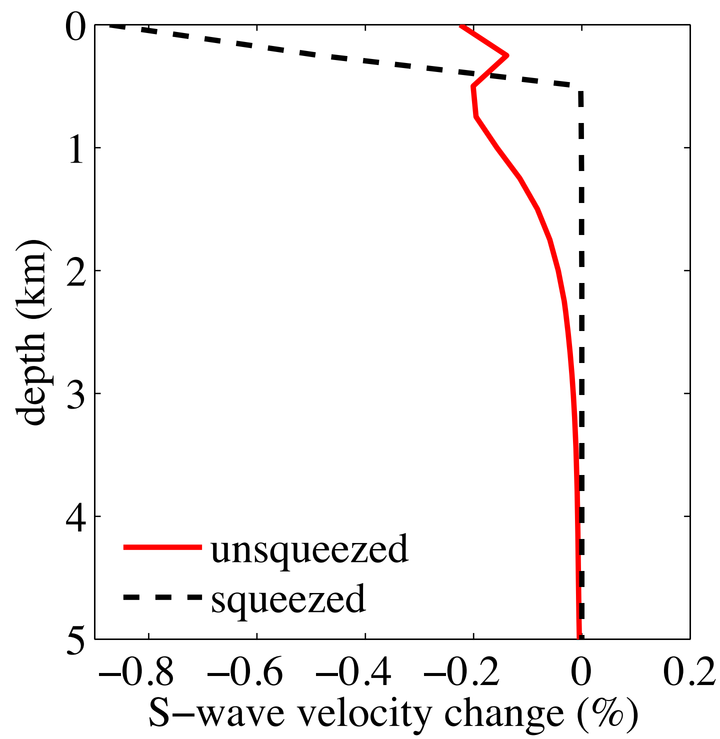
# Surface wave inversion results from passive noise

The red curve is *unsqueezed* inversion result and the black curve is *squeezed* inversion result. Squeezed means we force the velocity changes to the shallower depths in the inversion, to estimate how deep the Vs must be to fit the observed phase velocity changes.

San Simeon




Parkfield



We saw an overview of Nonlinear elastic effects in earth materials, and nonlinear effects in Earth.