Two Observational Stories

I. Earthquakes Triggered by Seismic Waves

II. The Feedback Between Fault Surface Topography and Granular Flow Inside a Fault Zone

Earthquakes Triggered by Seismic Waves

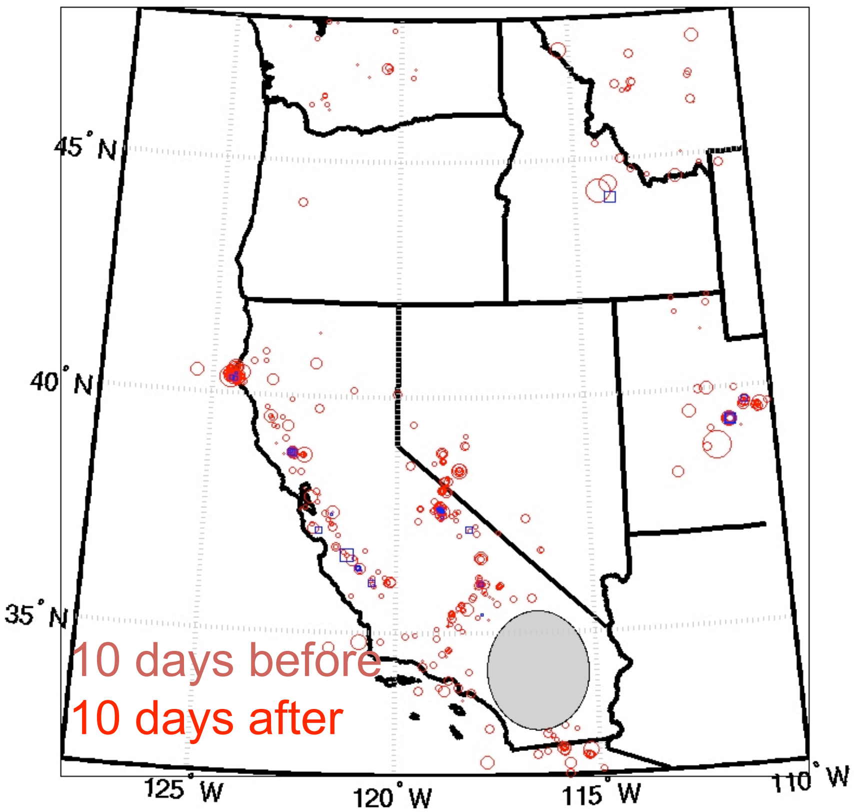
Emily E. Brodsky
UC Santa Cruz

Nicholas Van der Elst
UC Santa Cruz

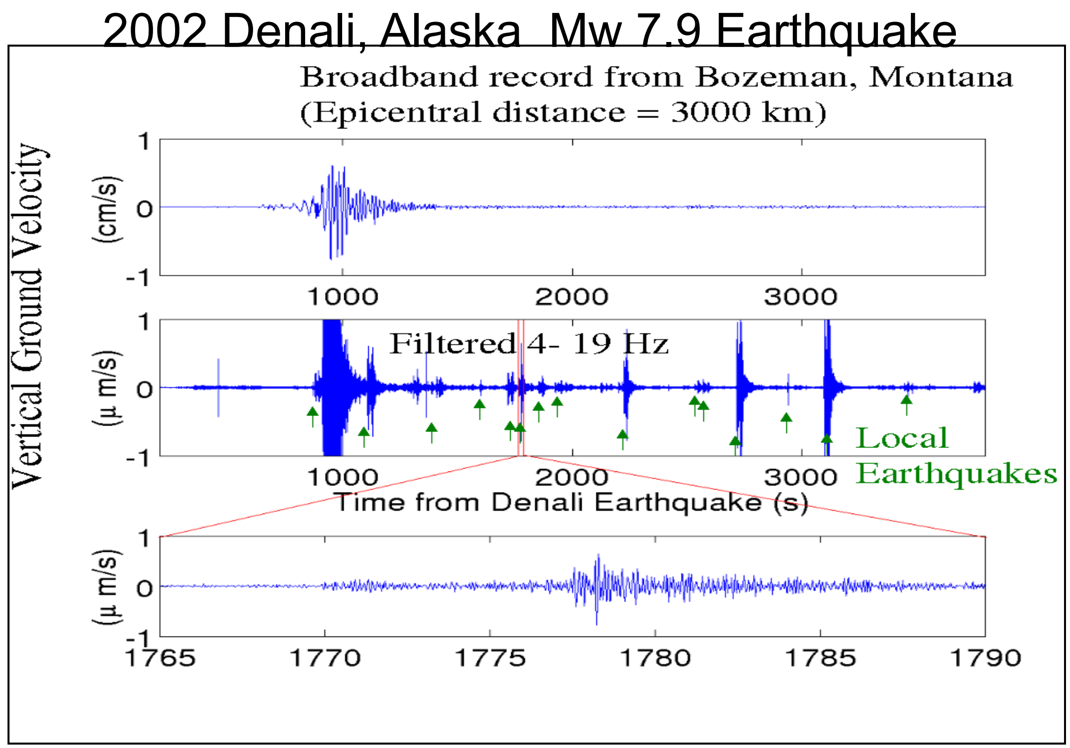
Jean Elkhoury, Caltech
Karen Felzer, USGS

Seismic waves trigger earthquakes

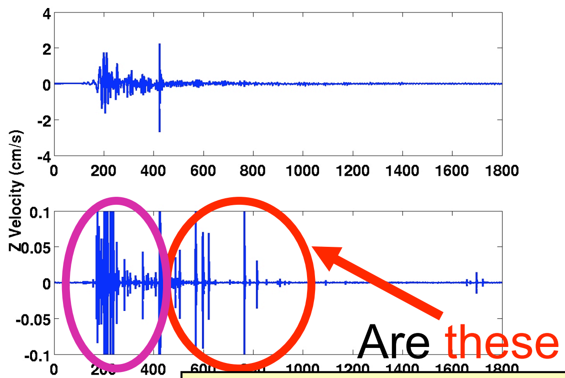
M_w=7.3 1992 Landers Earthquake

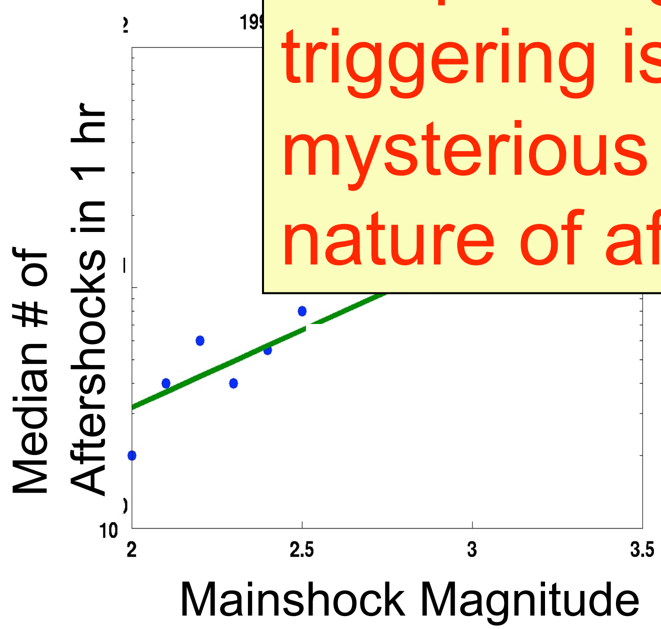


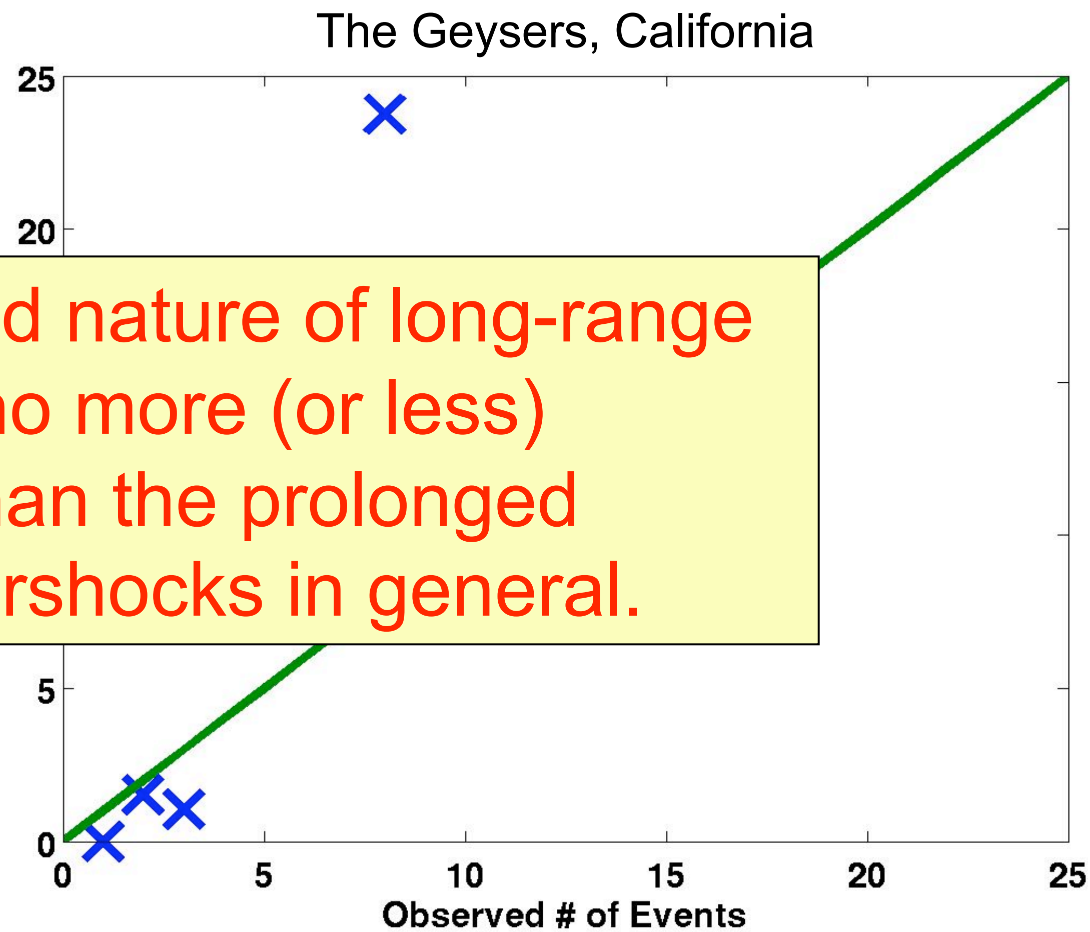
Hill et al., Science, 1993



Sustained Long Range Triggering







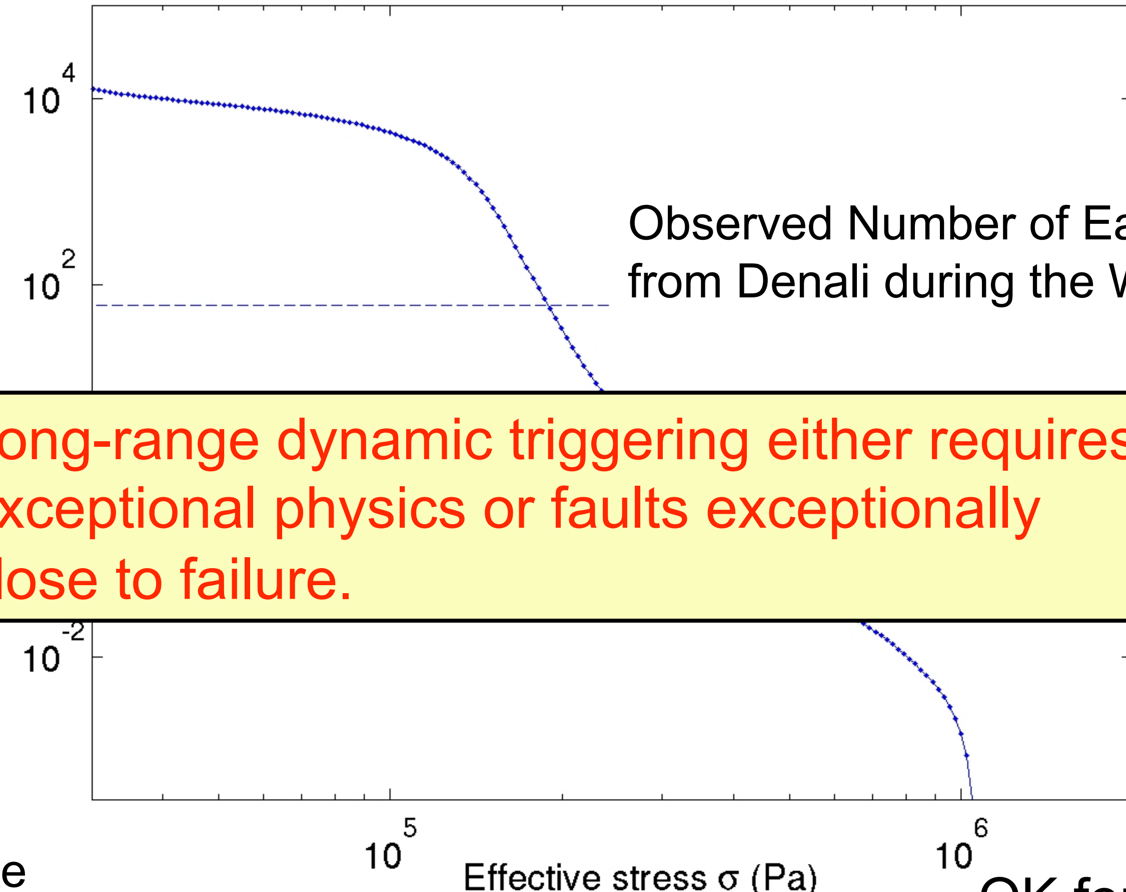
The prolonged nature of long-range triggering is no more (or less) mysterious than the prolonged nature of aftershocks in general.

Brodsky, *GRL*, 2006

Making Earthquakes From Small Stresses is Hard

Rate and State Prediction

(Dieterich 1994)



Observed Number of Earthquakes from Denali during the Wavetrain

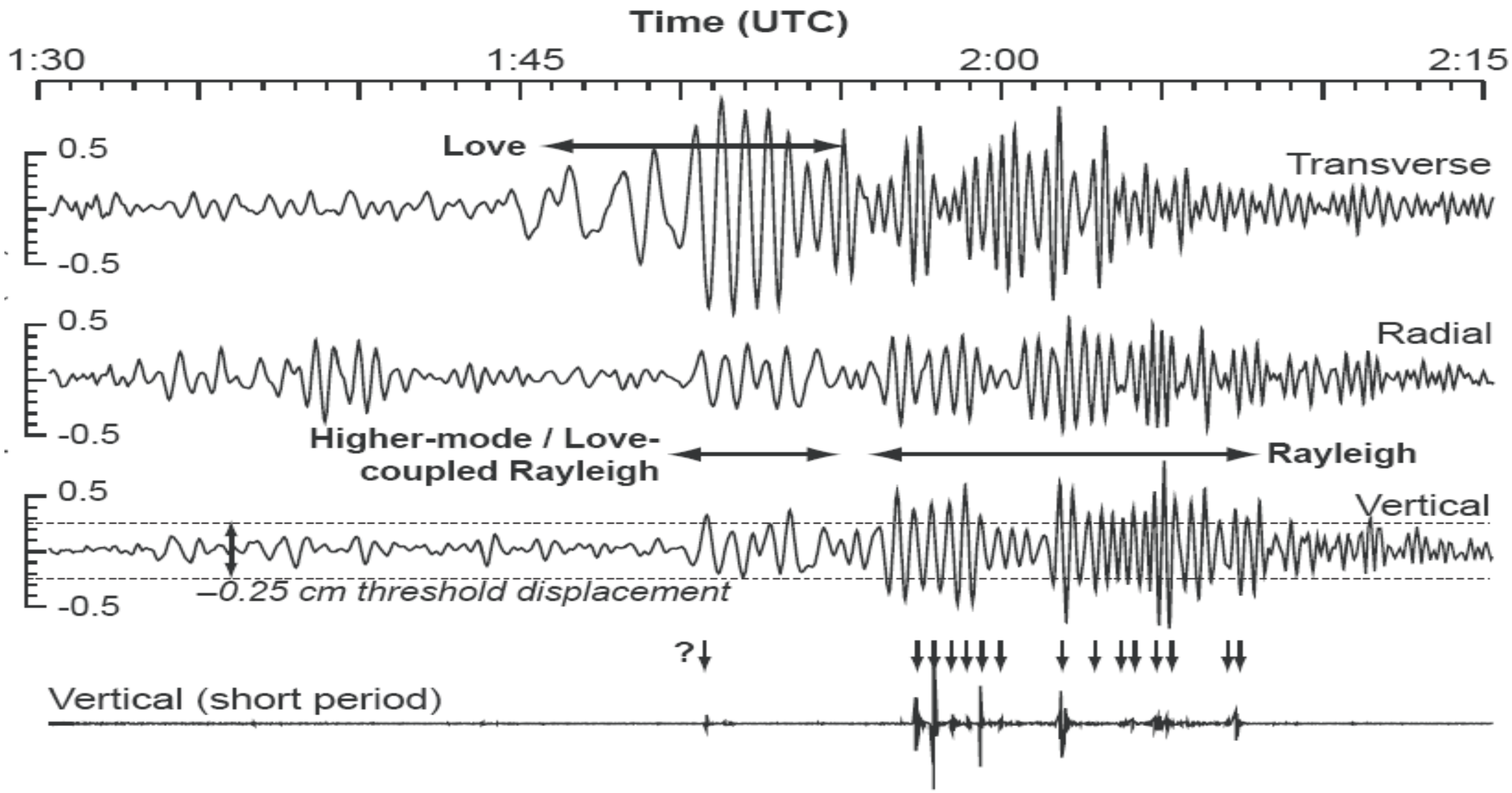
(Lithostatic stress – pore pressure)

Long-range dynamic triggering either requires exceptional physics or faults exceptionally close to failure.

Ingredients:
-Rate-state frictional failure
-Distribution of nuclei designed to provide a constant seismicity rate

OK for Long Valley,
But not Geysers

Synchronized triggered earthquakes

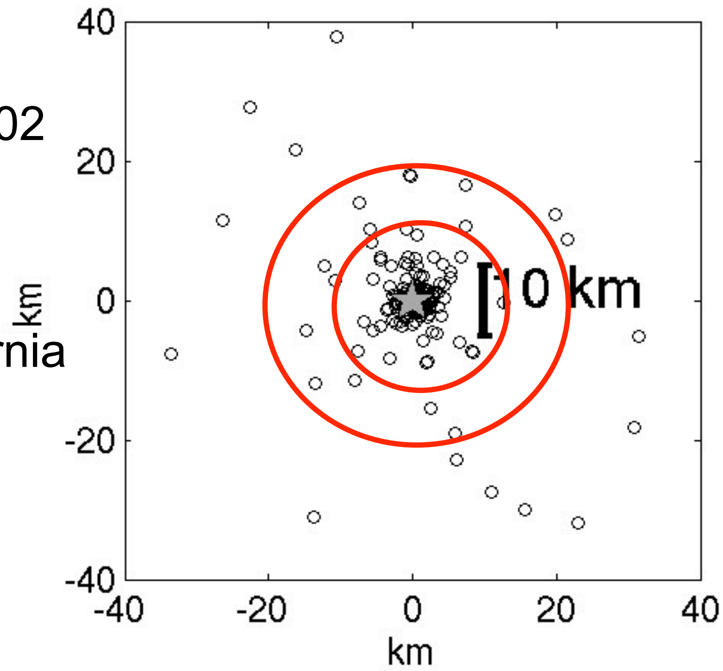


West et al., *Science*, 2005

Intermediate-Field Aftershocks

Combined aftershocks of M3-4 mainshocks 1984-2002 for 30 minutues after the mainshock

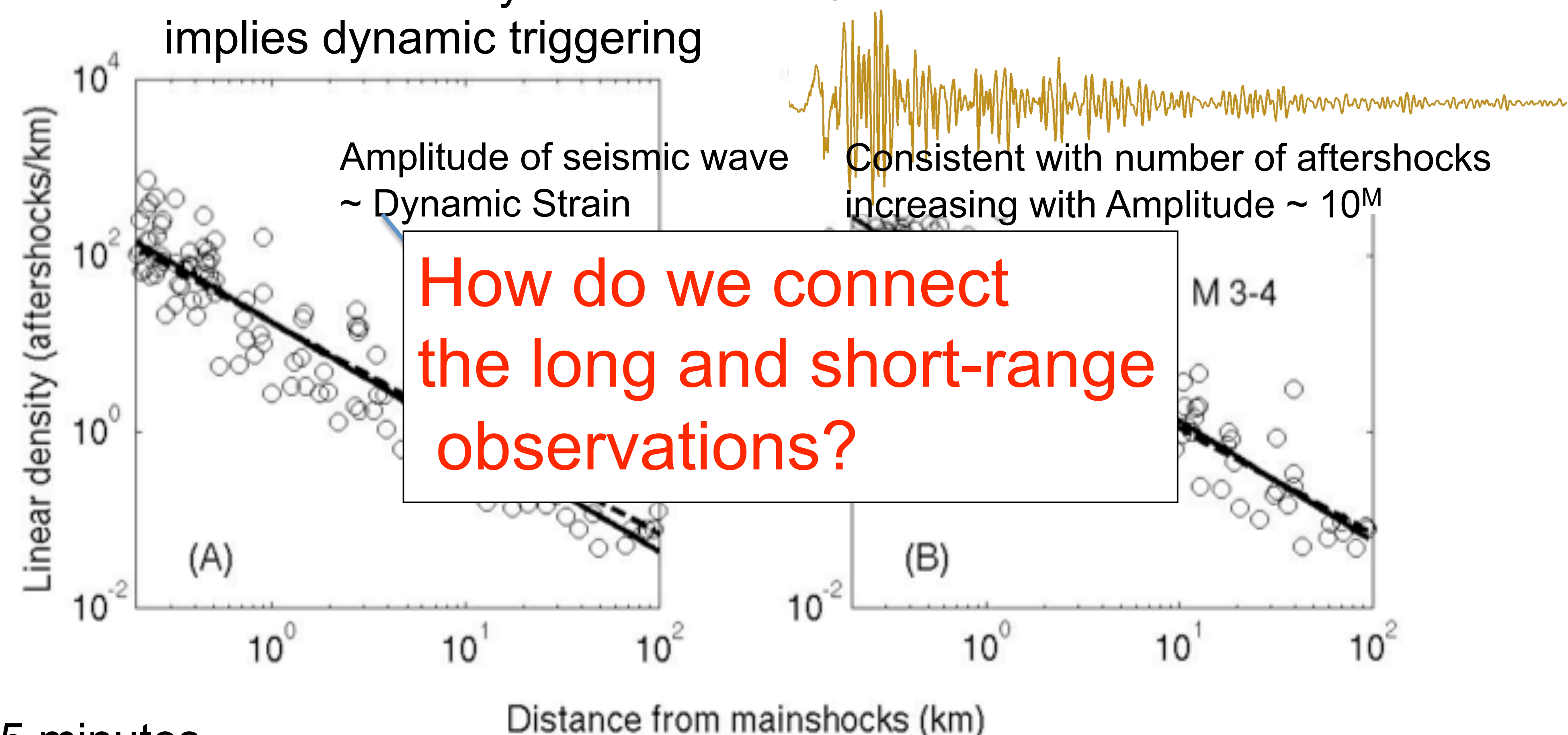
Relocated Southern California catalog (Shearer et al., 2005)



Felzer and Brodsky, *Nature*, *2006*

Aftershock Spatial Decay

Consistent decay function to large distances
implies dynamic triggering



Amplitude of seismic wave
~ Dynamic Strain

Consistent with number of aftershocks
increasing with Amplitude ~ 10^M

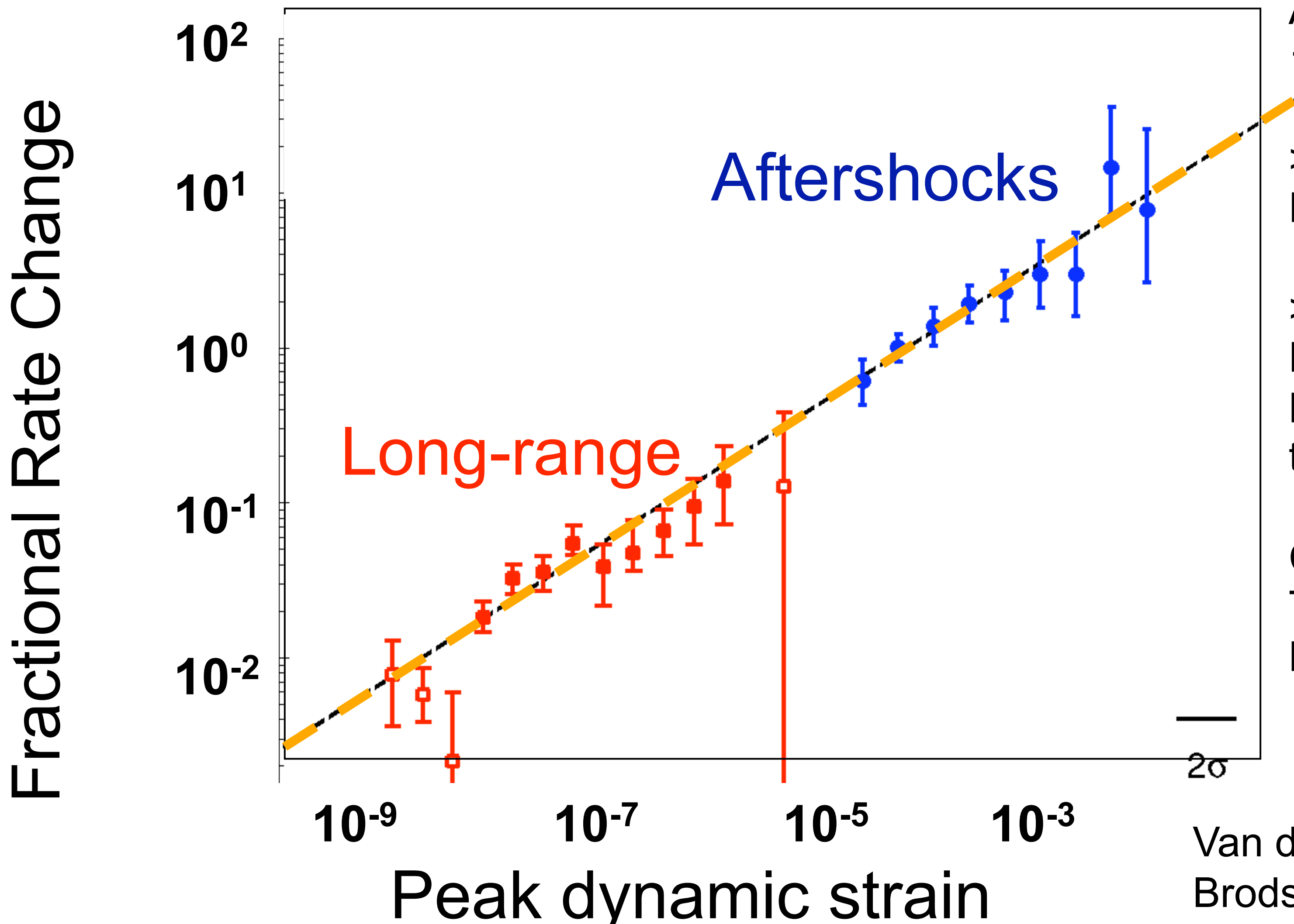
How do we connect
the long and short-range
observations?

5 minutes
after a mainshock

Aftershock Density ~ $C\,r^{-1.4}$

Felzer and Brodsky, *Nature*, *2006*

Connecting Long-Range and Short-range Triggering



ANSS
1984-2008

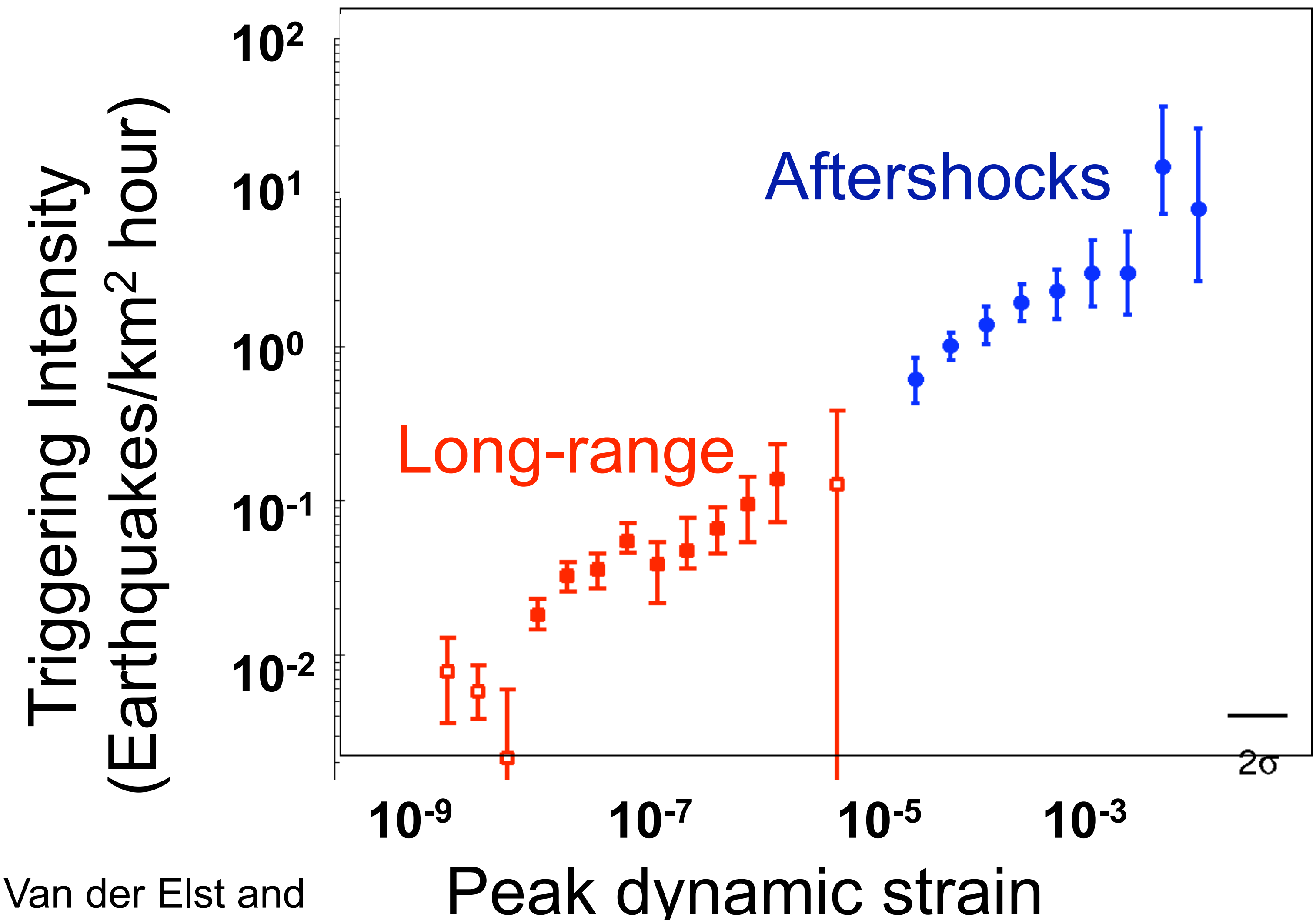
>125,000
Earthquakes

>2500
Potential
Long-range
triggers

Completeness
Threshold
M2.1

Van der Elst and
Brodsky, *JGR*,
submitted

California



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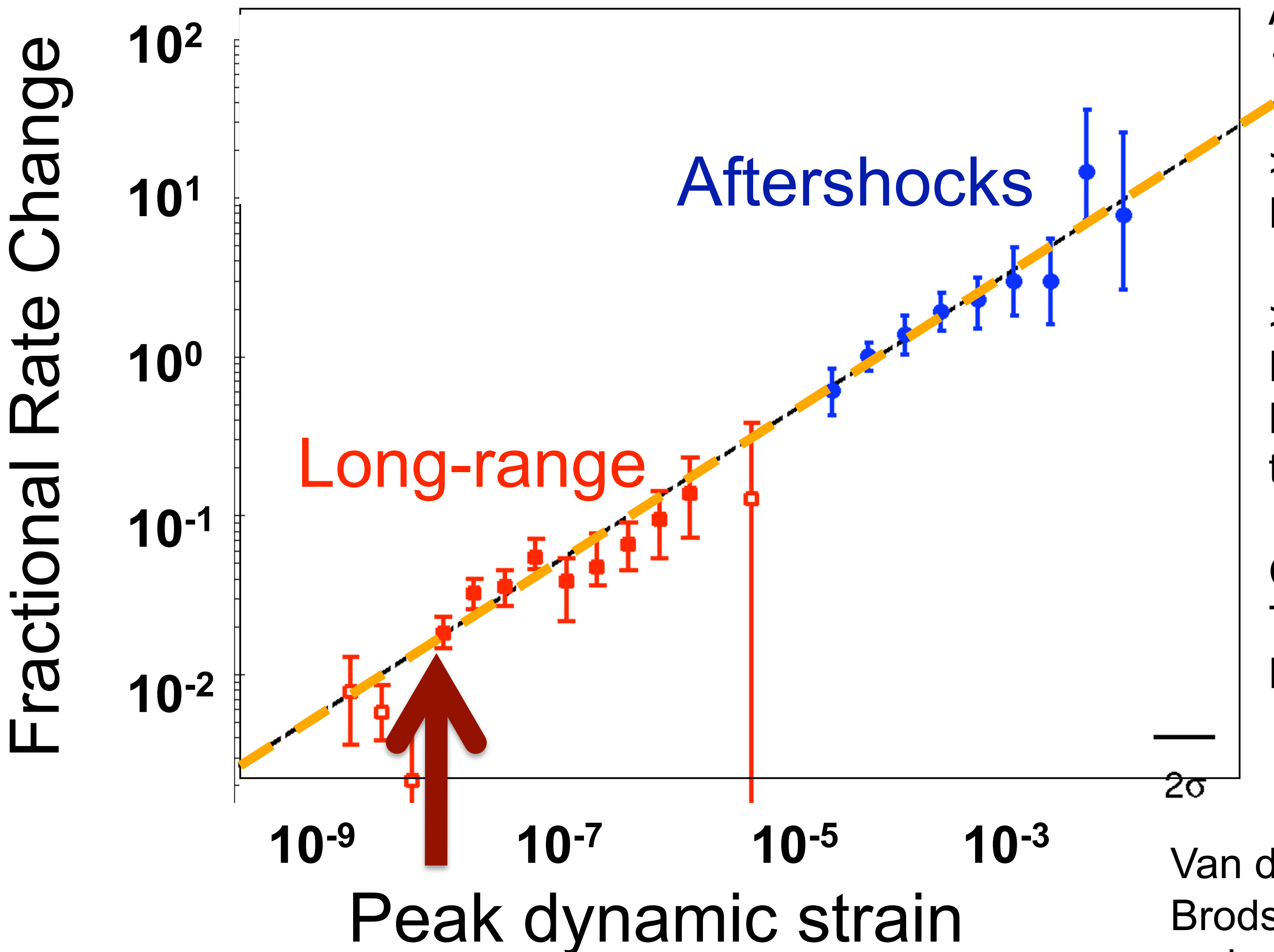
Van der Elst and
Brodsky, *AGU*, 2008

Connecting Long-Range and Short-range Triggering



ANSS
1984-2008

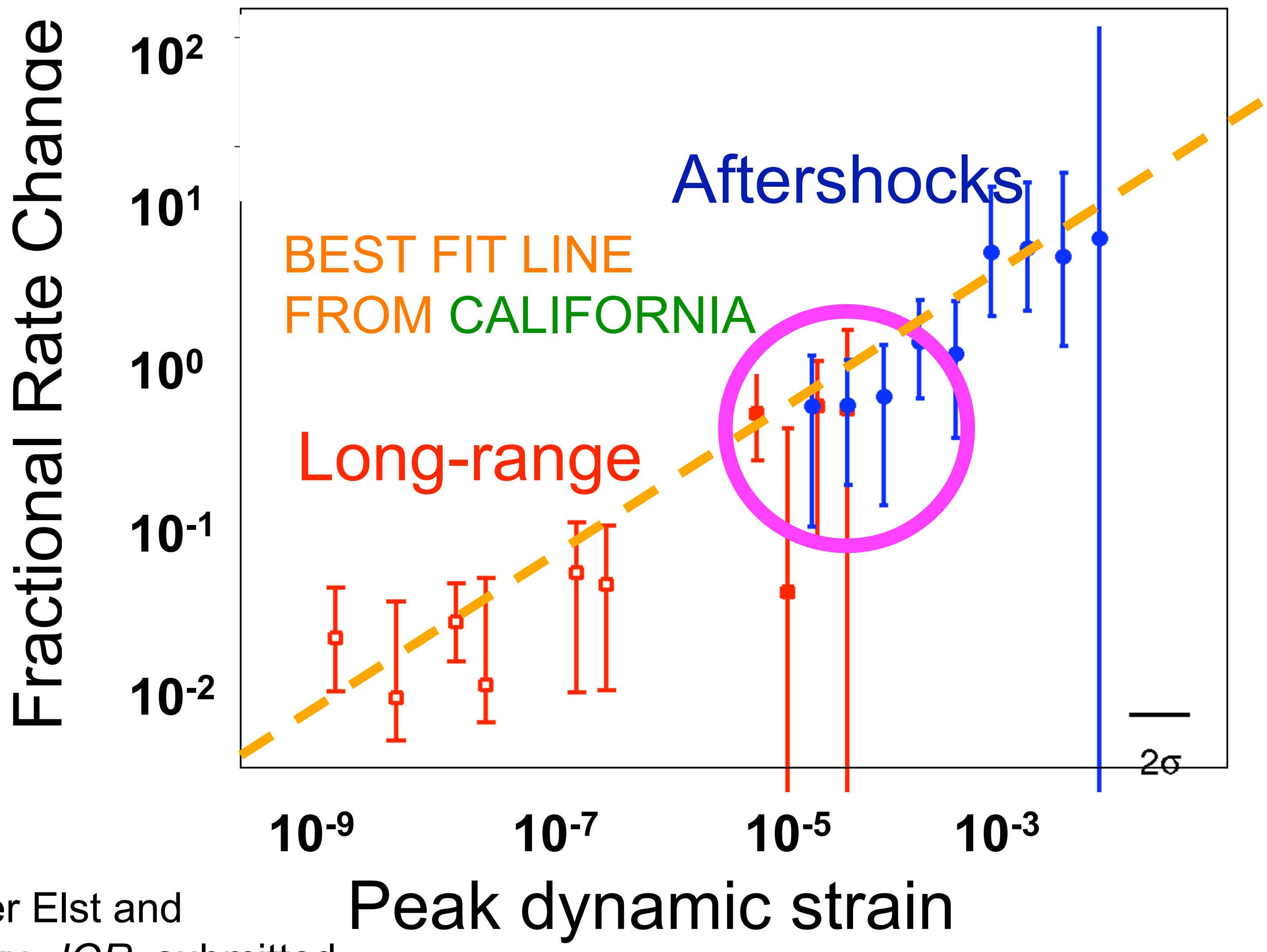
>125,000
Earthquakes

>2500
Potential
Long-range
triggers

Completeness
Threshold
M2.1

Van der Elst and Brodsky, *JGR*, submitted

Crustal Japan

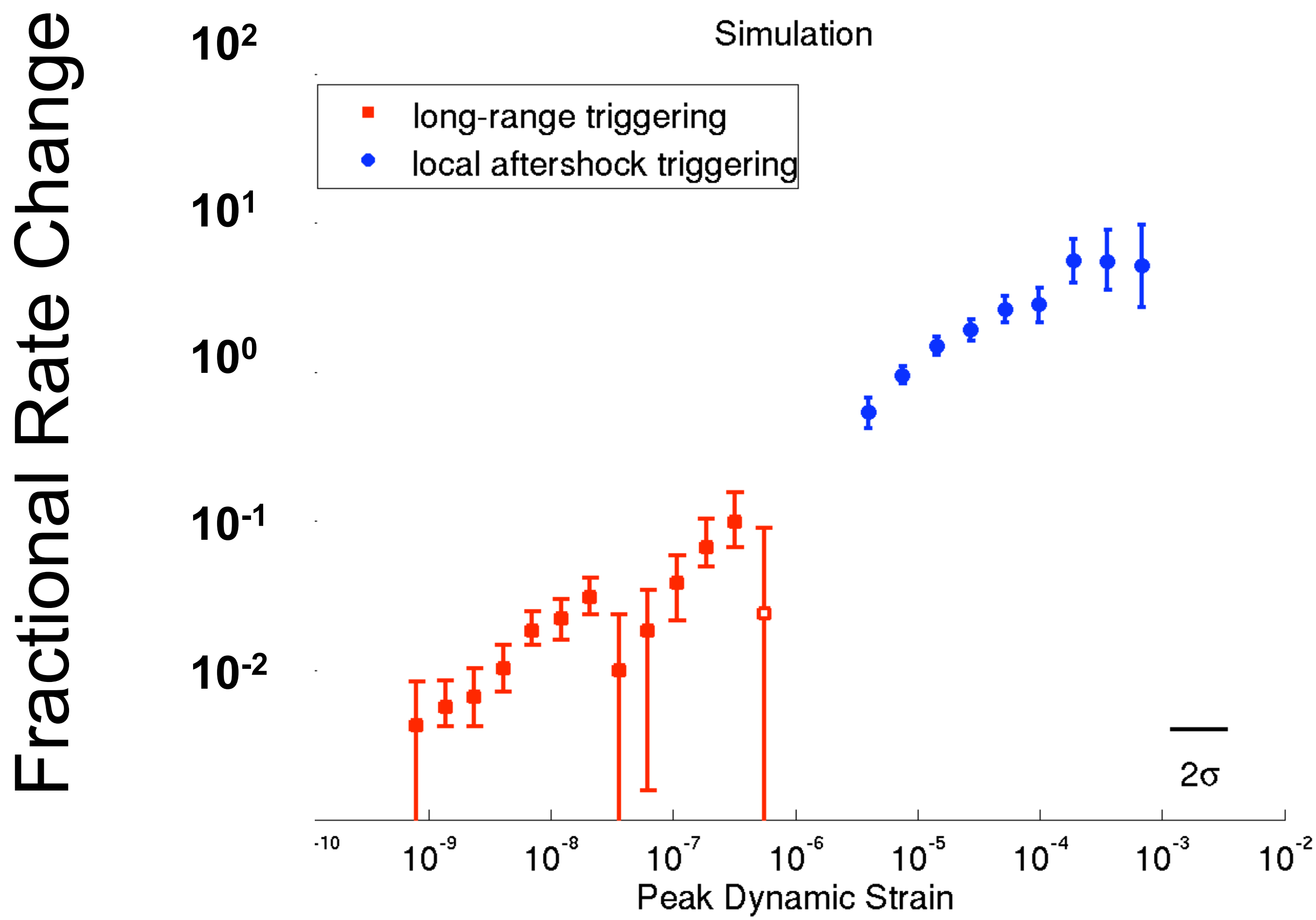


JMA
1997-2006

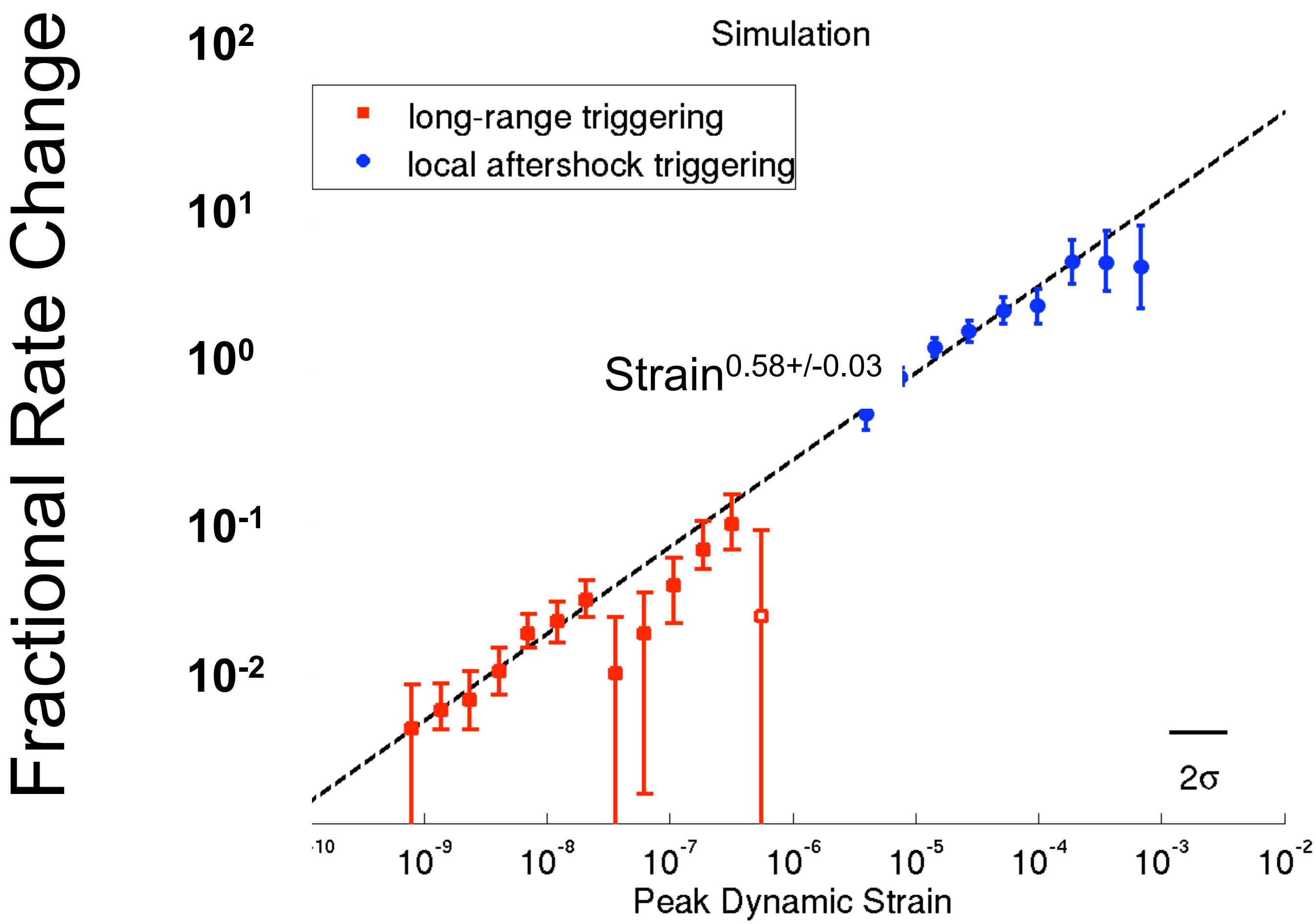
>25,000
earthquakes

Van der Elst and
Brodsky, *JGR,* submitted

Synthetic: Triggering Rate Proportional to Dynamic Strain



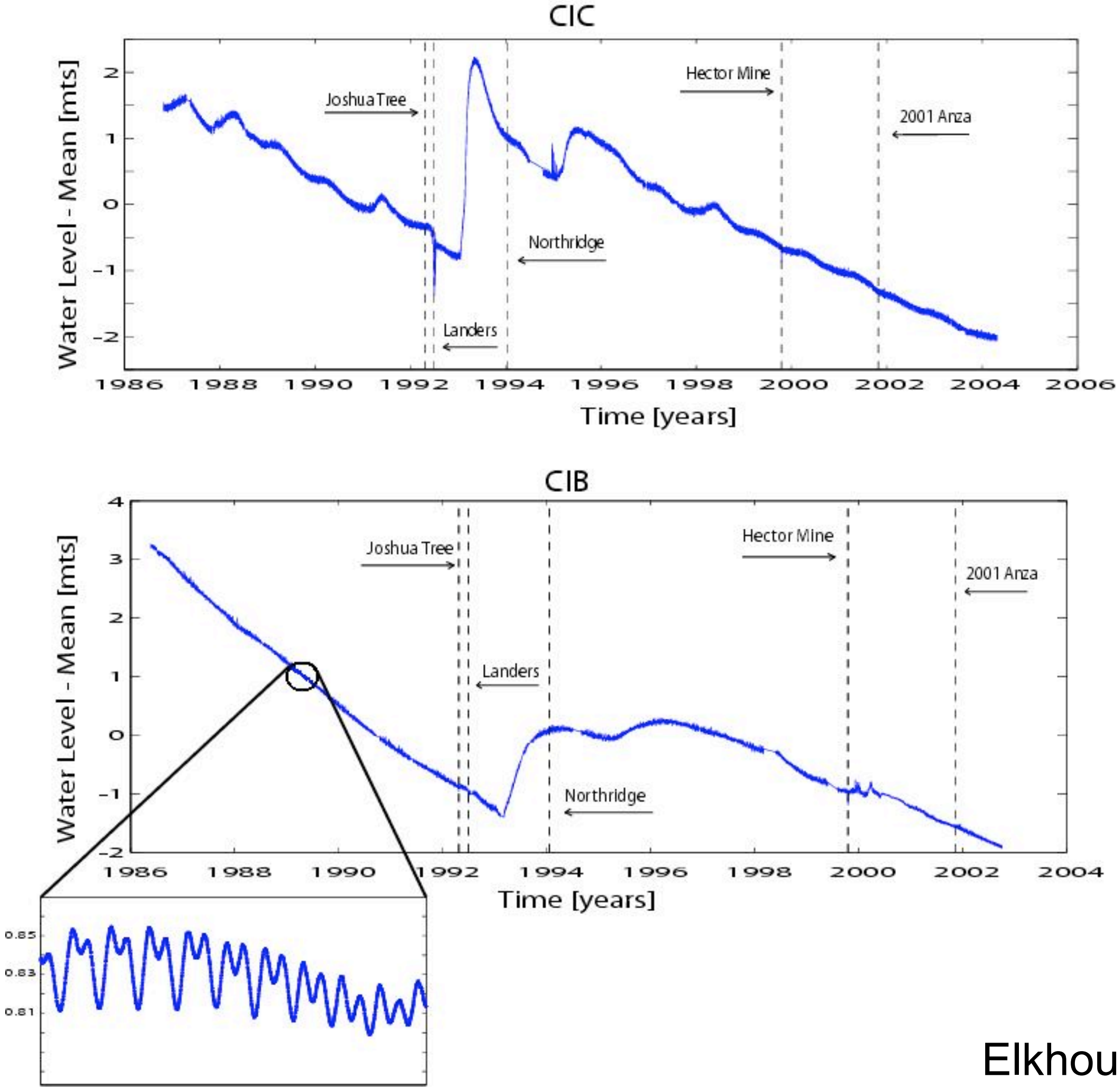
Synthetic: Triggering Rate Proportional to Dynamic Strain

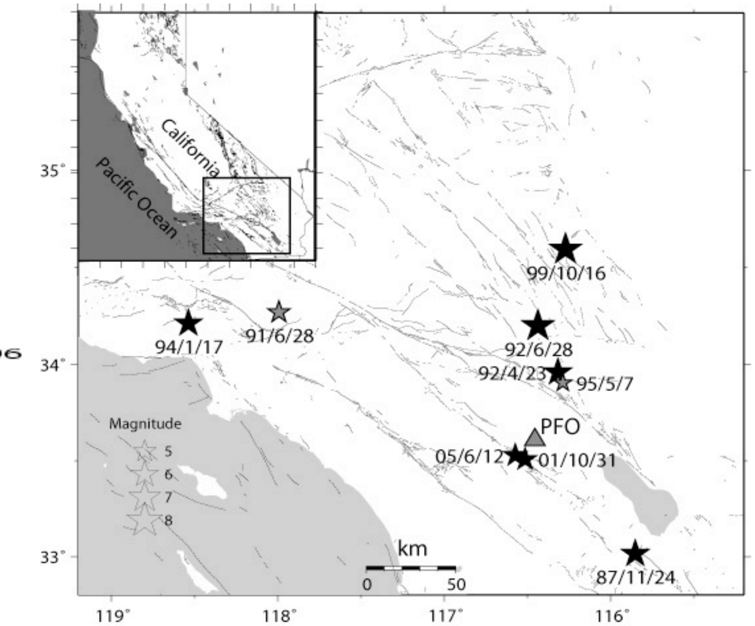


What is the Physics?

- Distribution maps strengths of faults
- Look for clues by finding other observables that have the same features:
  - Correlate with seismic wave amplitude
  - Trigger with very small strains

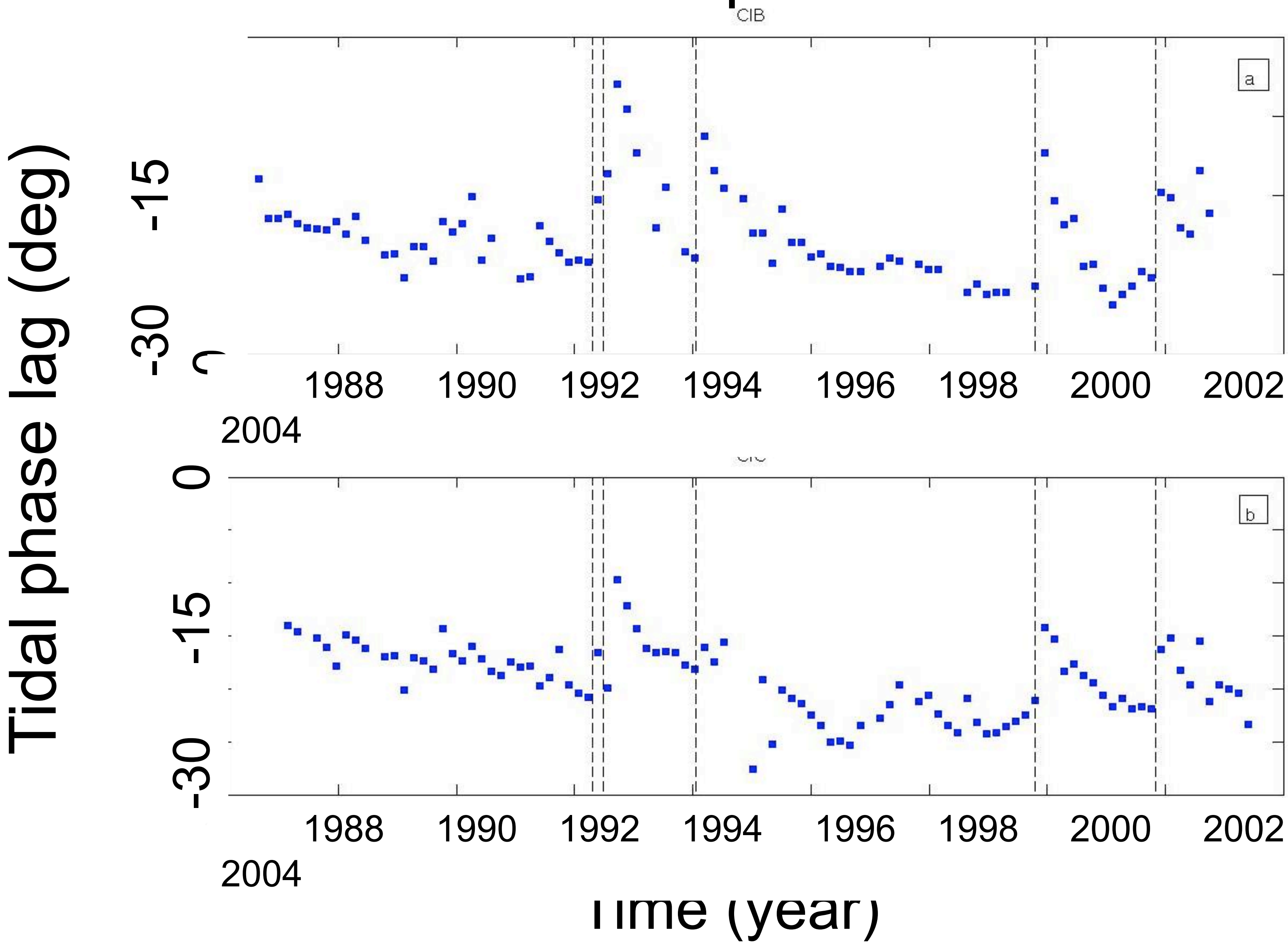
Tidal responses as a probe of permeability



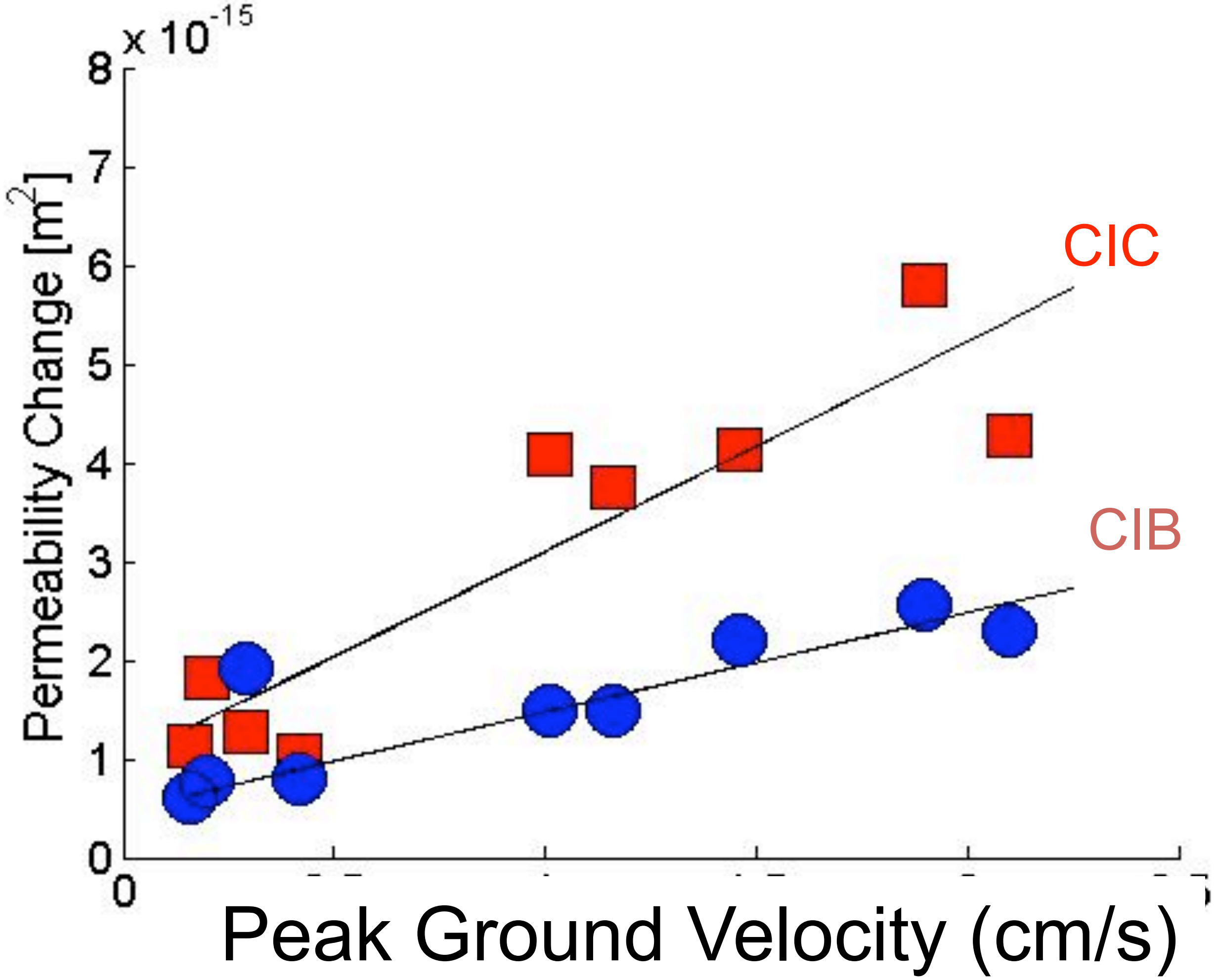


Elkhoury, Brodsky and Agnew, *Nature*, *2006*

Phase Changes at the Time of Earthquakes



Permeability Increases with Shaking

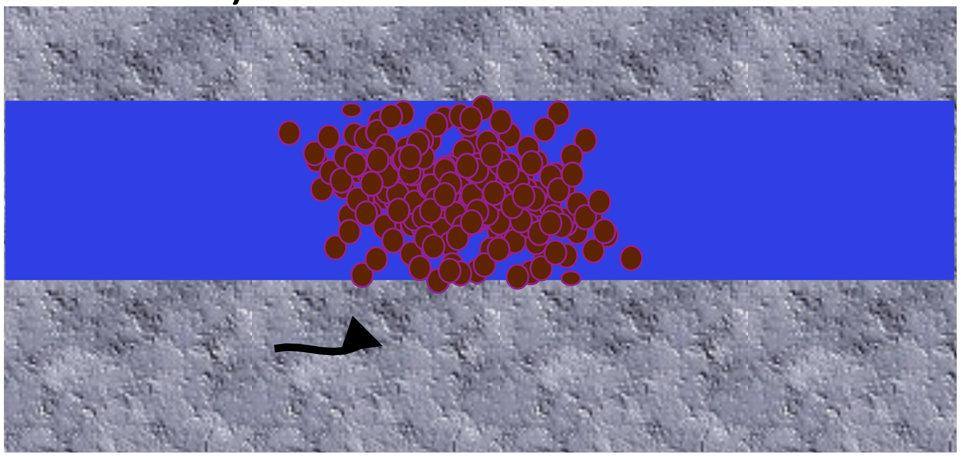


1 cm/s ~0.1 MPa

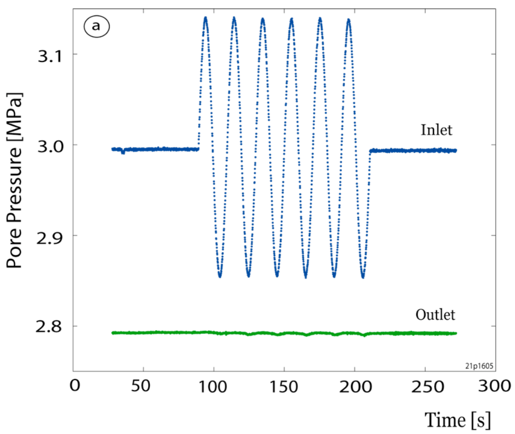
Elkhoury, Brodsky and Agnew, *Nature*, *2006*

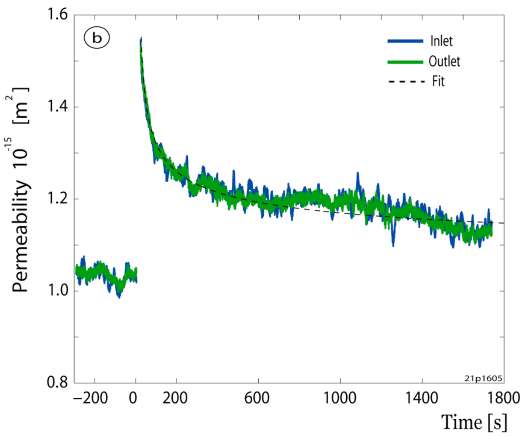
An Idea:
Unclogging Fractures

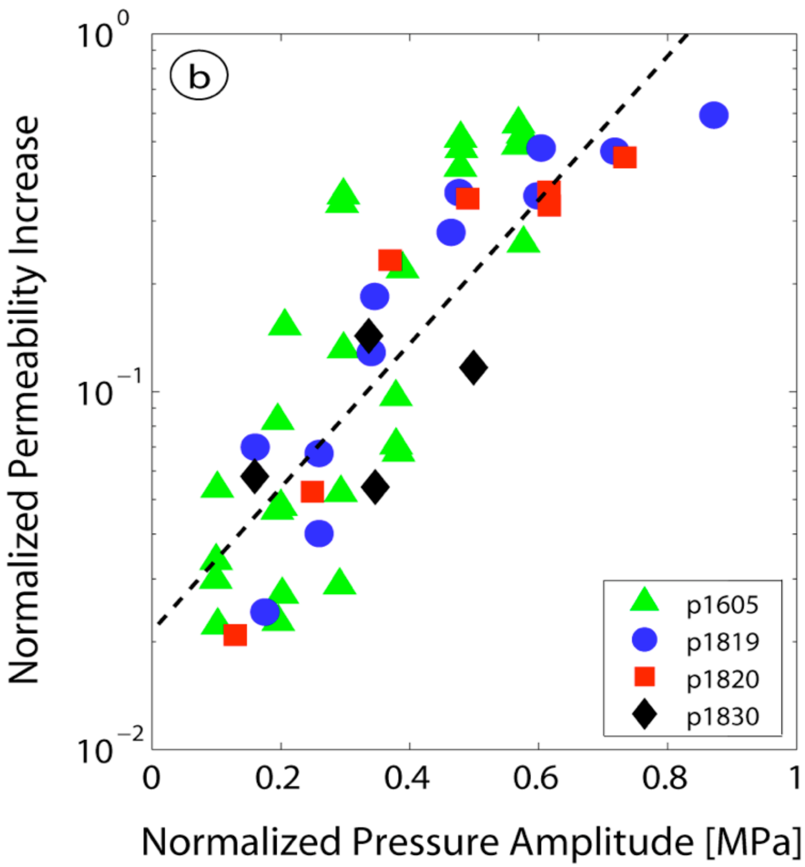
- Waves rearrange pore pressure in faults
  - Small stresses amplified in flow
  - Sustained pressure
  - Permeability change
    - (Also explains other well data)



And Reproduced in the Lab?







Elkhoury et al., *JGR*, submitted

Conclusions Categorized by Confidence

- *We know:*
  - Seismic waves trigger earthquakes
    - Very small strains (10^{-9}) trigger (rarely)
      - Previous triggering thresholds (10^{-6}) are likely observational, not physical
    - Regions vary in their triggerability
      - Japan is less triggerable than California
- *We think:*
  - Triggering intensity based on time ratio connects long and short range triggering
  - Dynamic strain$^{1/2}$ is a good indicator of the triggered rate change
    - This is (perhaps trivially) earthquake prediction (or at least forecasting).
    - Can compute short-term probability based on the seismic wave field
  - Triggering number is proportional to peak strain
- *We speculate:*
  - The consistent trend implies over 6 orders of magnitude strains suggests that seismic waves are a major component of the triggering at all distances.
  - The repeatable and predictable variations observed in hydrological systems from seismic waves are recording a related form of damage/mobilization or effective stress change.

The Feedback Between Fault Surface Topography and Granular Flow Inside a Fault Zone

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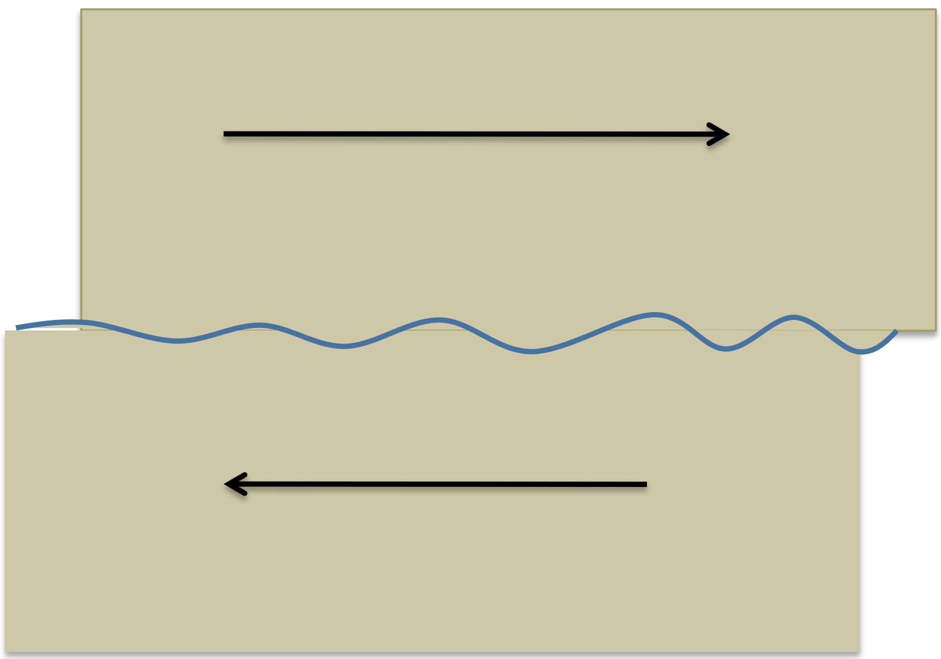
Amir Sagy*
University of California, Santa Cruz

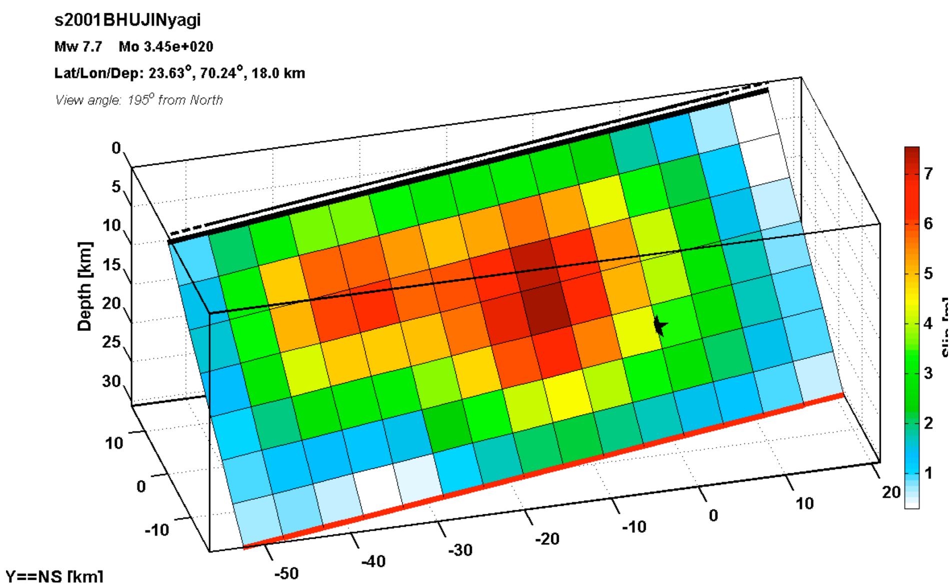
* Now at Geological Survey of Israel

A Fault

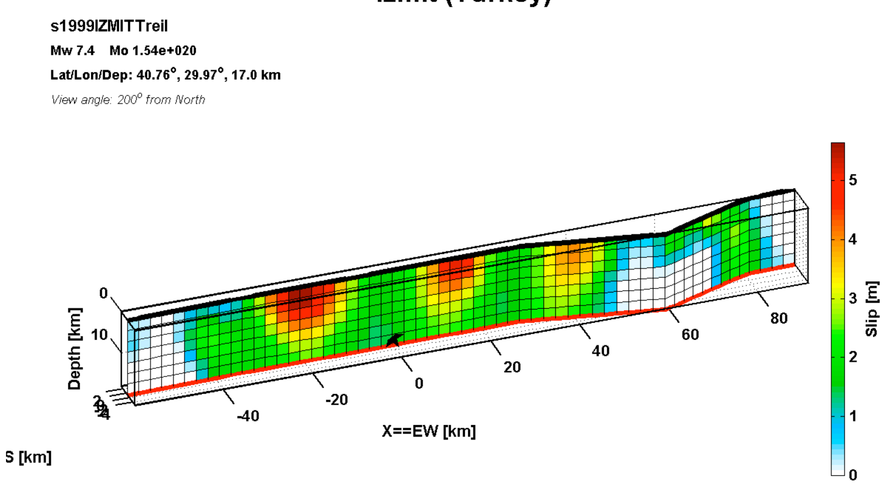


Asperities and Earthquake Slip

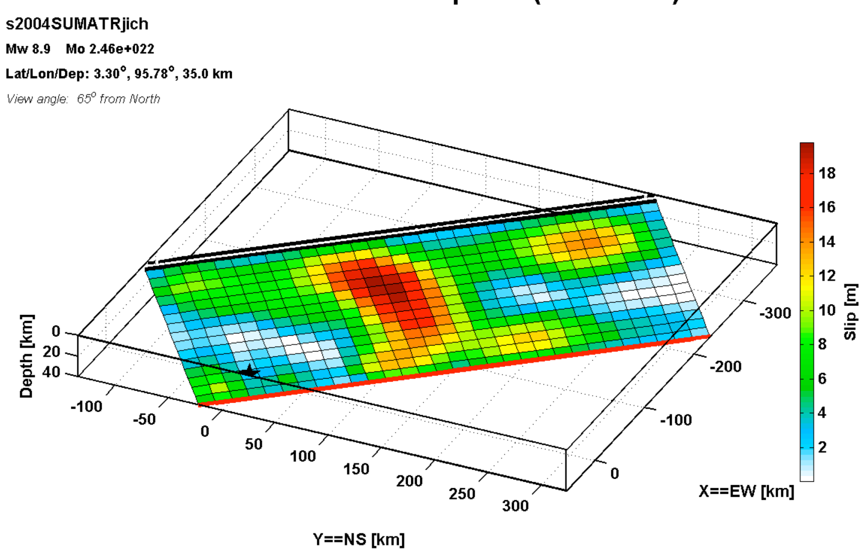
Bhuj (India)



Izmit (Turkey)

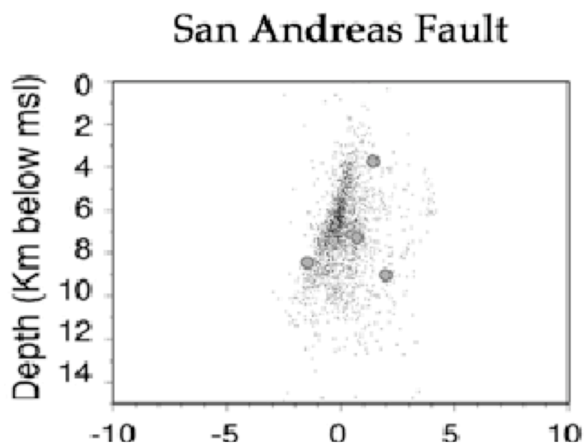


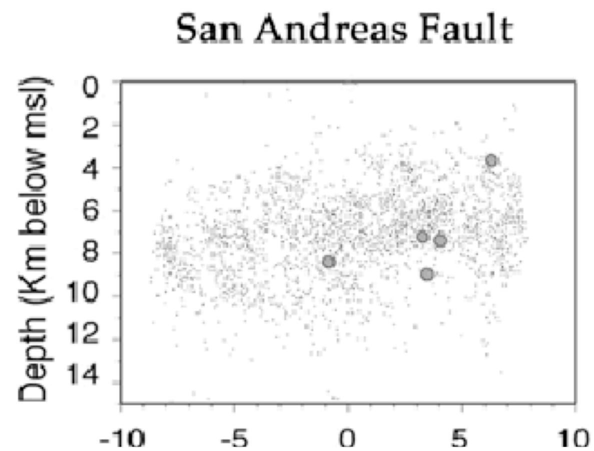
Giant Sumatra Earthquake (Indonesia)

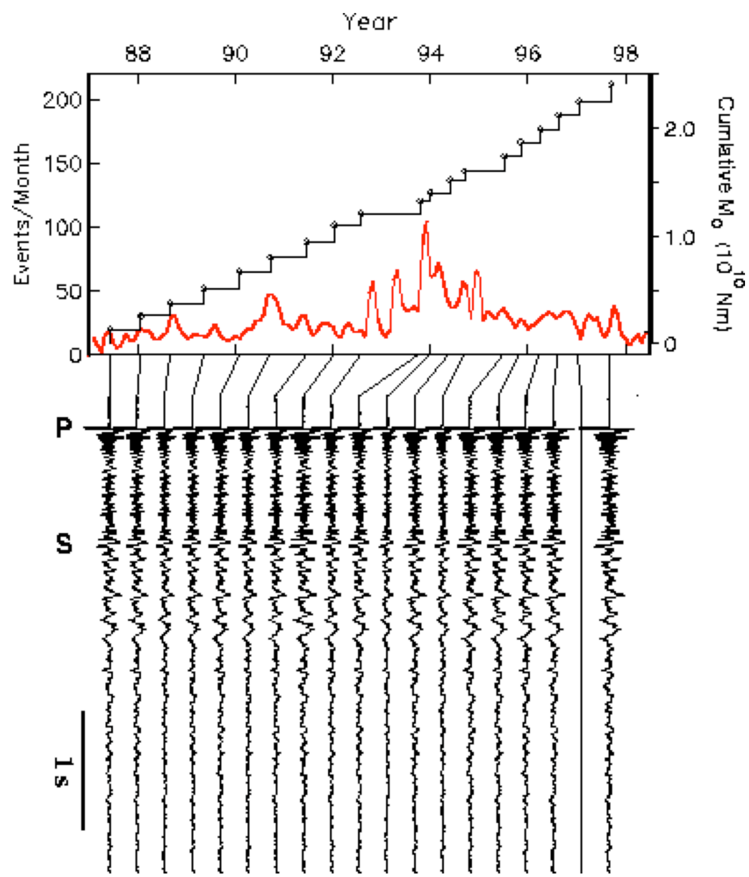


M. Mai database

Asperities and Repeating Earthquakes



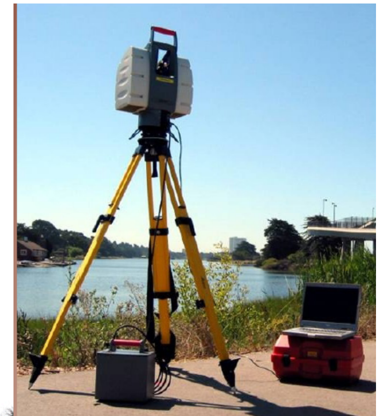


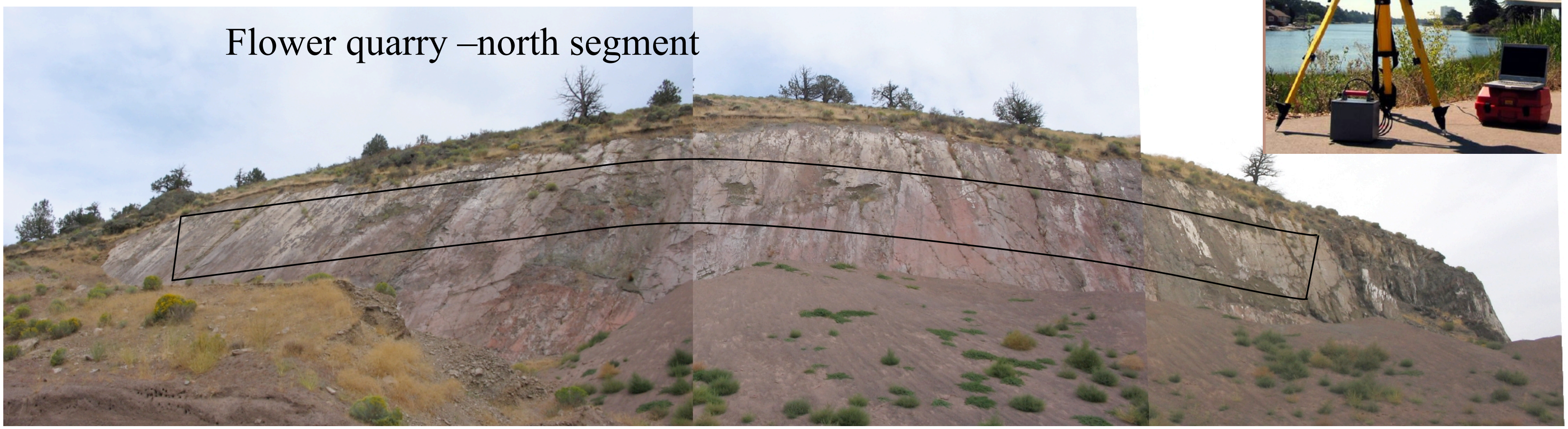


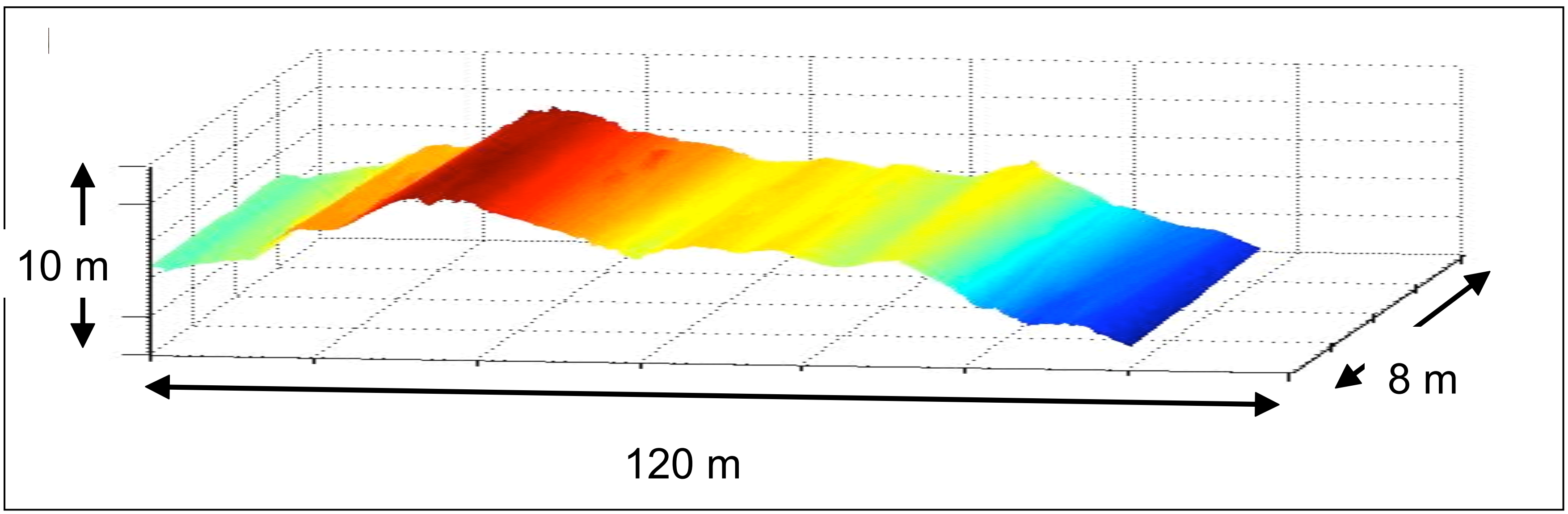
McEvilly et al.

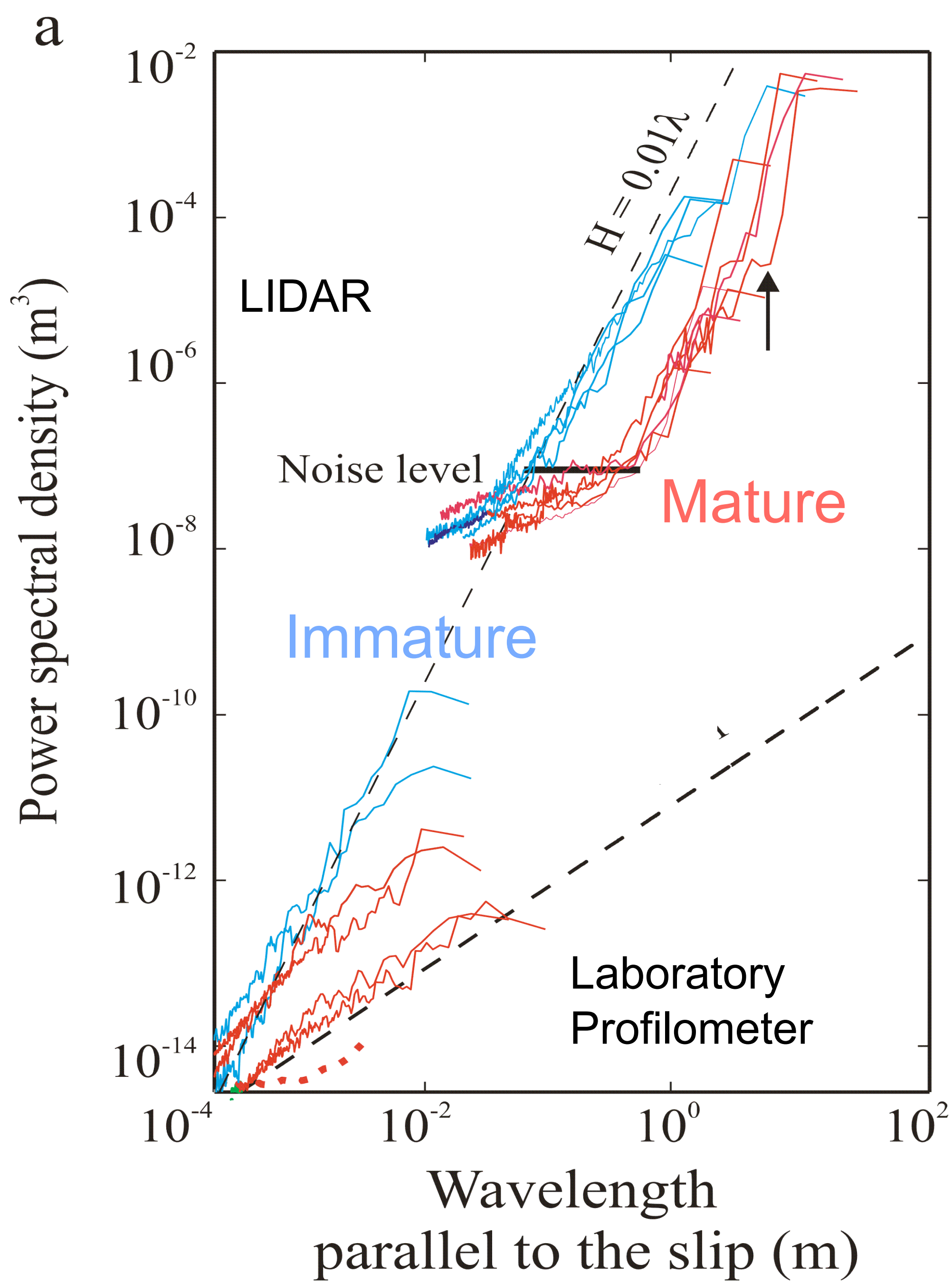
Monte Maggiore

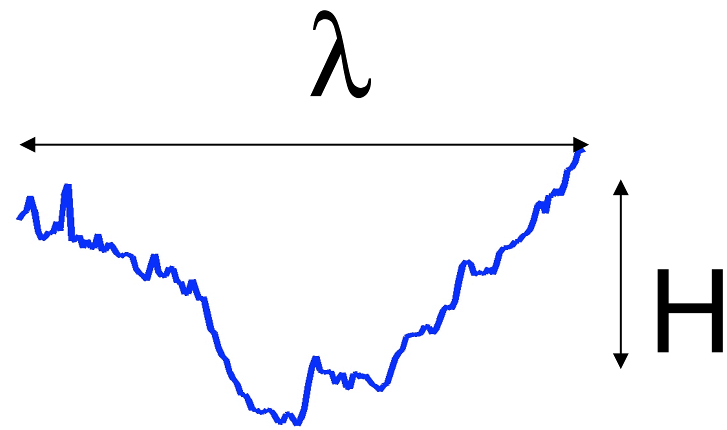
Fault Geometry at the Scale of Earthquake Slip: LiDAR



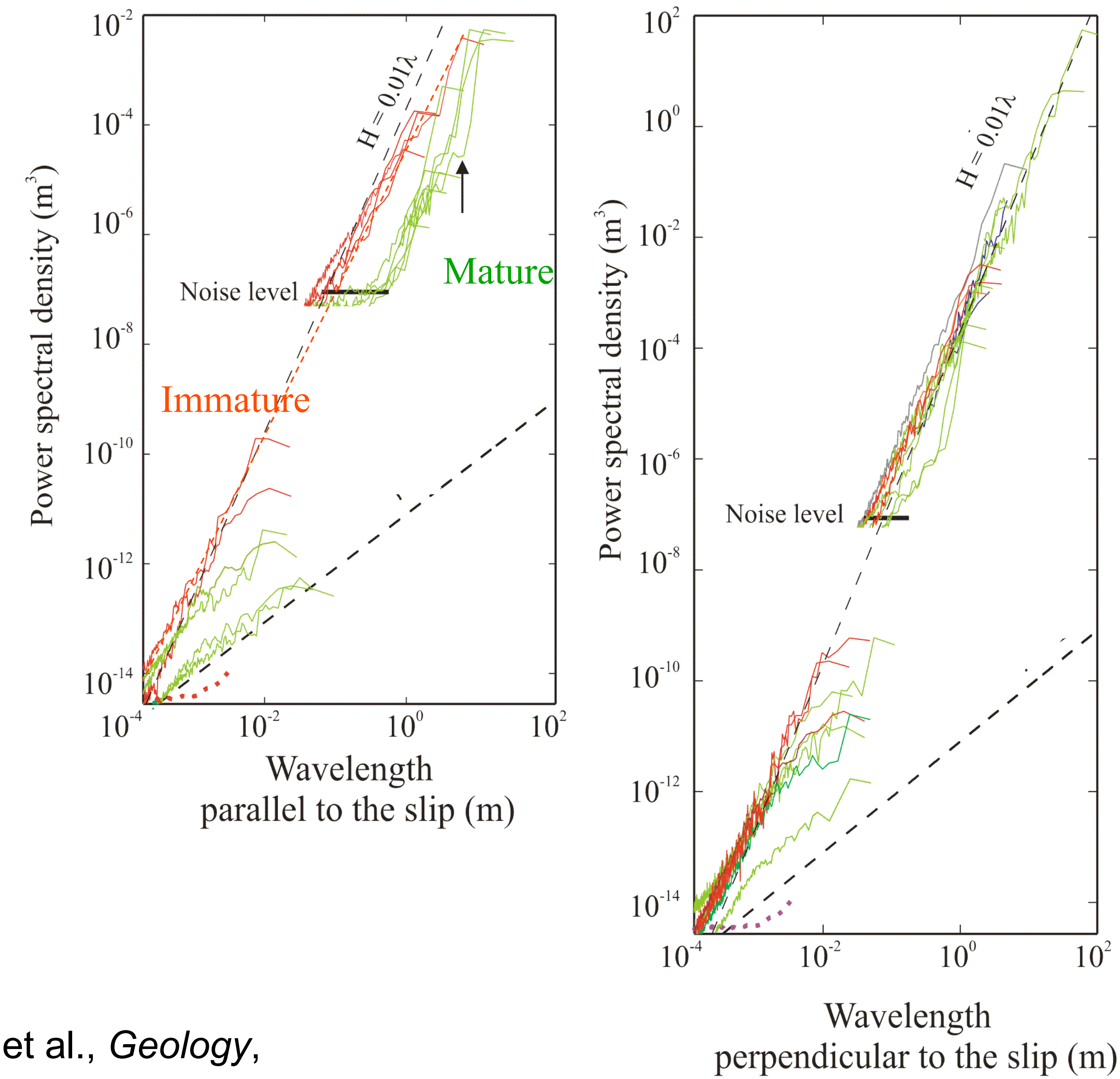




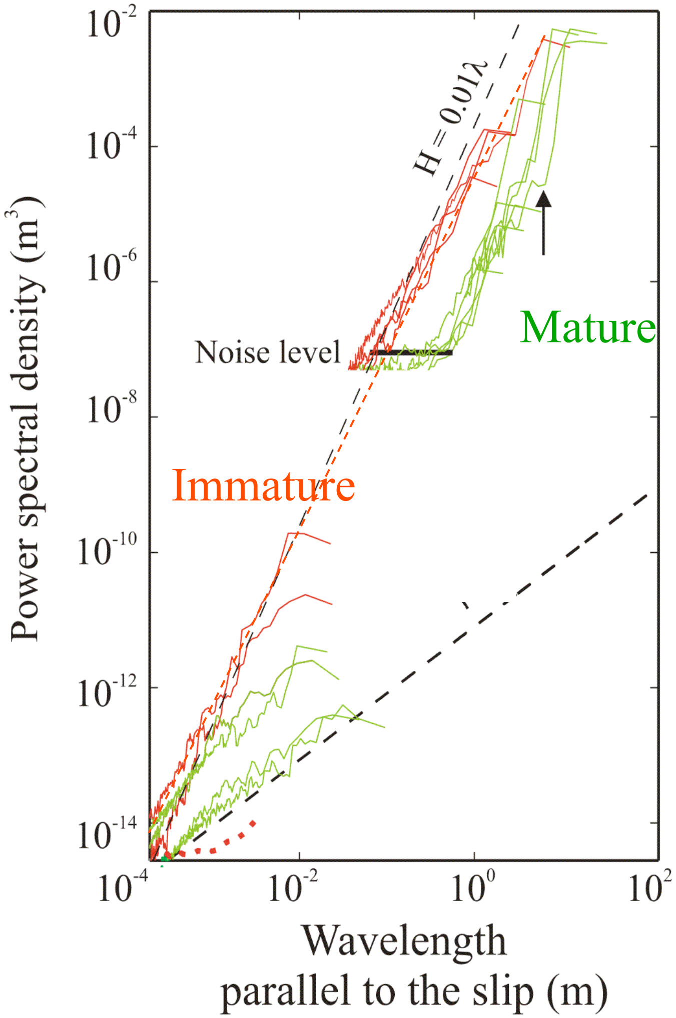


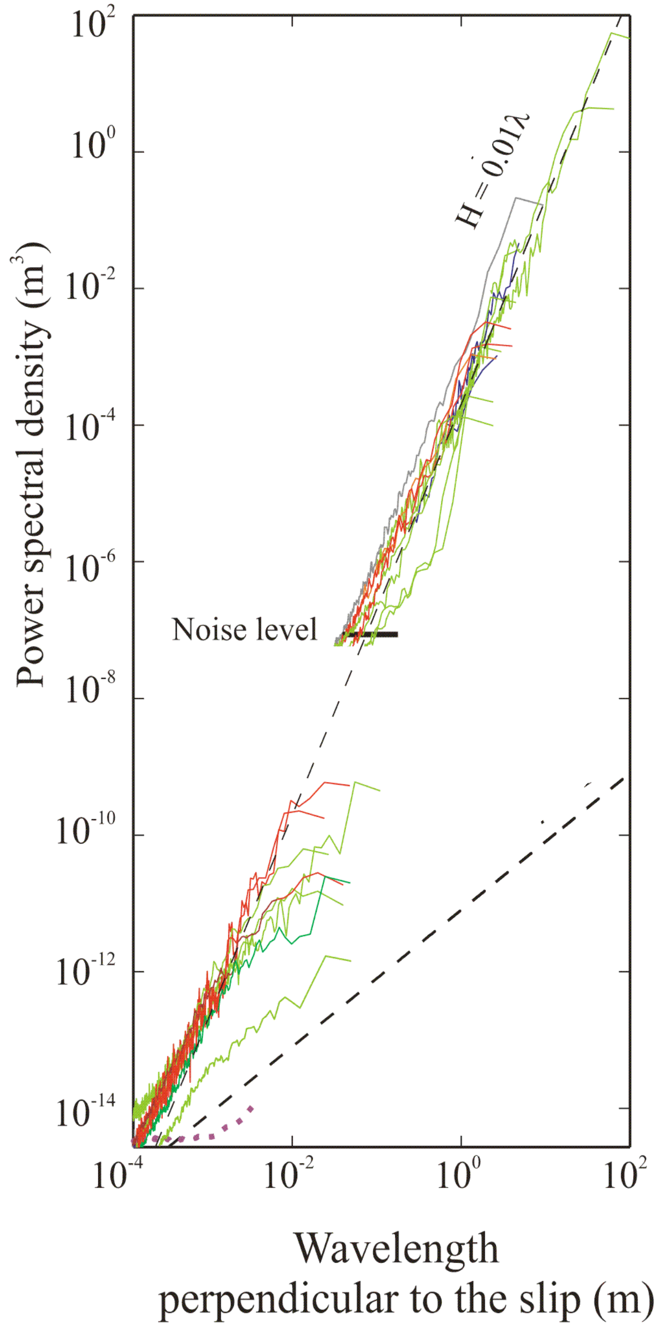


Sagy et al., *Geology*, 2007.



Sagy et al., *Geology*, 2007

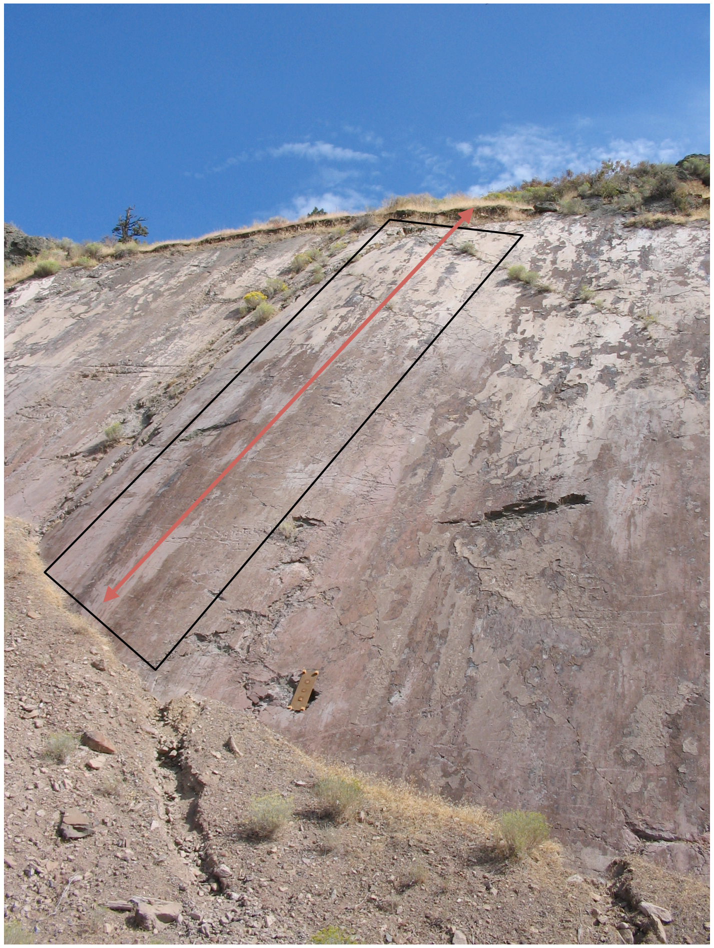




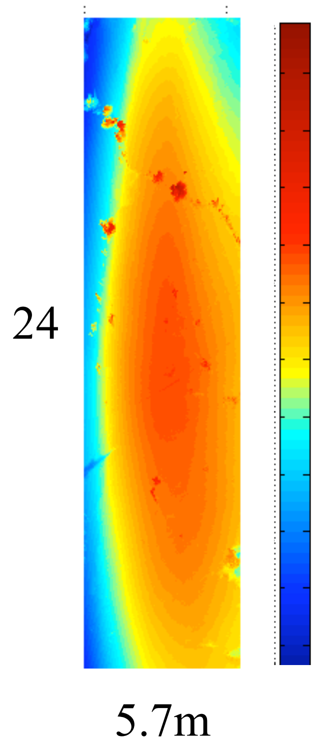
Sagy et al., *Geology*, 2007

Western Fucino Basin, Italy

N. Borcola Pass

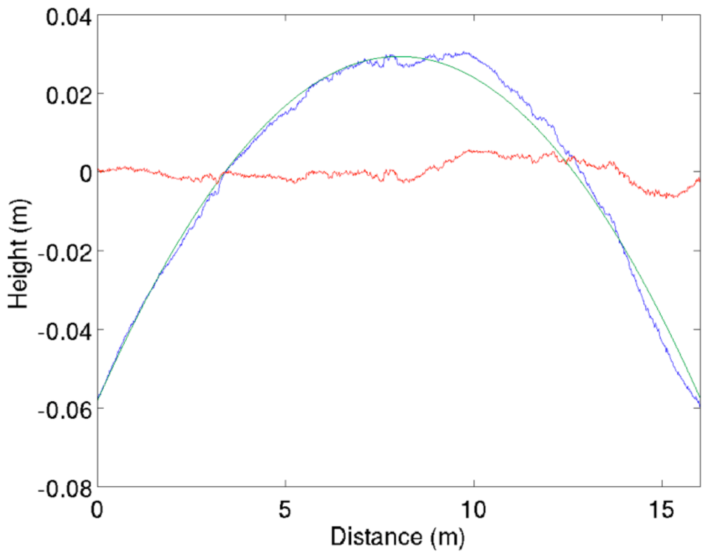


Flower Pit Fault, Oregon

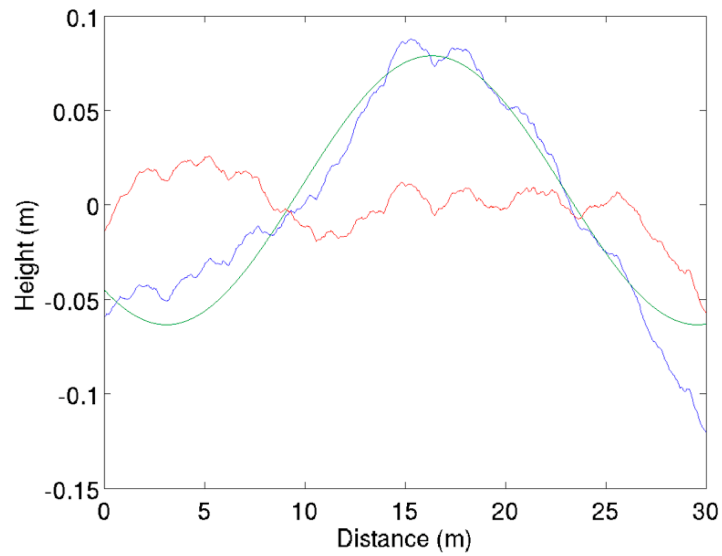


Geometrical Asperities (Bumps) on Mature Faults

Is the bump scale significant?

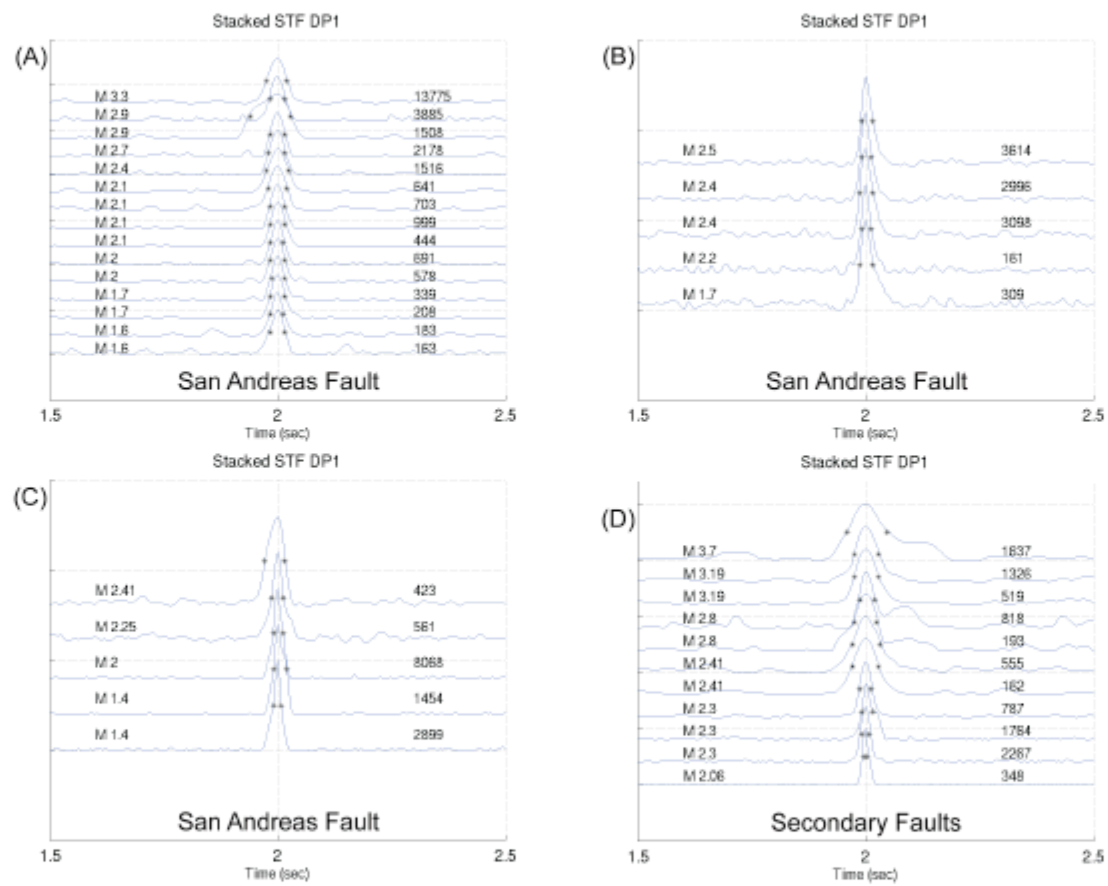


Observed bump
Monochromatic fit
Residual



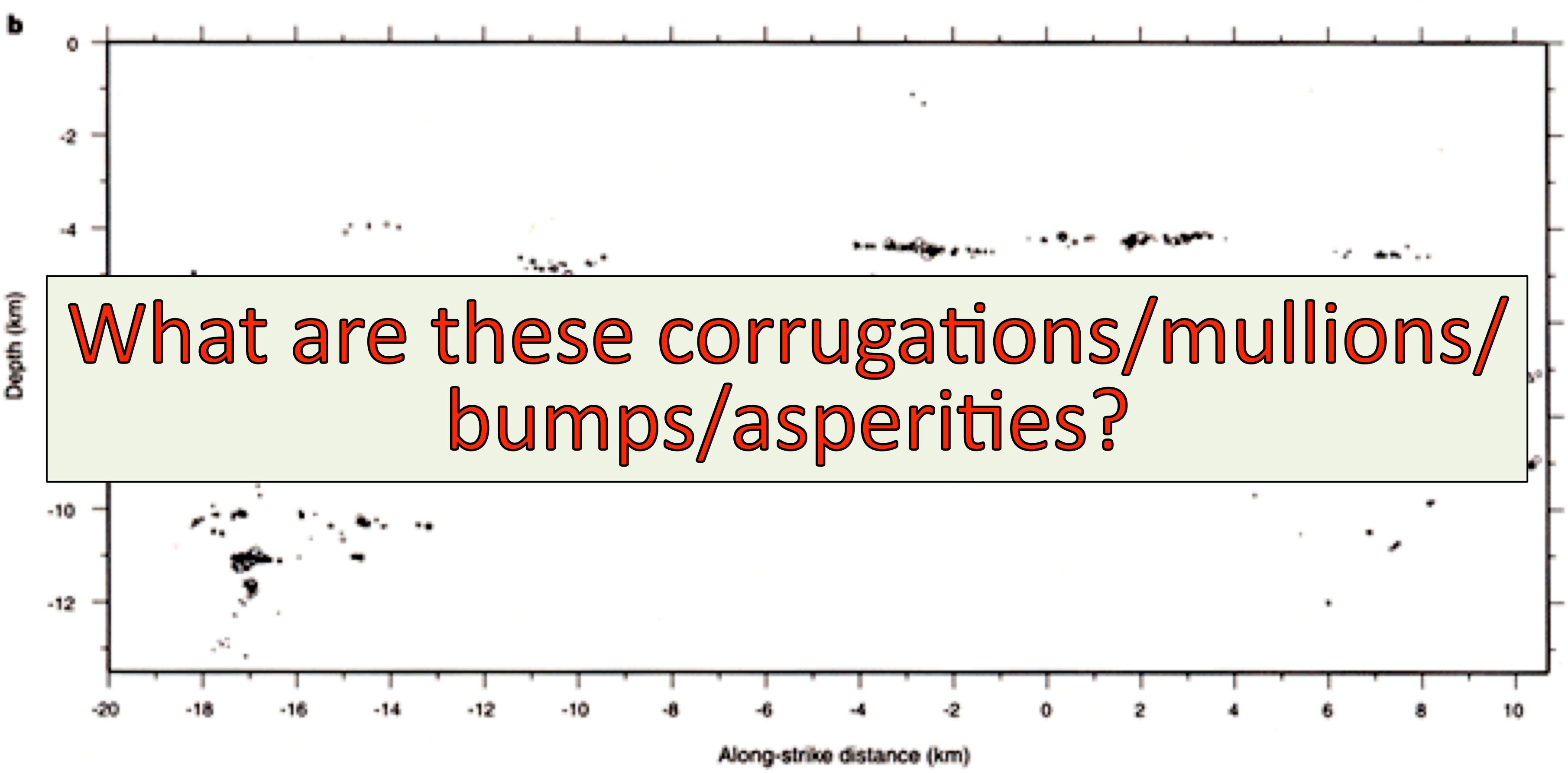
Synthetic self-affine bump
Monochromatic fit
Residual

Distinct Length Scale in Parkfield on the San Andreas



Harrington and Brodsky, *Bull. Seism. Soc. Amer.*, in press.

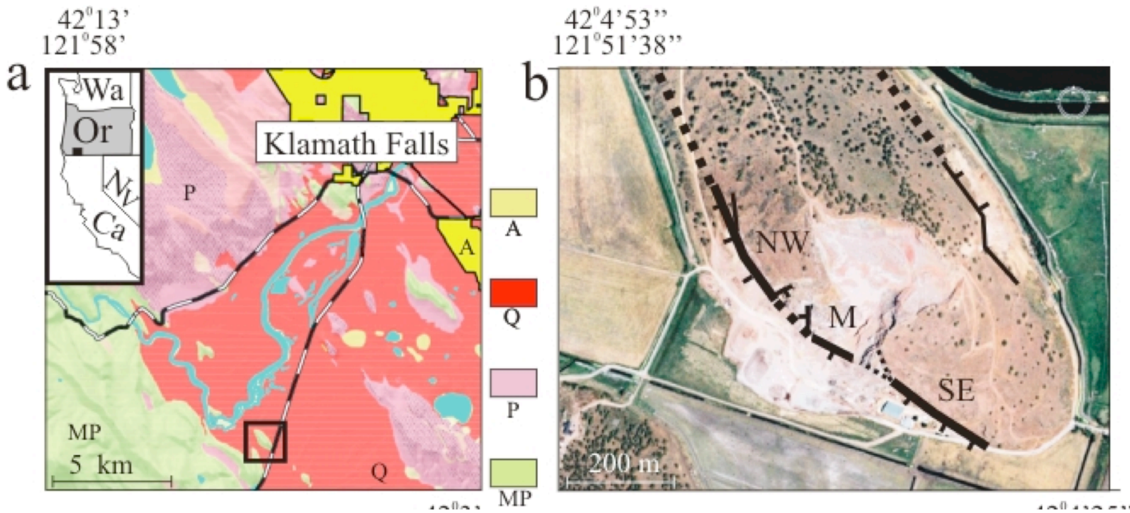
Streaks on the San Andreas



What are these corrugations/mullions/bumps/asperities?

Rubin, 1999

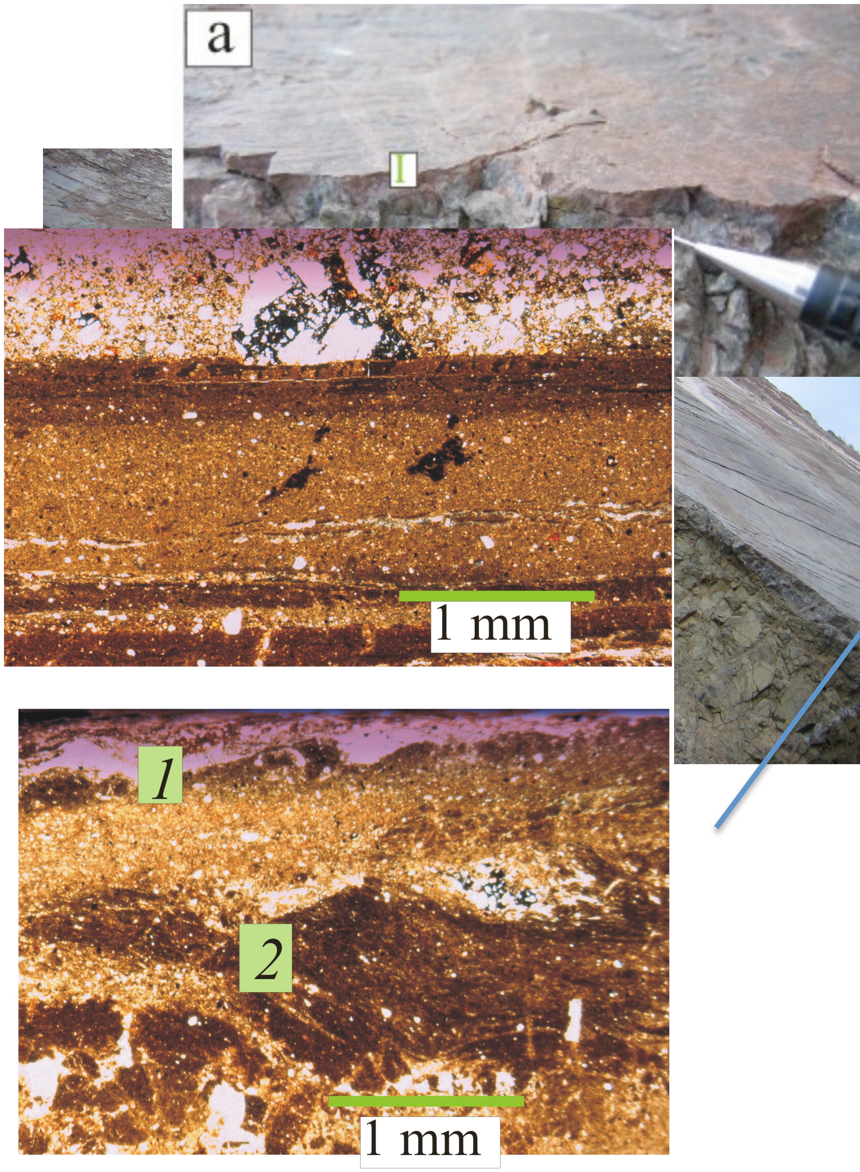
Flower Pit Fault, Oregon

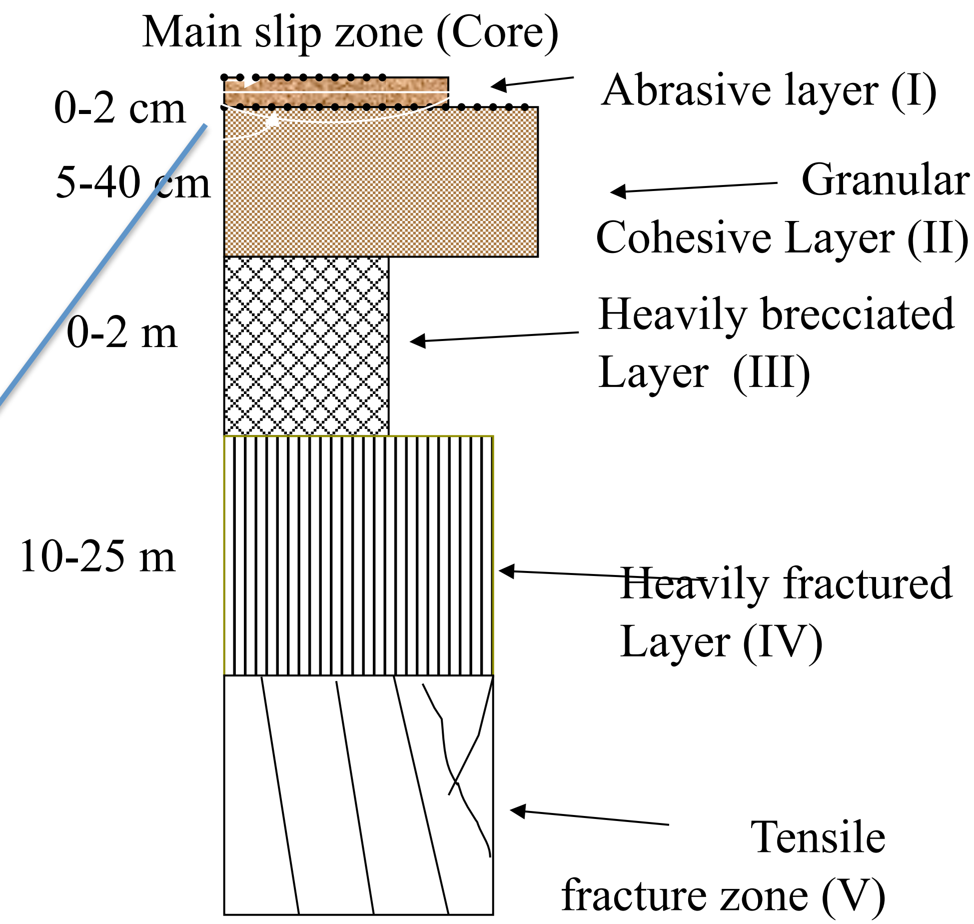


Southwest Oregon
geological map
(Jenks et al., 2007)

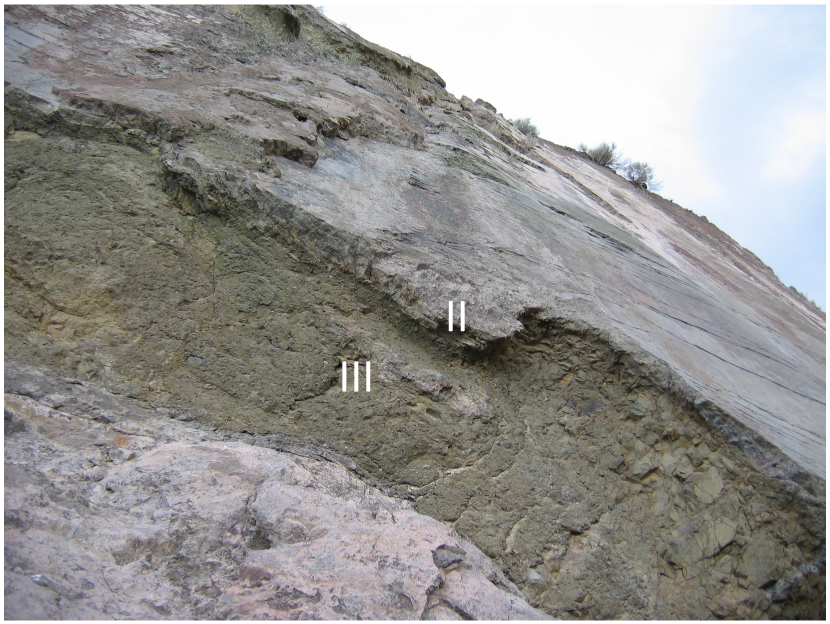
Fault Zone Architecture

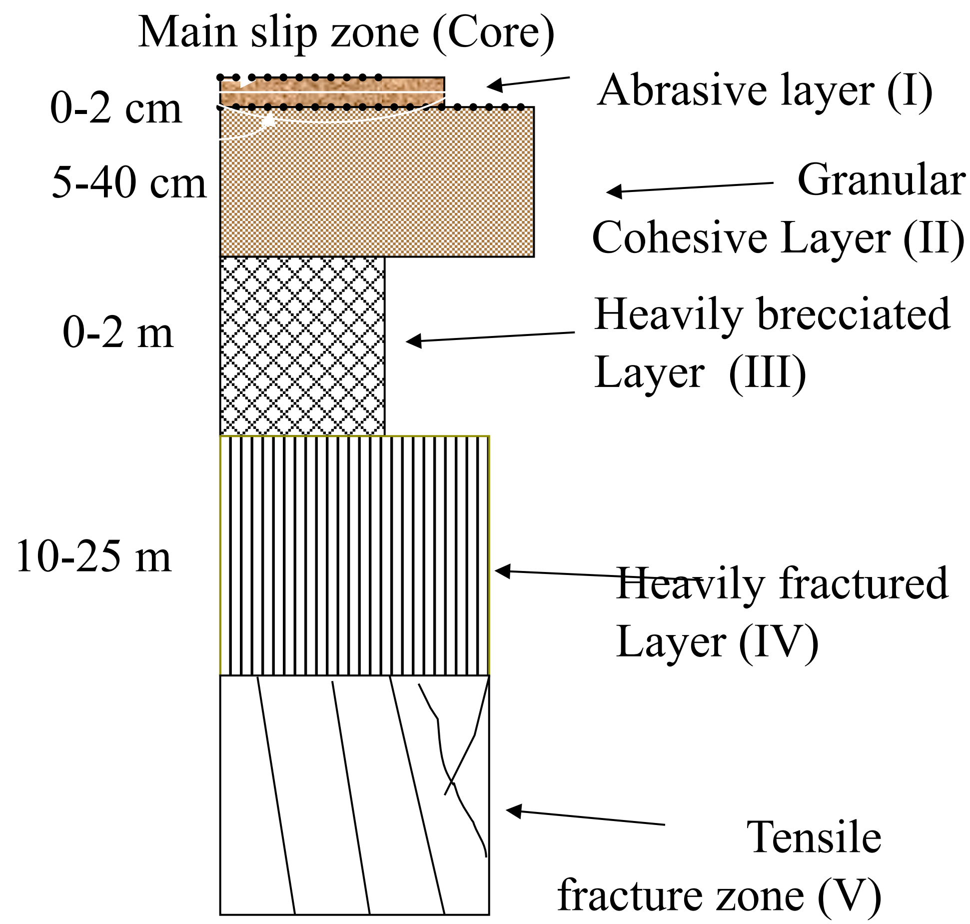
Fault zone architecture



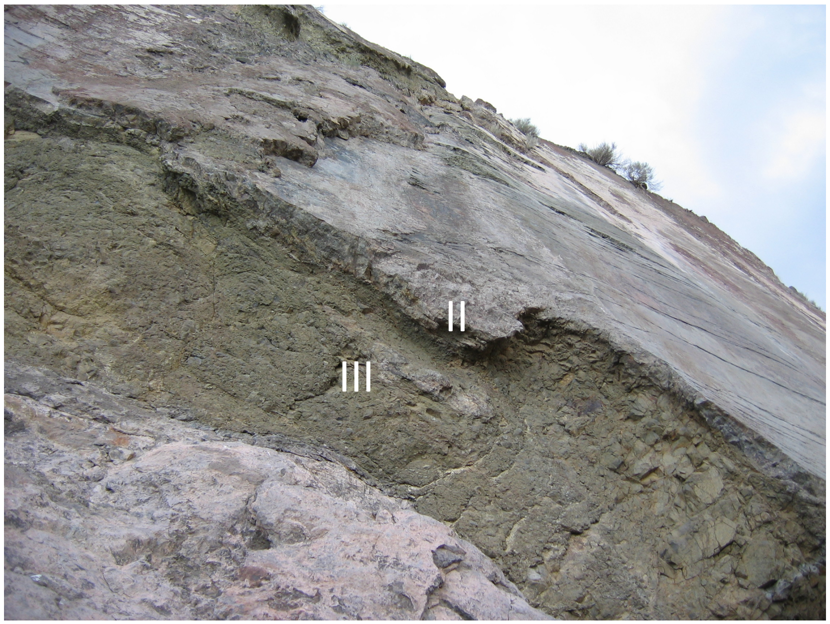


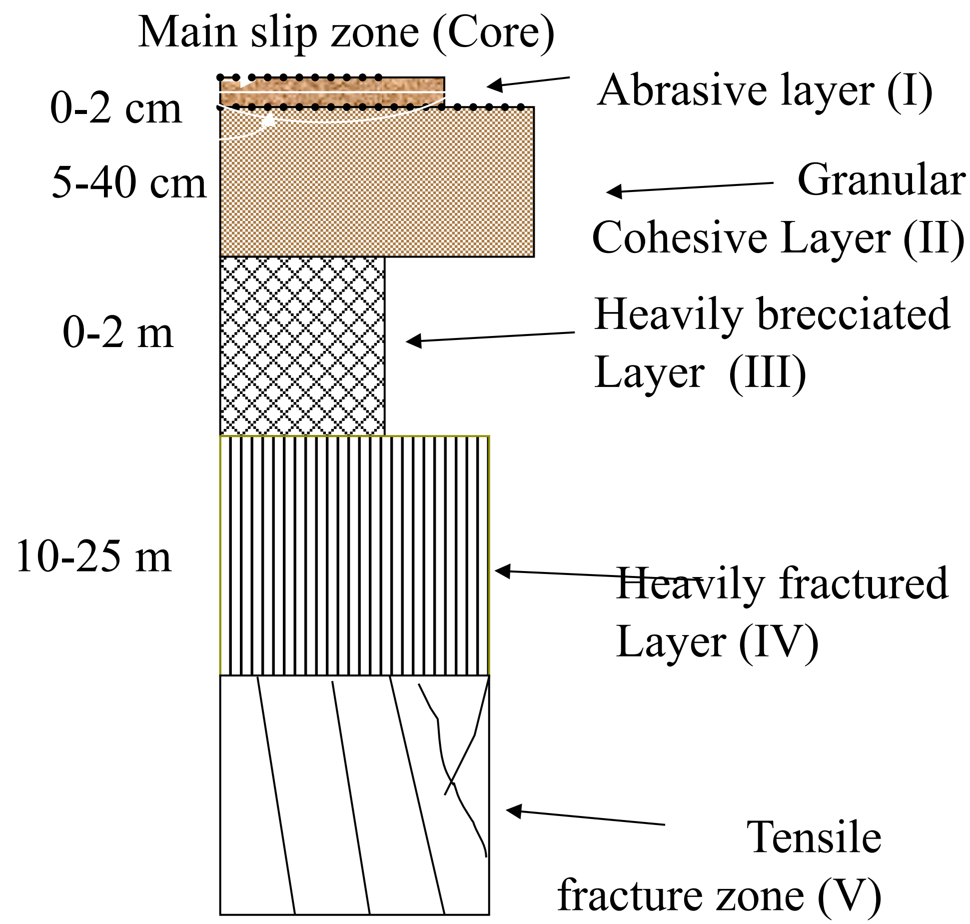
Fault zone architecture

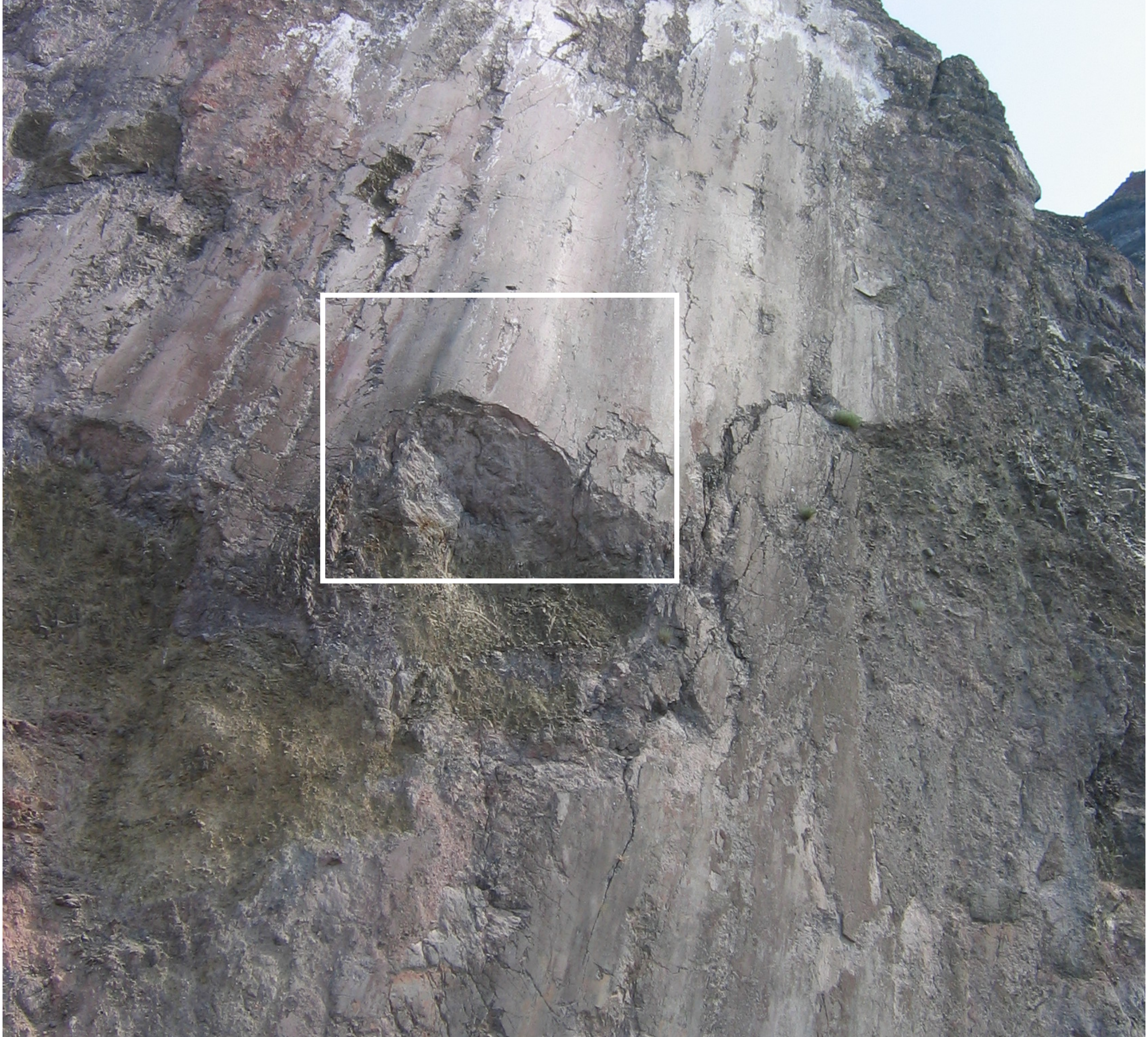




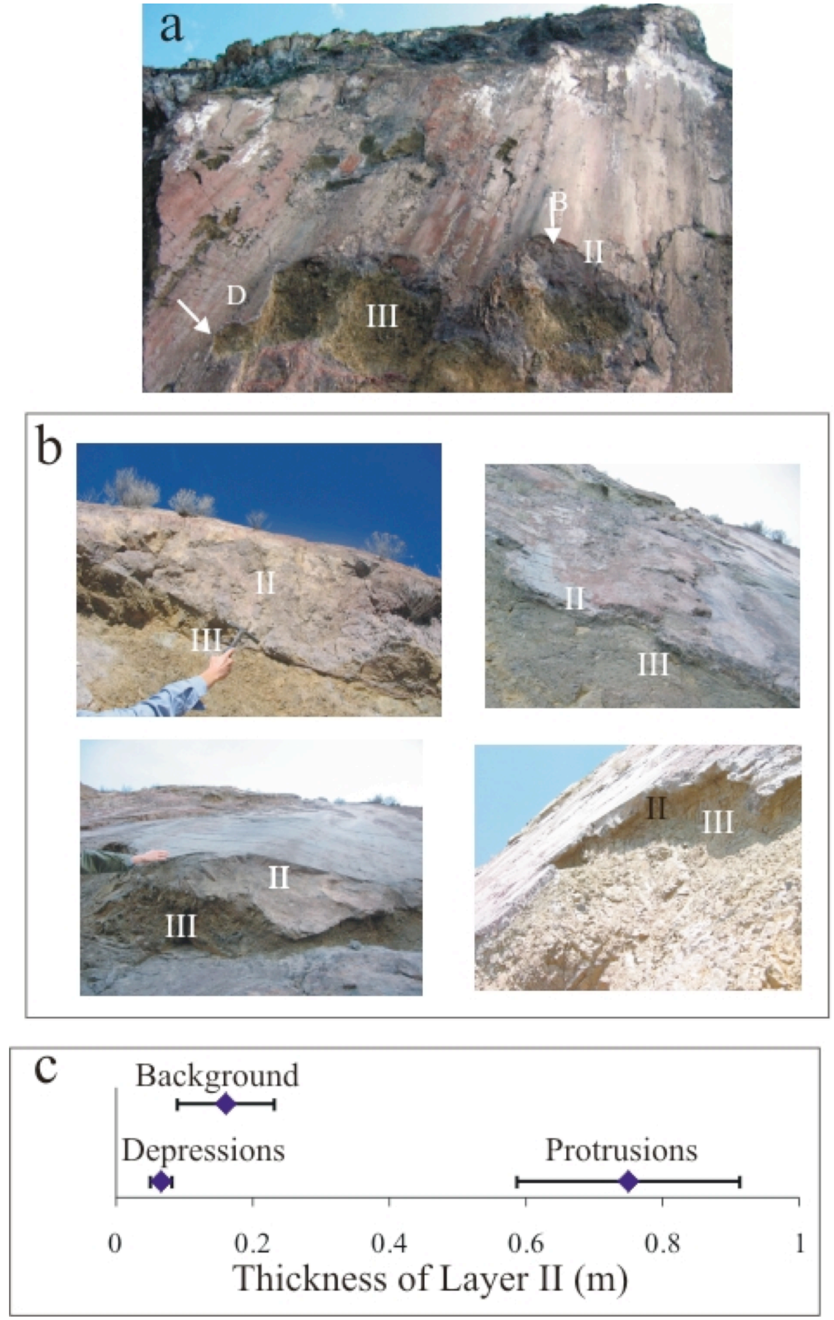
Fault zone architecture







Fault Zone Architecture Under the Bumps

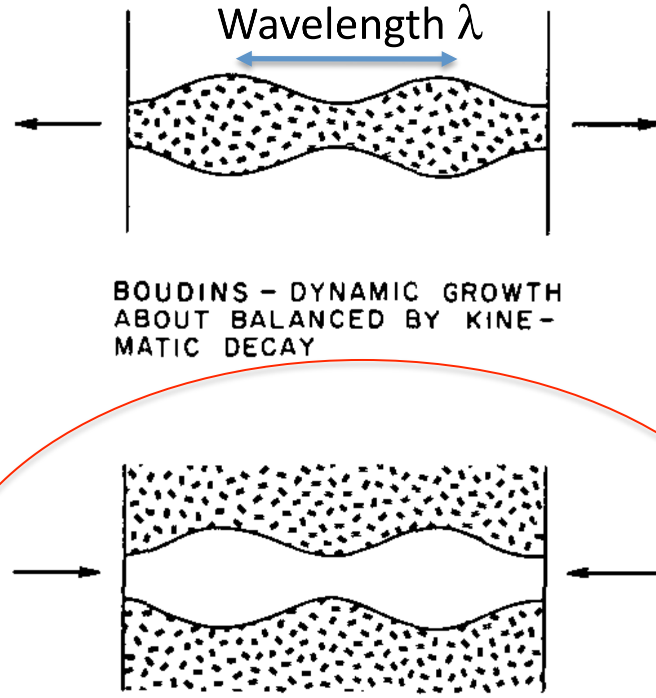


Bumps are due to lensing of granular flow.

Corollary: Bumps are both rheological and geometrical asperities

Pinch and Swell Instabilities

http://campus.greenmtn.edu
/geotrips/Images/Blog/Field/
Boudinage.jpg

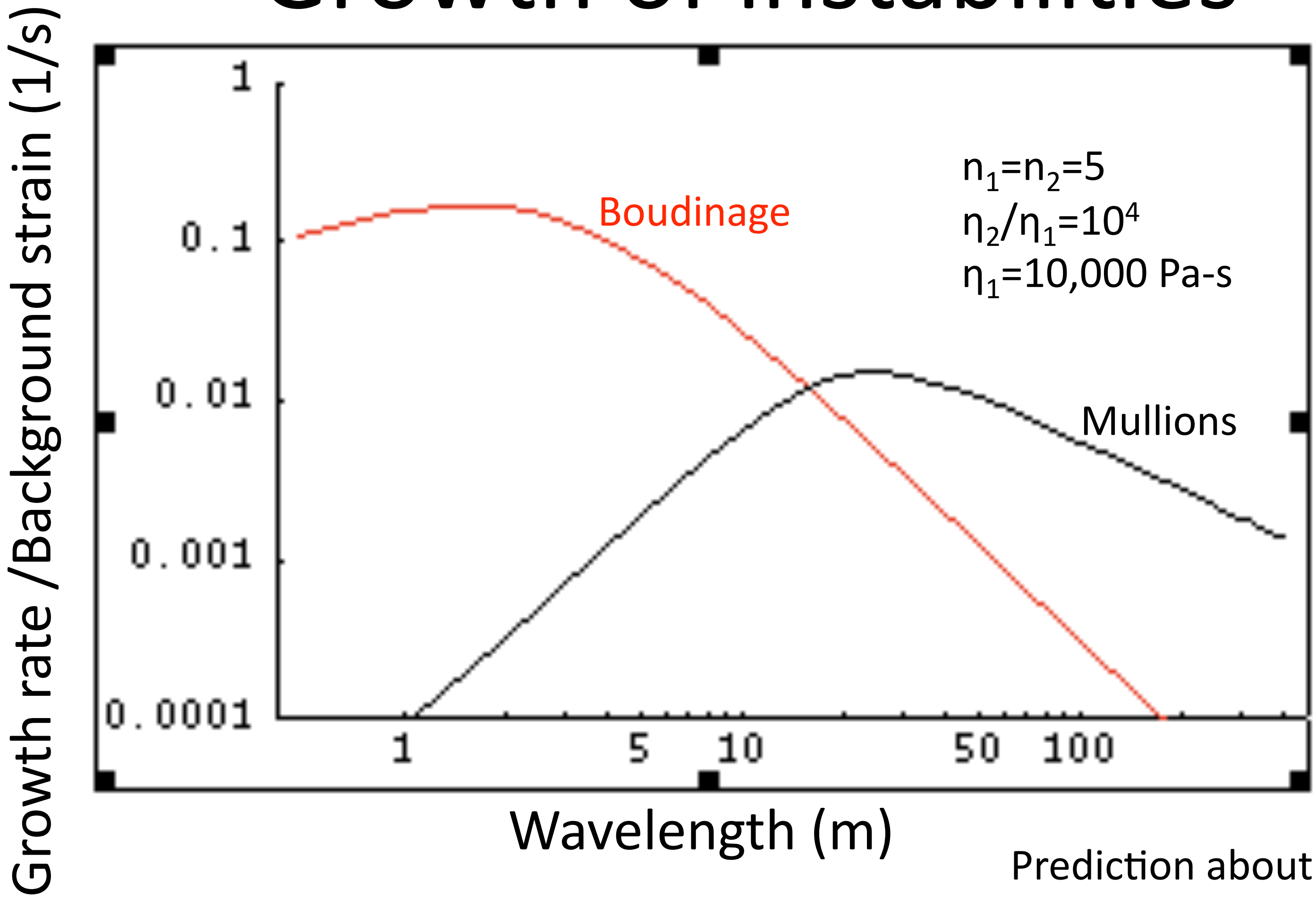


Strong Materials

Weak Materials

Smith (1975)

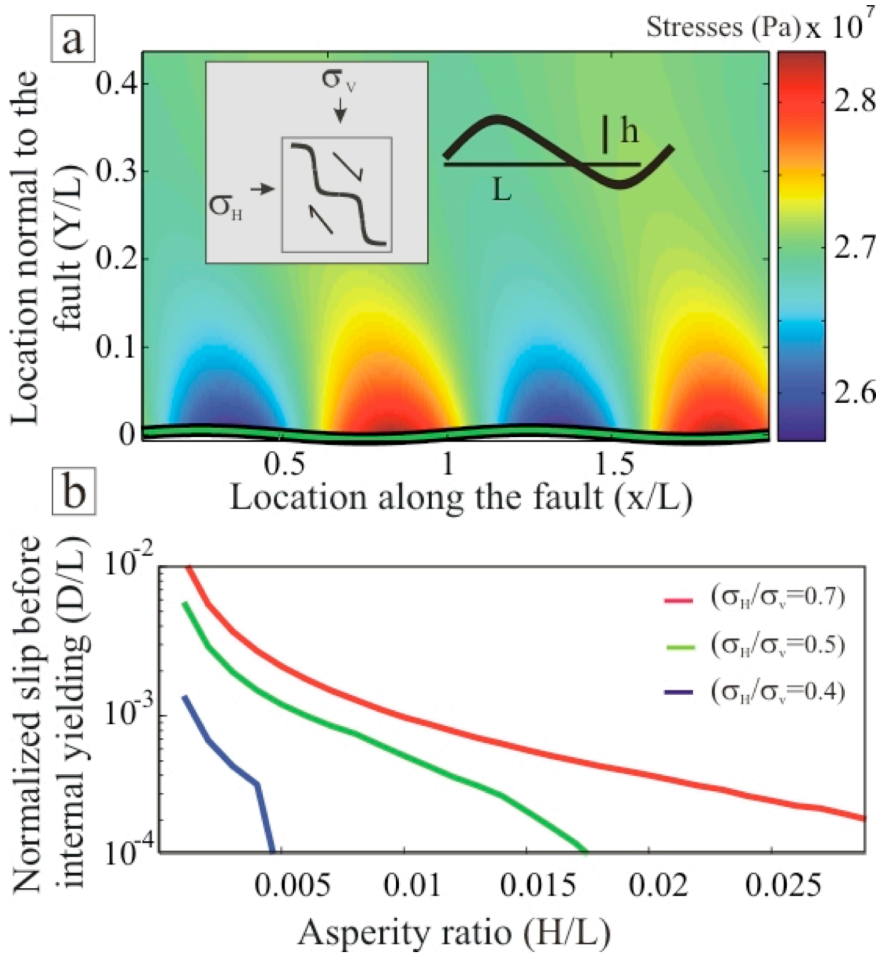
Growth of instabilities



Prediction about rheology needs to be test experimentally

Linear stability analysis of two-layers on Non-Newtonian fluid.

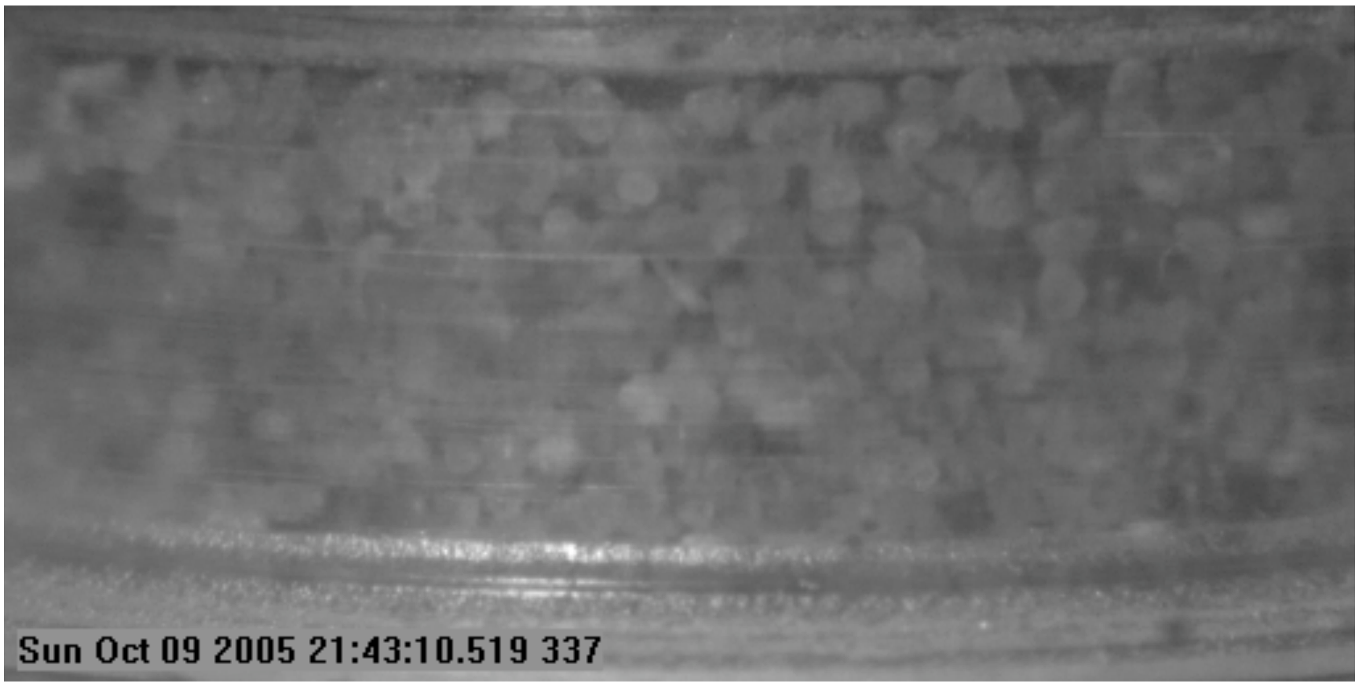
Bumps must fail internally



Elastic solution modified from Chester and Chester (2000)

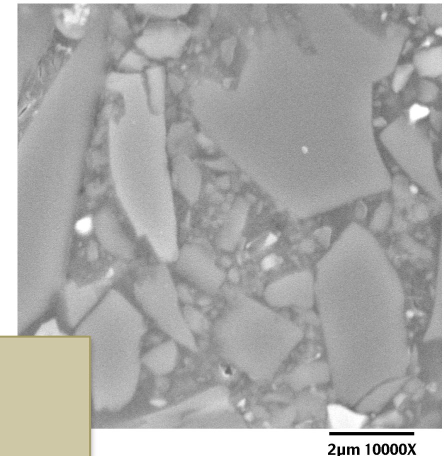
-> Bumps are continually Failing internally

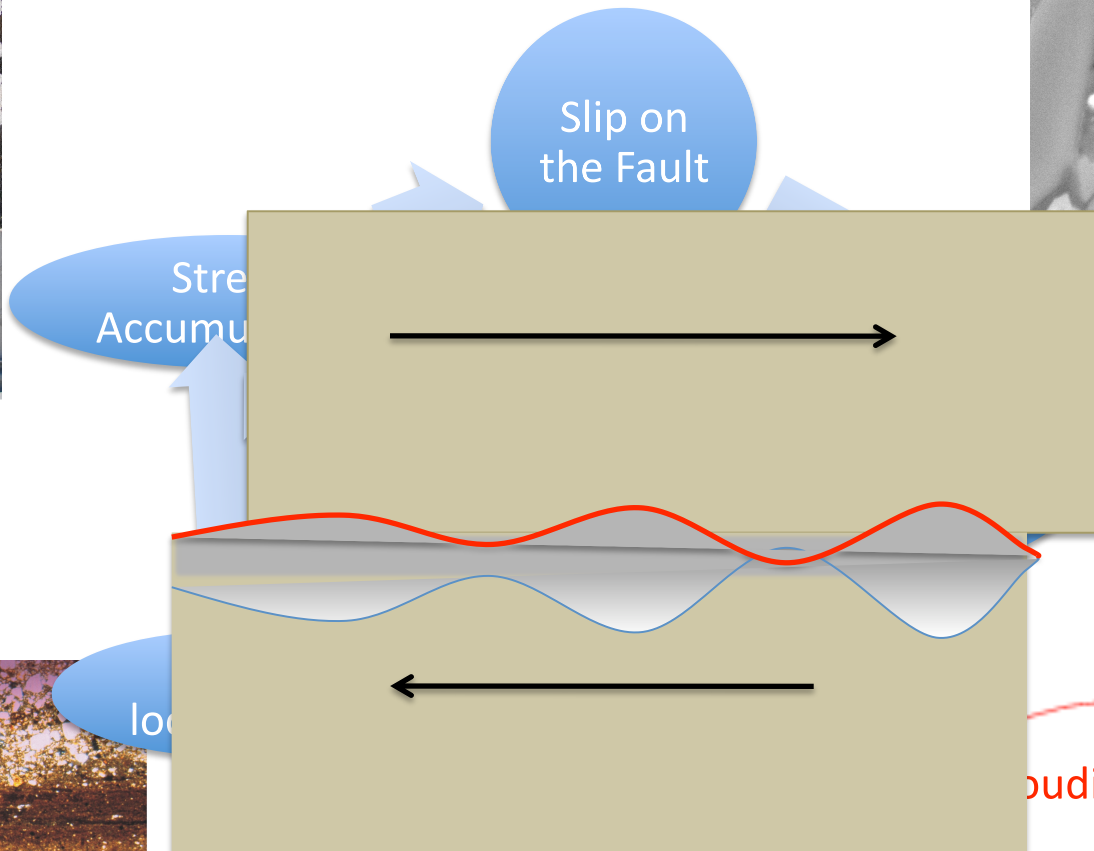
Shear Localization in Granular Flows

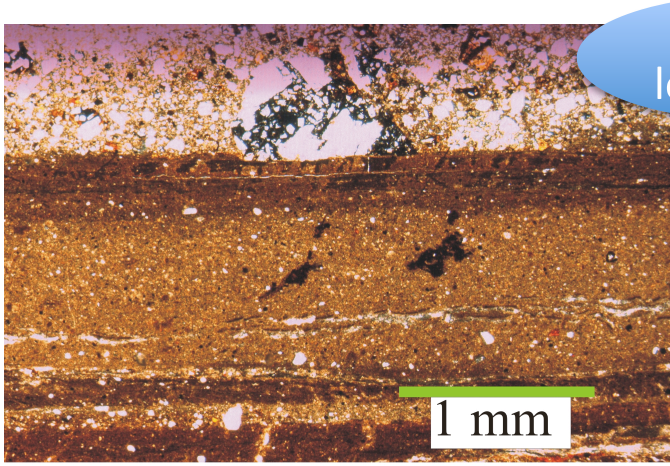


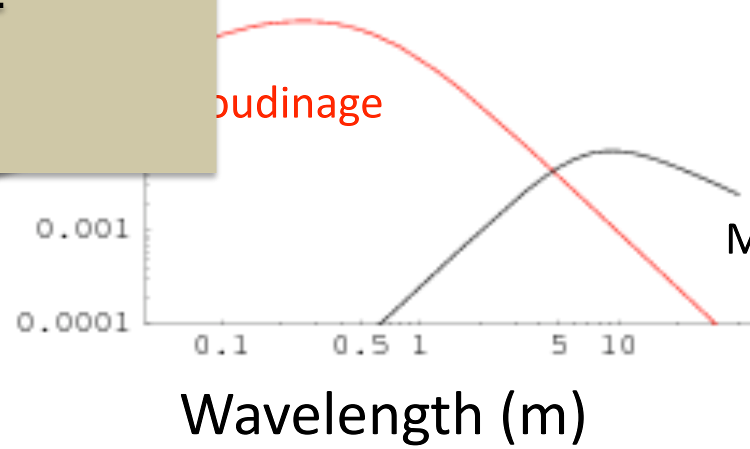
Kevin Lu, UCLA

The Fault Zone Cycle









Conclusions

- The bumps are reflections of the ponding of the granular flow layer
  - Simultaneously rheological and geometrical features
- Implies significant feedback cycle linking slip, abrasion and internal deformation during an earthquake