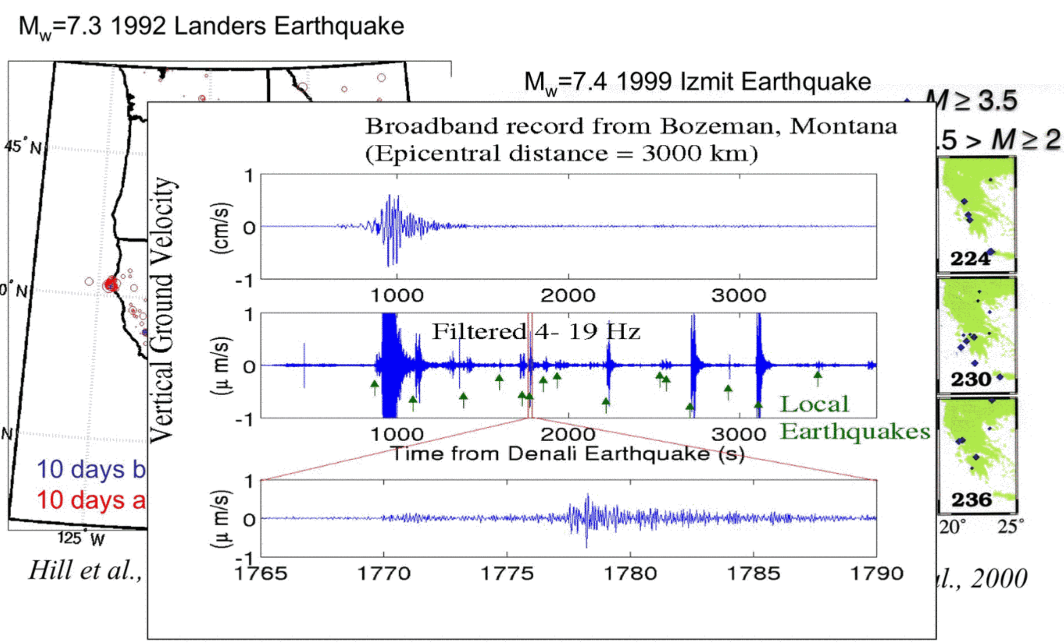
Long-Range Triggering of Earthquakes

Emily E. Brodsky
UCLA

Evelyn Roeloffs, Cascade Volcano Observatory, USGS
Stephanie Prejean, Alaska Volcano Observatory, USGS
Jean Elkhoury, Rebecca Harrington and Allen Husker, UCLA
Doug Woodcock and Ivan Gall, Oregon Water Res. Dept.
Duncan Agnew, UCSD Scripps



Today's Agenda

I. Facts about long-range triggering
II. Mechanism based on water well studies
III. Triggering thresholds and further evidence on the effects of very small stresses

Fact #1: Seismic Waves Trigger Earthquakes

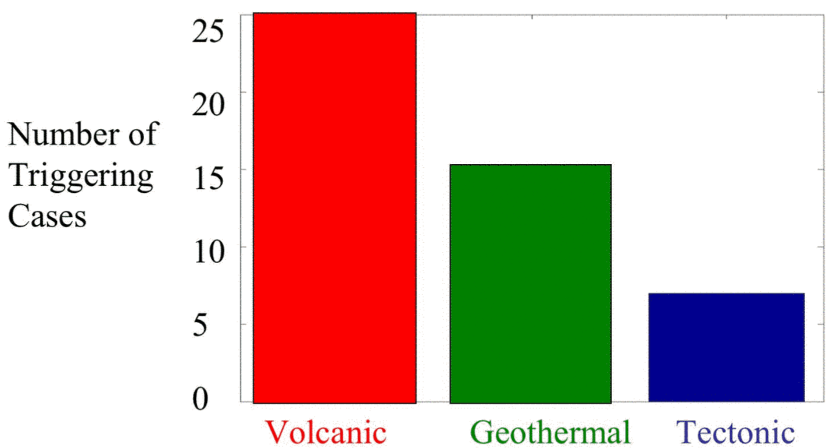
At a station in Greece 589 km from M_w 7.4 Izmit, Turkey earthquake

Dynamic Stress (Seismic waves)	0.2 MPa
Static Stress	$\leq 10^{-4}$ MPa
Tidal Stress	$\sim 10^{-3}$ MPa

➡ Dynamic stresses in seismic waves are the largest potential triggering stress

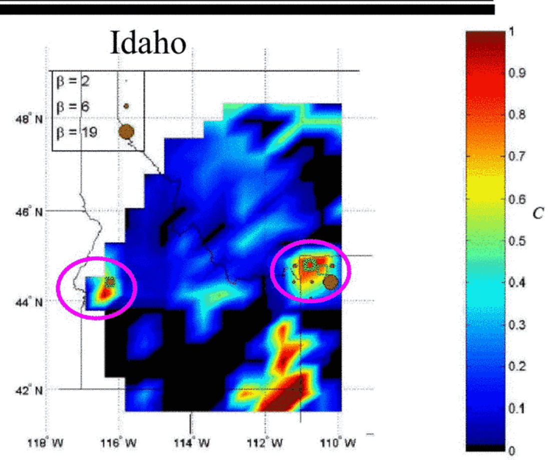
Fact #2

Long-range triggering is observed more often in volcanic or geothermal areas.



Caveat A: Observational Problems

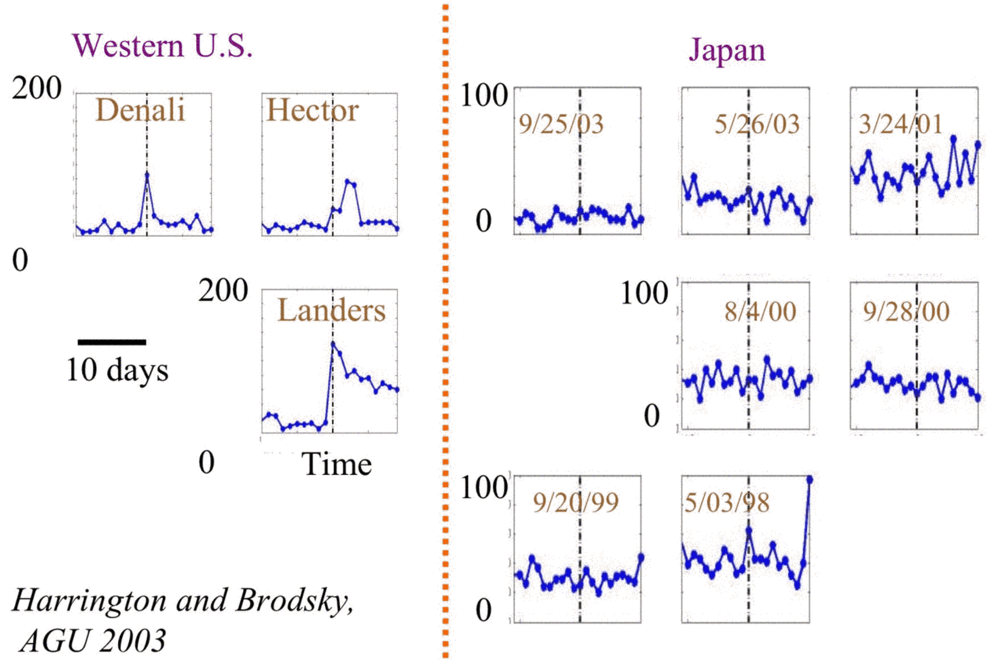
- Network bias
  - However, a few densely-instrumented tectonic areas do not trigger (e.g., Parkfield)
- Faults generate hot springs
  - Triggering may be in deep-rooted, mineral-rich systems



Combined water chemistry,
heat flow
and seismicity data

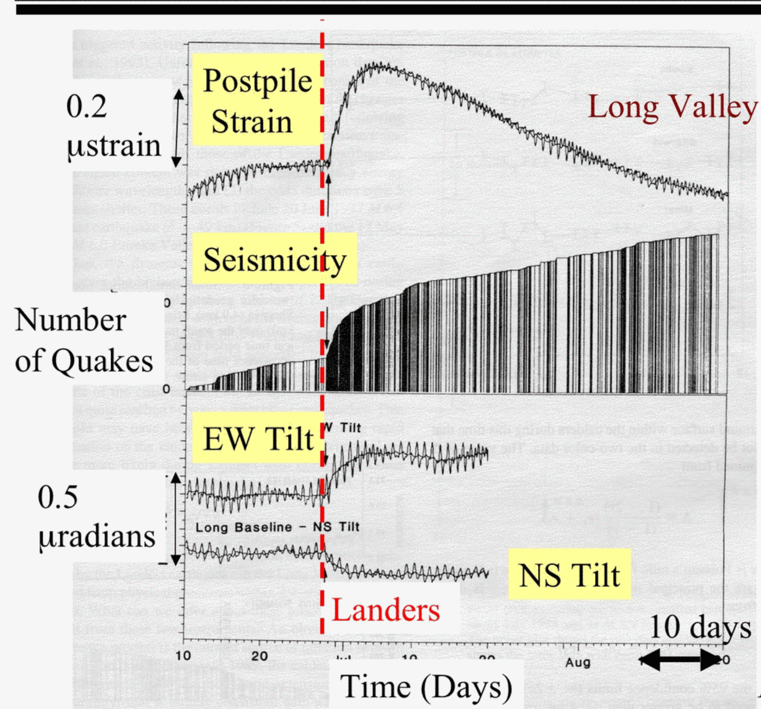
Husker and Brodsky, BSSA, 2004.

Caveat B: Japan Triggers Less Than Western U.S.



Harrington and Brodsky, AGU 2003

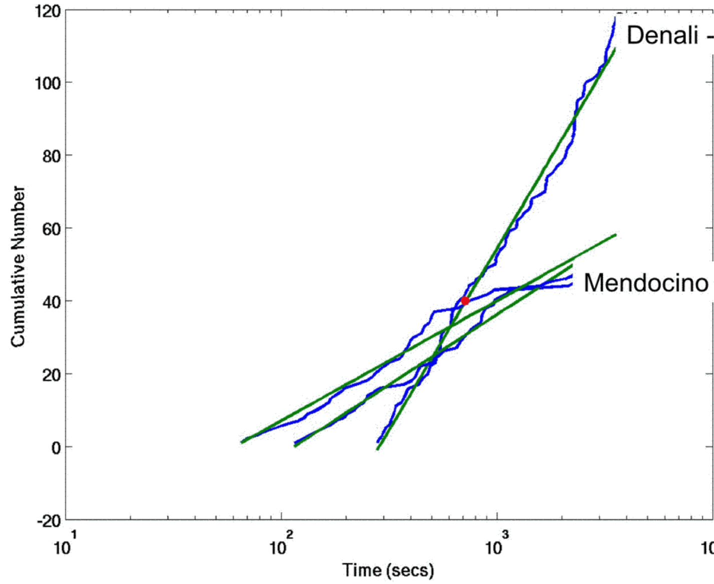
Facts #3 & #4: Seismicity persists and Other Observables Exist



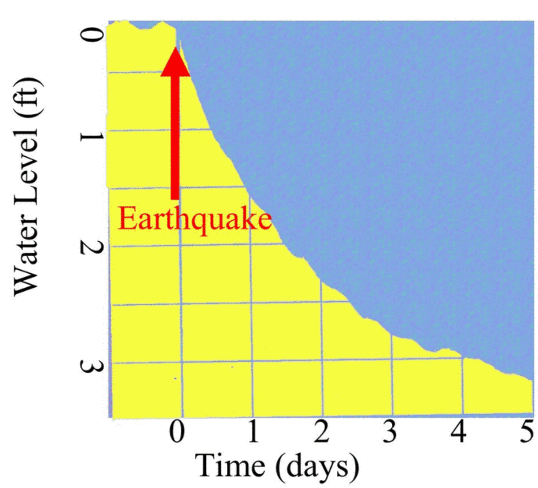
Persistent deformation results from a transient signal (seismic waves)

Hill et al., 1995

Fact #3 (cont.) Omori's Law



Fact #4 (cont.): Water Level (Pore Pressure)

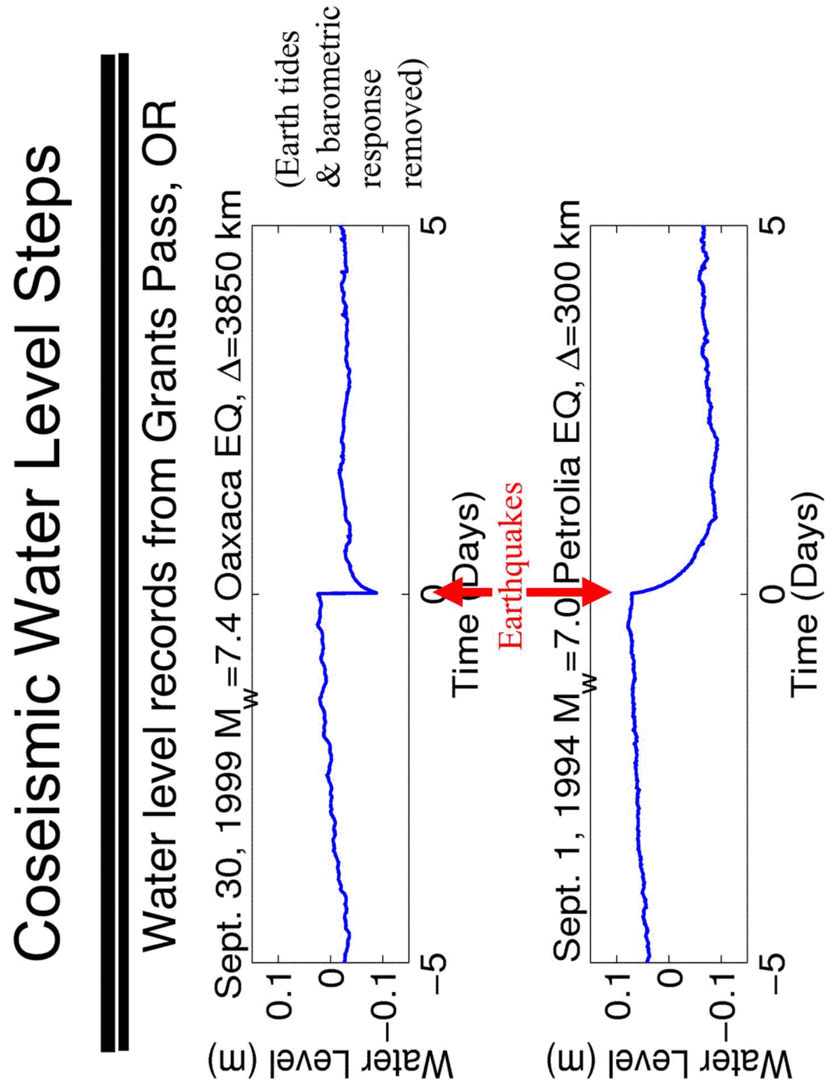


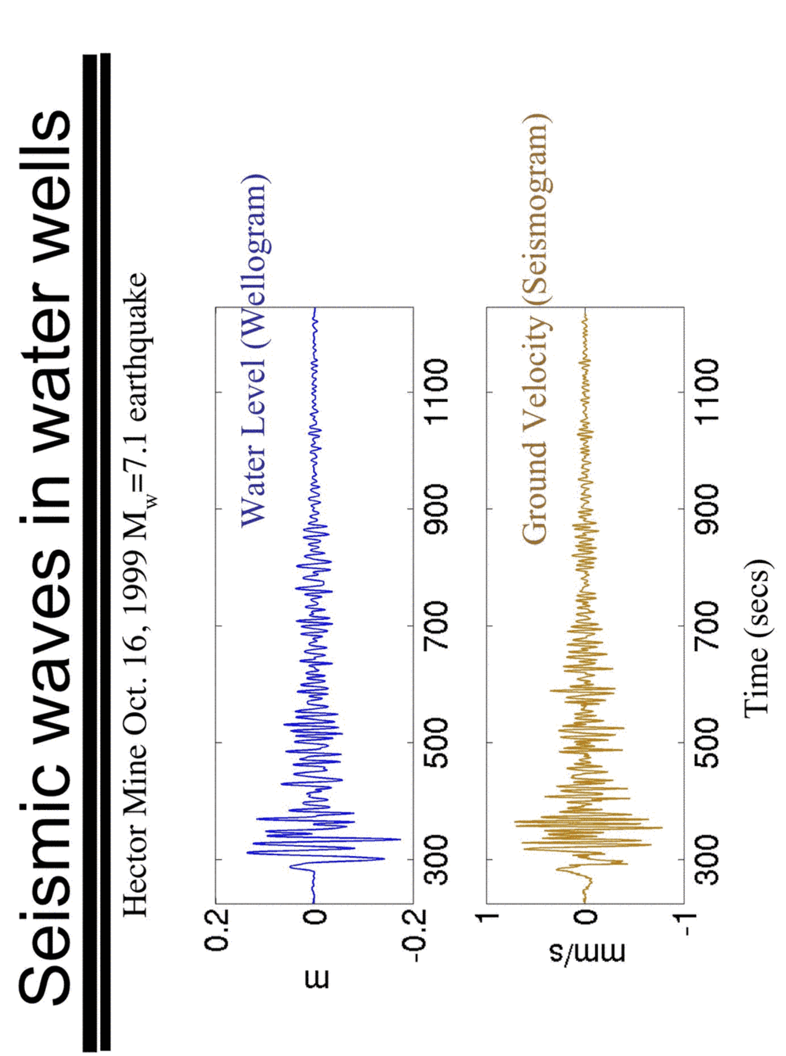
1964 Alaska M_w=9.2 earthquake

↓

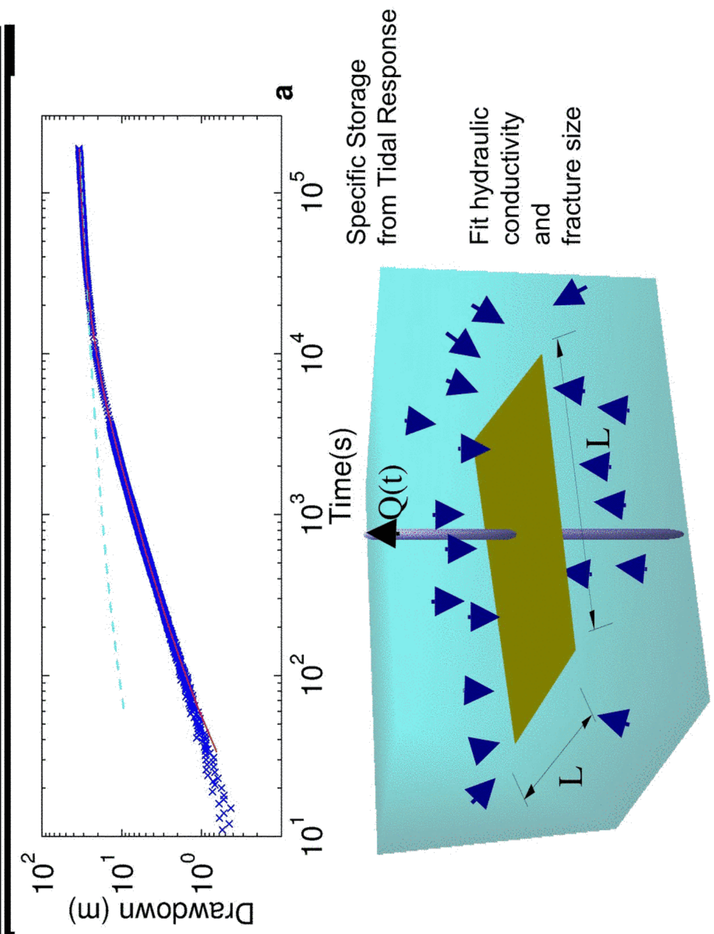
Clay County, Florida (~ 5000 km from the epicenter)

Vorhis (1968)


Coseismic Water Level Steps
Water level records from Grants Pass, OR
(Earth tides & barometric response removed)
Sept. 30, 1999 M$_w$=7.4 Oaxaca EQ, Δ=3850 km
Sept. 1, 1994 M$_w$=7.0 Petrolia EQ, Δ=300 km
Earthquakes
Water Level (m)
Time (Days)
0.1
0
−0.1
−5
0
5


Seismic waves in water wells
Hector Mine Oct. 16, 1999 M$_w$=7.1 earthquake
Water Level (Wellogram)
Ground Velocity (Seismogram)
m
mm/s
Time (secs)
0.2
0
-0.2
1
0
-1
300
500
700
900
1100

Pumping Test: Fracture Solution Fit



Quarry near Grants Pass well

Amplification Function

$$\chi \equiv \left|\frac{x_w}{\dot{x}_s}\right|$$

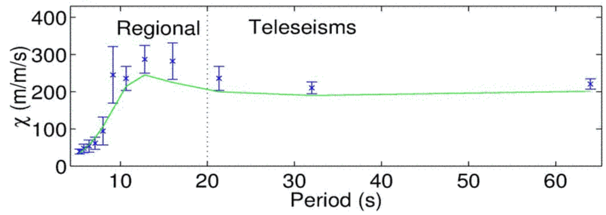
$$\propto \left|1 - \frac{4\pi^2 H f^2}{g} + \frac{\pi r_w^2}{2L^2}\sqrt{\frac{\pi f}{K S_s}}(1+i)\right|^{-1}$$

where:

x_w = Water level amplitude
$\dot{x}_s$ = Ground velocity (seismic amplitude)

H = Water column height
f = Frequency
g = Gravity
r_w = Well radius

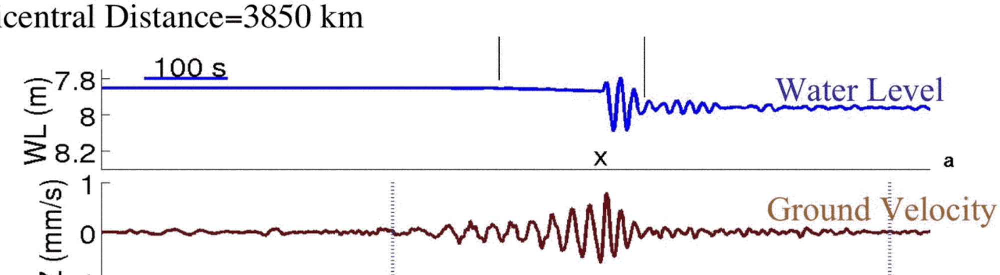
S_s = Specific storage
L = Fracture length
K = Wallrock (matrix) hydraulic conductivity



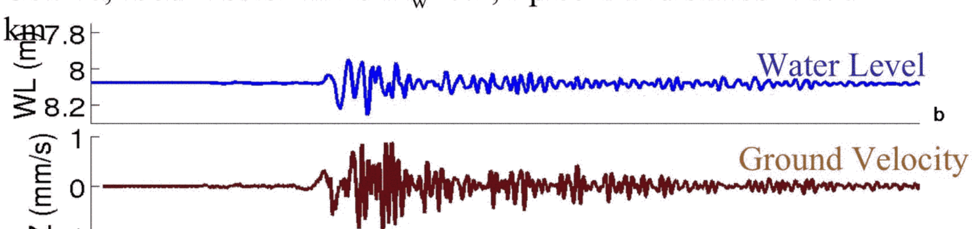
(Derived following method of Cooper et al., 1965 for modified geometry)

Seismic Waves & Steps

Sept. 30, 1999 Oaxaca M_w=7.4
Epicentral Distance=3850 km

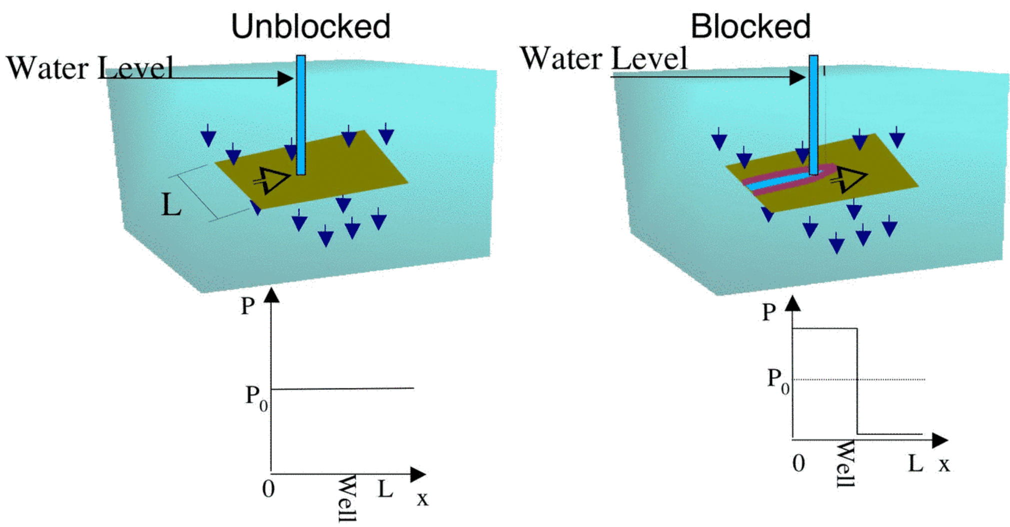


Oct. 16, 1999 Hector Mine M_w=7.1; Epicentral distance=1070 km



Amplification is 40x less than normal before the step.

Temporary Barriers

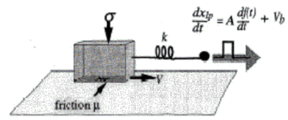


Implications for Seismicity

- Steps redistribute pore pressure on fractures *or faults* generating seismicity by rapidly reducing the strength locally.
- Faster precipitation in geothermal areas → thicker barriers → larger pressure changes
  - Model predicts 4×10^{-2} MPa all else being equal
    - Sufficient to trigger EQs from static stress studies (Hardebeck et al, 1998)

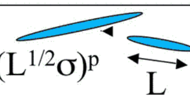
Triggering Mechanisms

- Friction instabilities
  (Gomberg et al., 1998)

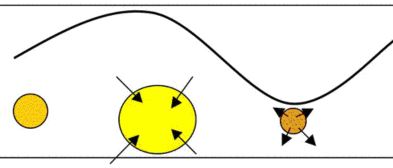


- Subcritical crack growth
  (Brodsky et al, 2000; Gomberg et al, 2001)

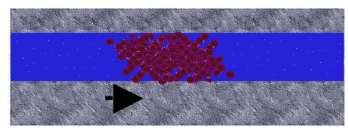
$\dot{L} \propto (L^{1/2}\sigma)^p$



- Bubble pressurization mechanisms
  (Linde et al. 1994, Sturtevant et al. 1996)



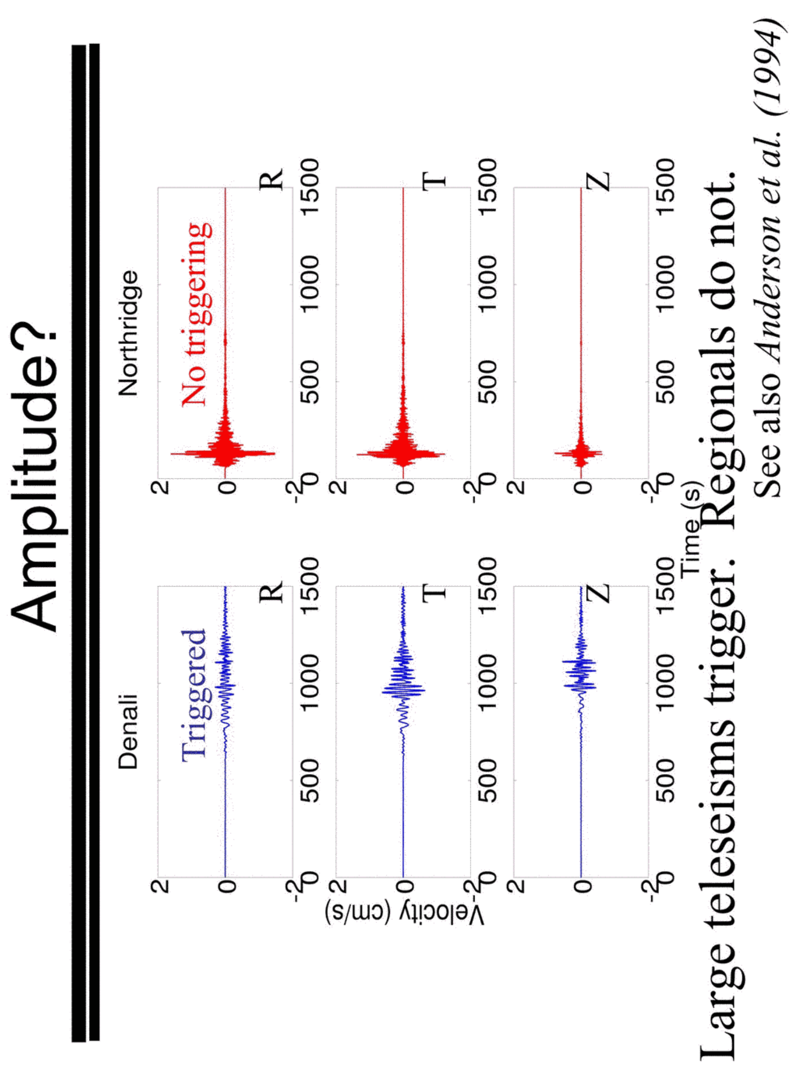
- Unclogging Fractures
  (Brodsky et al., 2003)

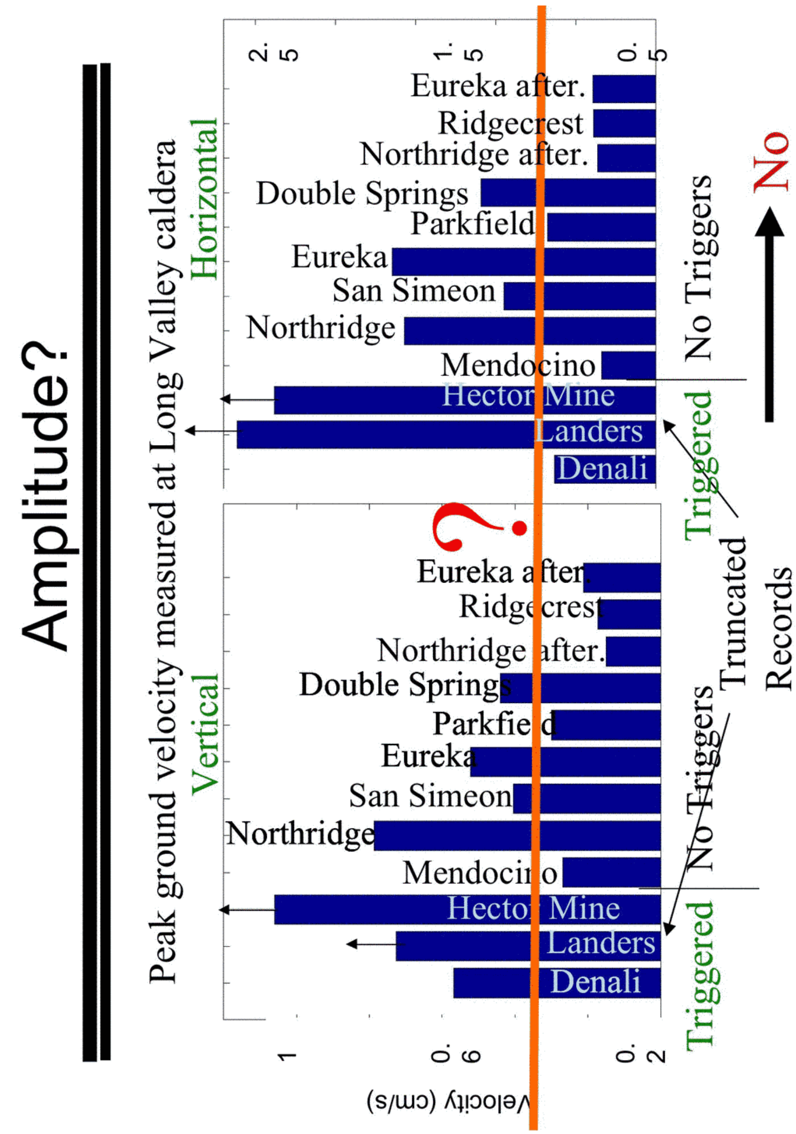


How do we observationally constrain the mechanism?

Testing by finding the Threshold..

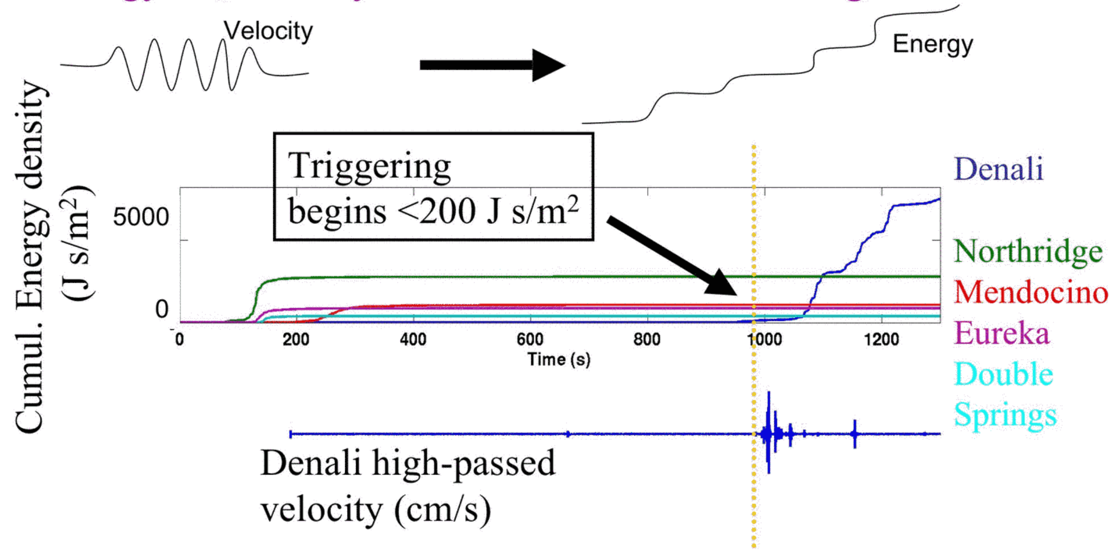
- Amplitude (0.2-6 cm/s)
- Duration or energy
- Frequency


Amplitude?
Denali
Northridge
Triggered
No triggering
R
T
Z
Velocity (cm/s)
Time (s)
Large teleseisms trigger. Regionals do not.
See also Anderson et al. (1994)


Amplitude?
Peak ground velocity measured at Long Valley caldera
Vertical
Horizontal
Eureka after.
Ridgecrest
Northridge after.
Double Springs
Parkfield
Eureka
San Simeon
Northridge
Mendocino
Hector Mine
Landers
Denali
Velocity (cm/s)
Triggered
No Triggers
Truncated Records
No

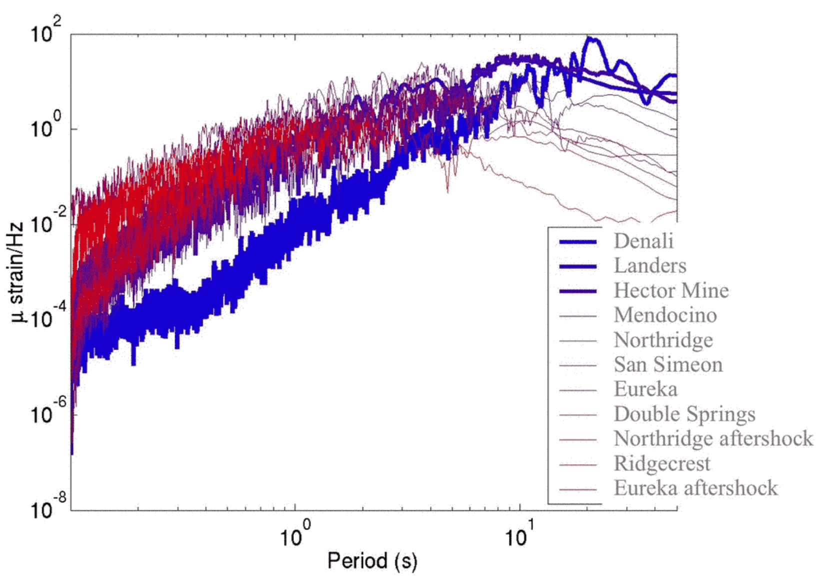
Energy?

Energy ∝ ∫velocity² dt measures total stressing over time

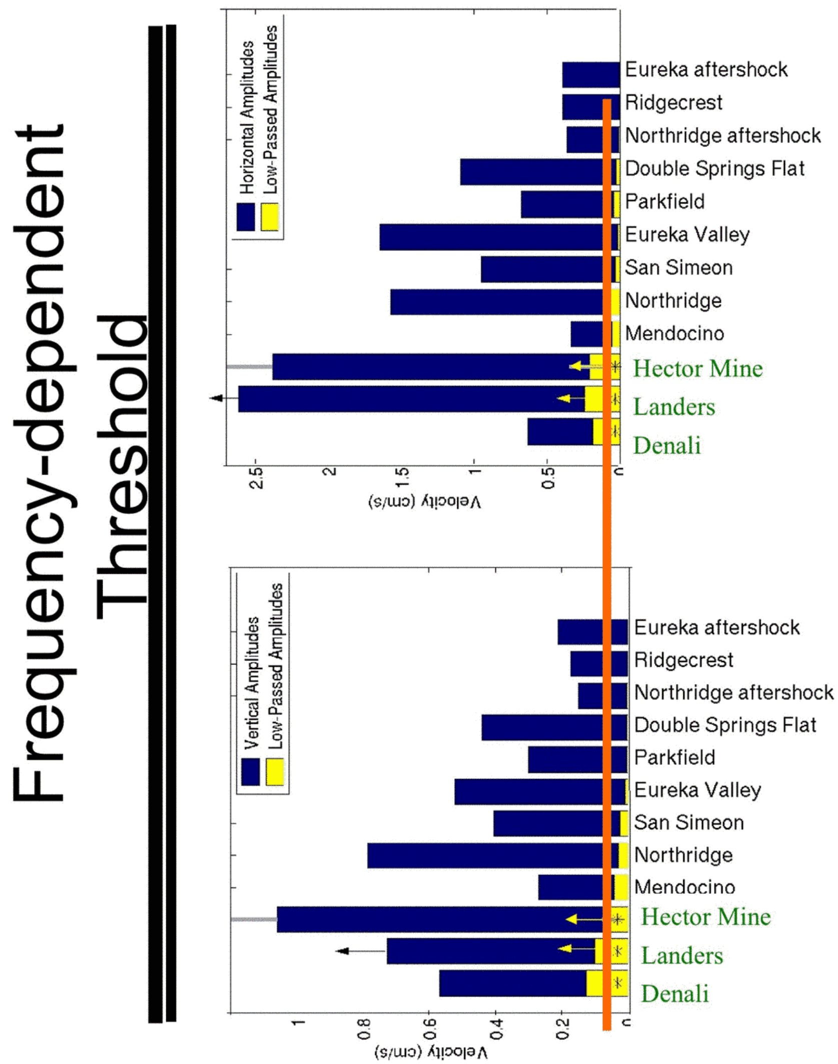


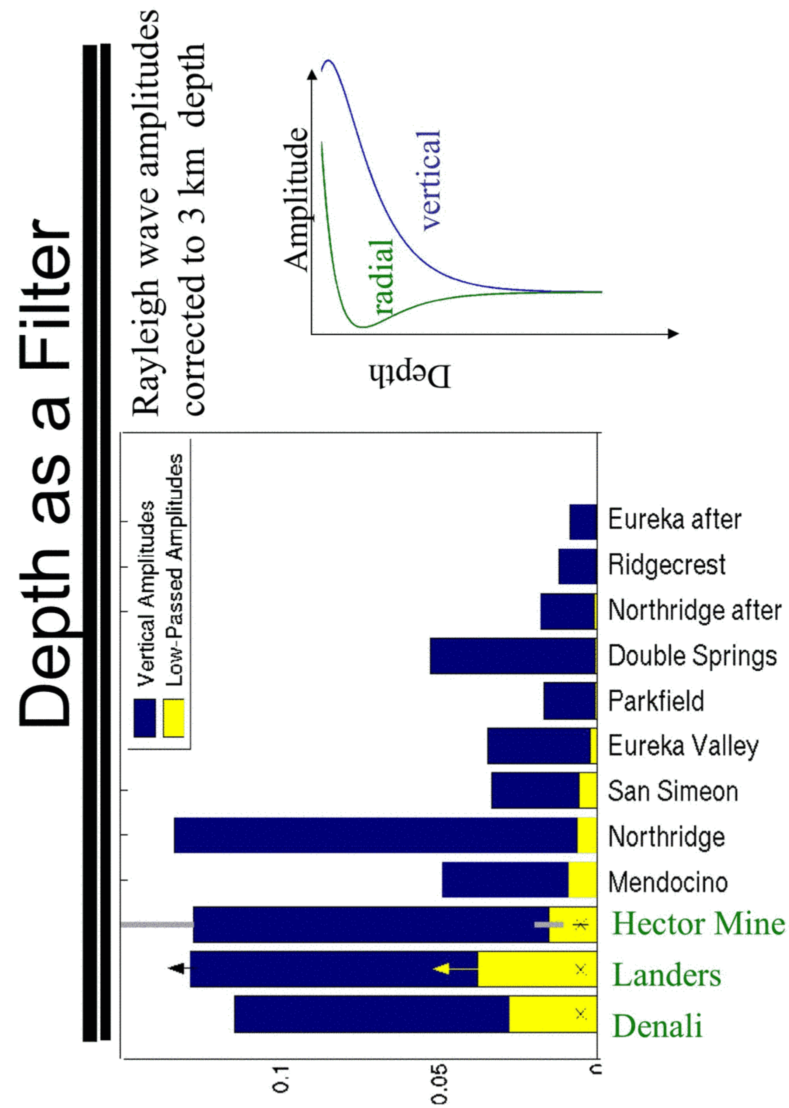
No

Frequency?

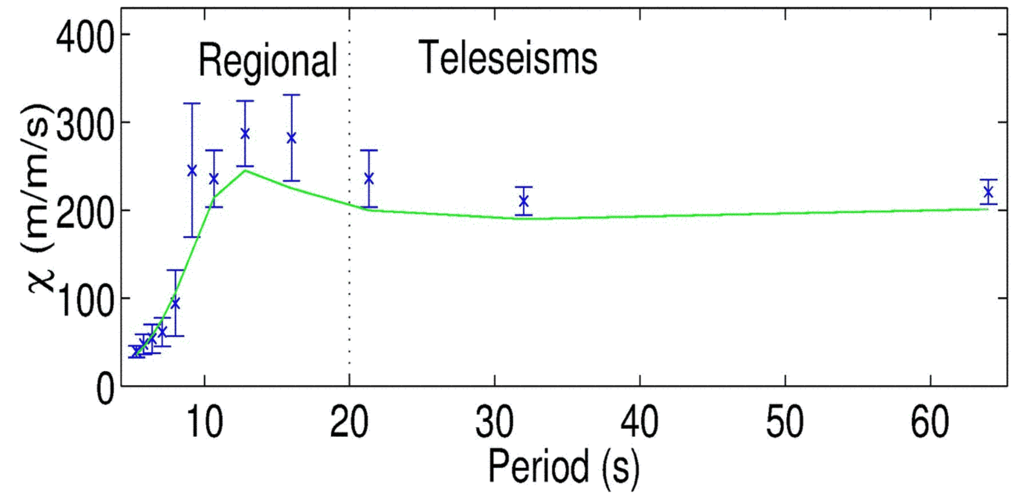


Yes

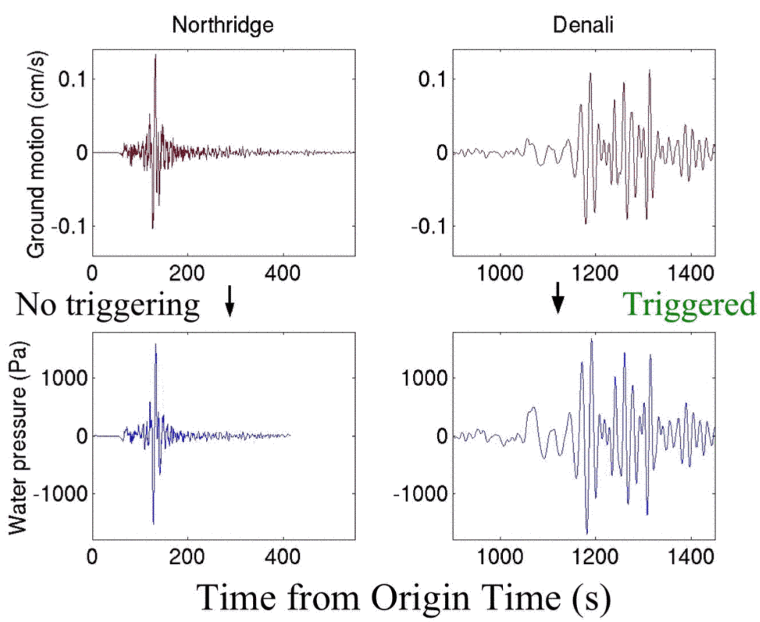

Frequency-dependent Threshold
Horizontal Amplitudes
Low-Passed Amplitudes
Eureka aftershock
Ridgecrest
Northridge aftershock
Double Springs Flat
Parkfield
Eureka Valley
San Simeon
Northridge
Mendocino
Hector Mine
Landers
Denali
Velocity (cm/s)
2.5
2
1.5
1
0.5
0
Vertical Amplitudes
Low-Passed Amplitudes
Eureka aftershock
Ridgecrest
Northridge aftershock
Double Springs Flat
Parkfield
Eureka Valley
San Simeon
Northridge
Mendocino
Hector Mine
Landers
Denali
Velocity (cm/s)
1
0.8
0.6
0.4
0.2
0


Depth as a Filter
Rayleigh wave amplitudes corrected to 3 km depth
Amplitude
Depth
vertical
radial
Vertical Amplitudes
Low-Passed Amplitudes
Eureka after
Ridgecrest
Northridge after
Double Springs
Parkfield
Eureka Valley
San Simeon
Northridge
Mendocino
Hector Mine
Landers
Denali
0.1
0.05
0

Alternative: Low-Pass Filter



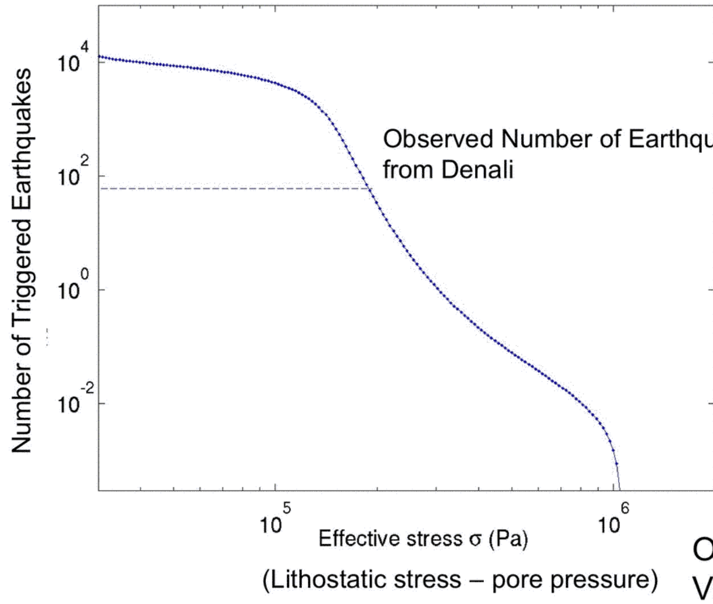
Example: Solution for flow into infinite planar fault



Specific storage
$S_{sm}=10^{-8} m^{-1}$
$S_{sf}=10^{-4} m^{-1}$
Fault width
a= 1 cm

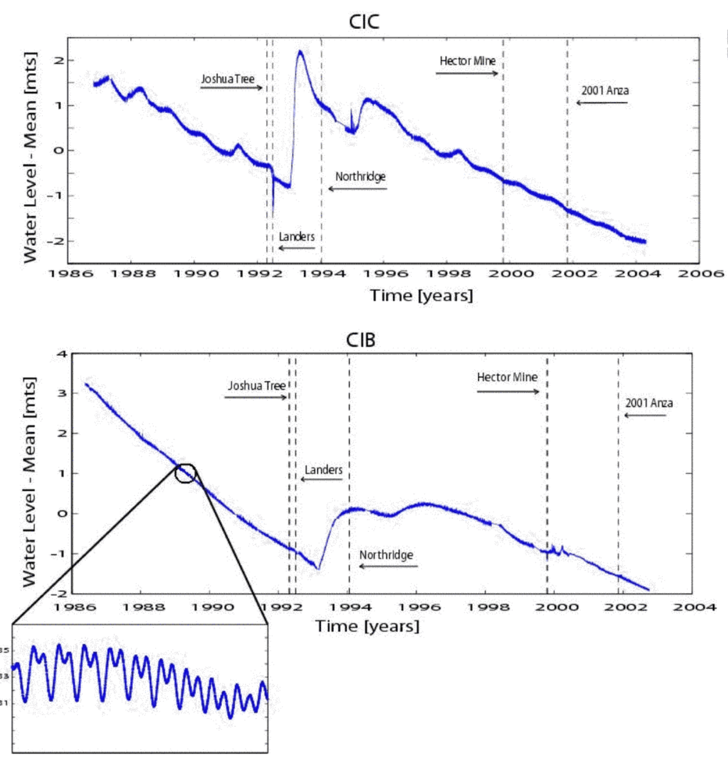
Hydraulic
Conductivity
$K=10^{-7}$ m/s

Making Eqs from small stresses

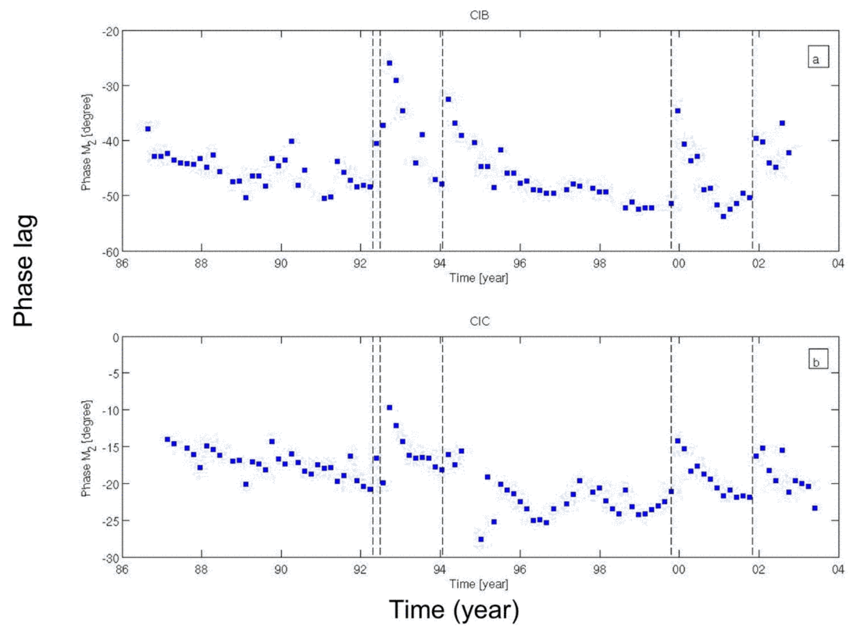


OK for Long Valley,
But not Geysers

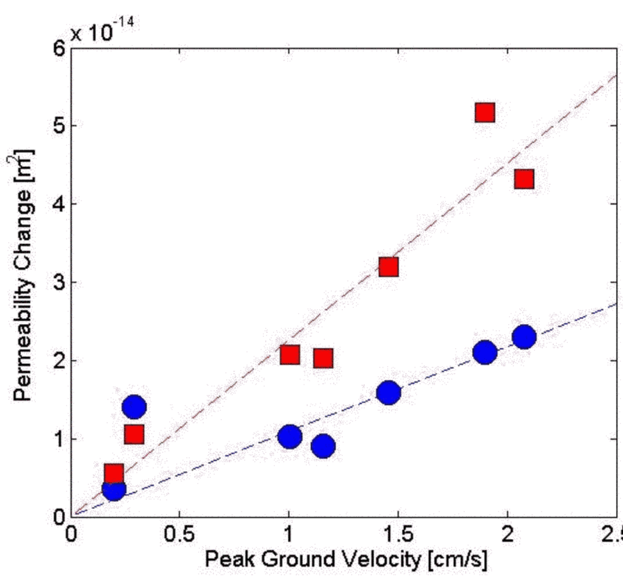
A Detour: Tidal Responses



Phase variability with time



Permeability and Shaking



1 cm/s ≈0.1 MPa

Mechanisms

- Friction
  (*Gomberg, 1998*)
  OK if pore pressure is *very* high (which it is not at The Geysers)
- Subcritical crack growth
  (*Brodsky et al, 2000*)
- ~~Bubble pressurization mechanisms~~
  ~~(*Linde et al. 1994, Sturtevant et al., 1996*)~~
- Unclogging fractures
  (*Brodsky et al., 2003*)
  May explain low-pass filter

The Answer?

- Long-range triggering is a result of fluid flow driven by seismic waves into faults
  - The flow can unclog fluid pathways and rearrange fluid pressure