Three (very) short stories utilizing the toolkit from observing ordinary earthquakes for the study of induced seismicity

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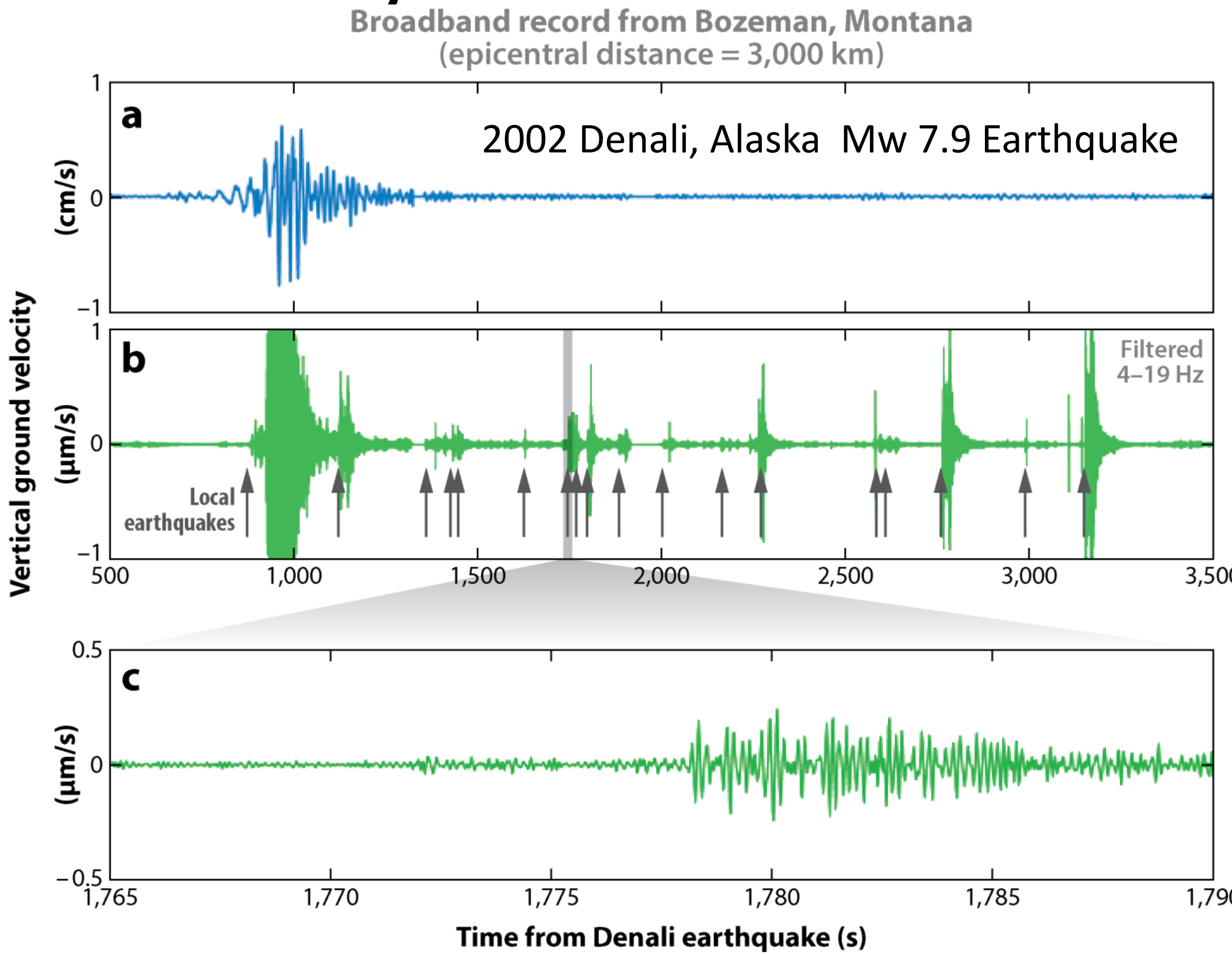
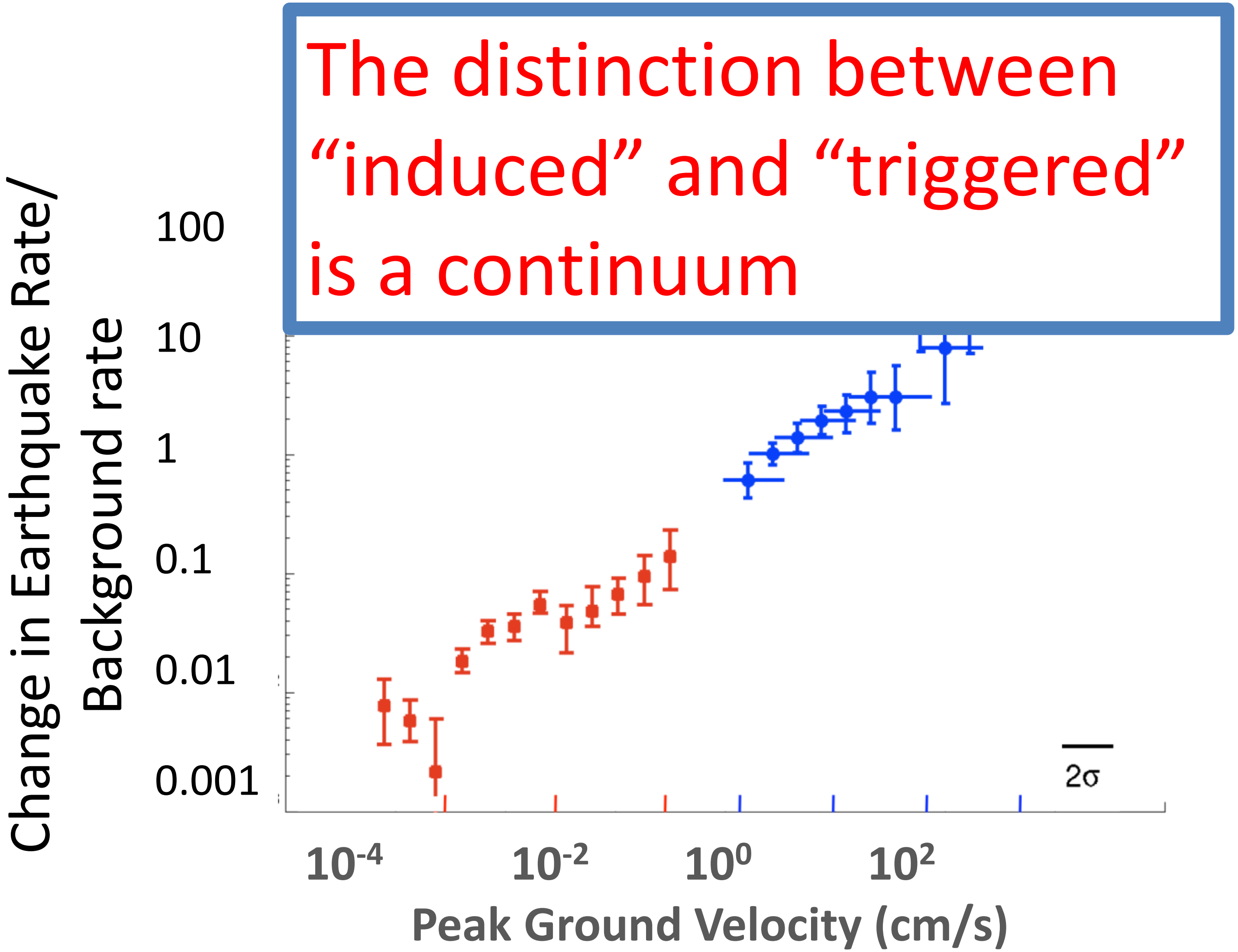
Part I:Dynamic Triggering of Earthquakes by Seismic Waves



Brodsky EE, van der Elst NJ. 2014.
Annu. Rev. Earth Planet. Sci. 42:317–39

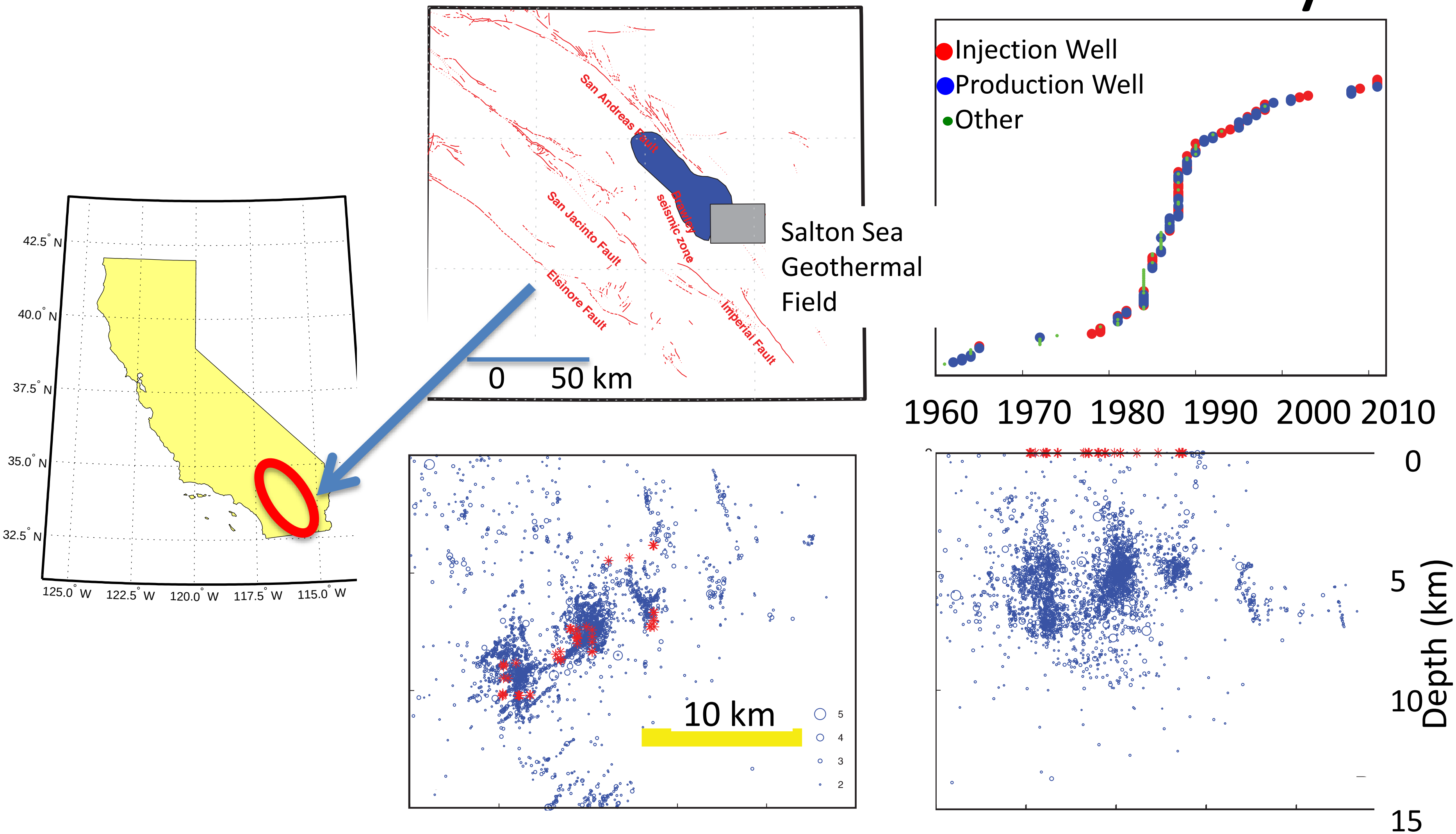
The distributionof triggering thresholds



California 1984-2008

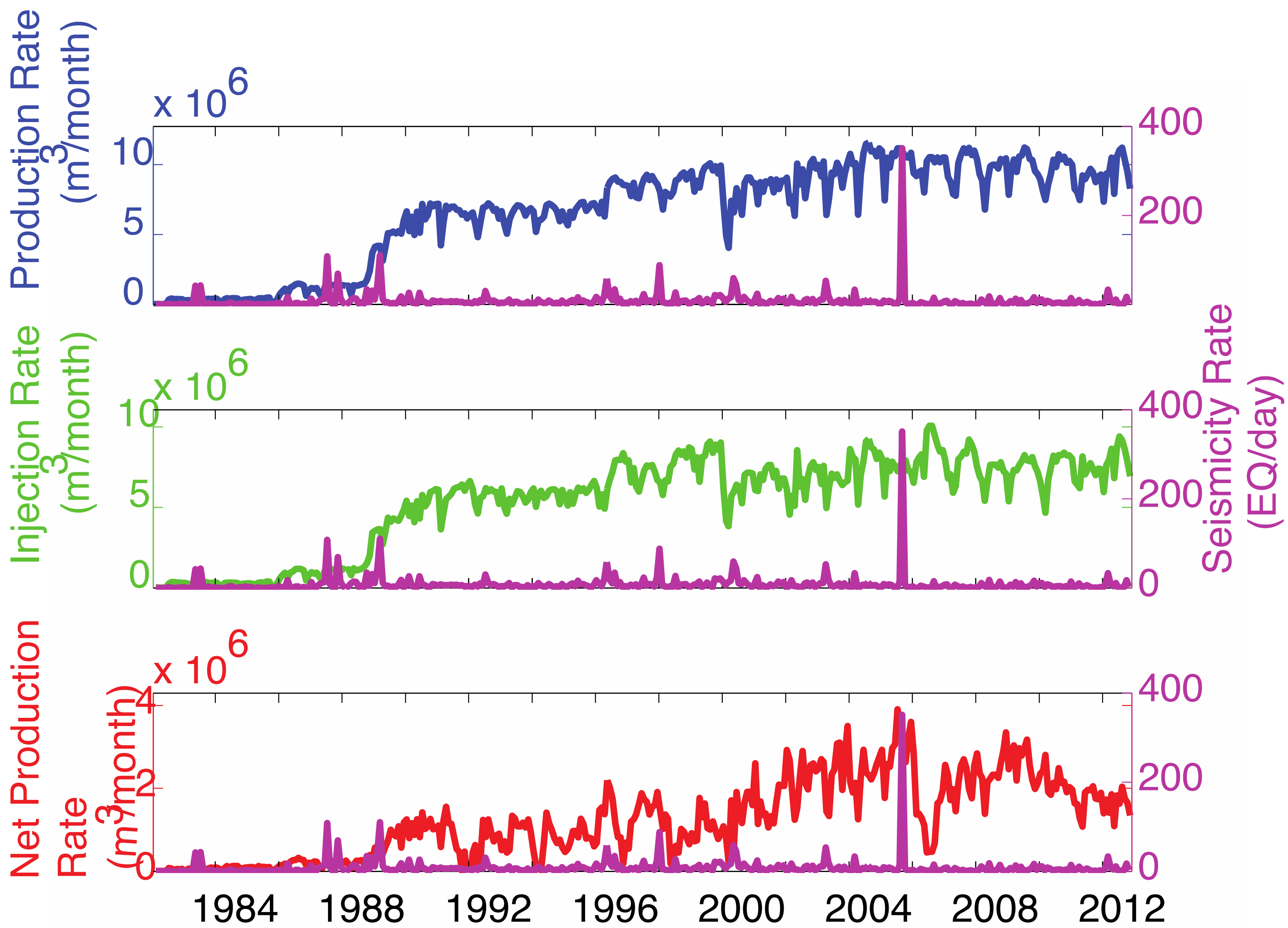
Van der Elst and Brodsky, *J. Geophysical Research* 2010

Part II:
Aftershocks and Induced Seismicity

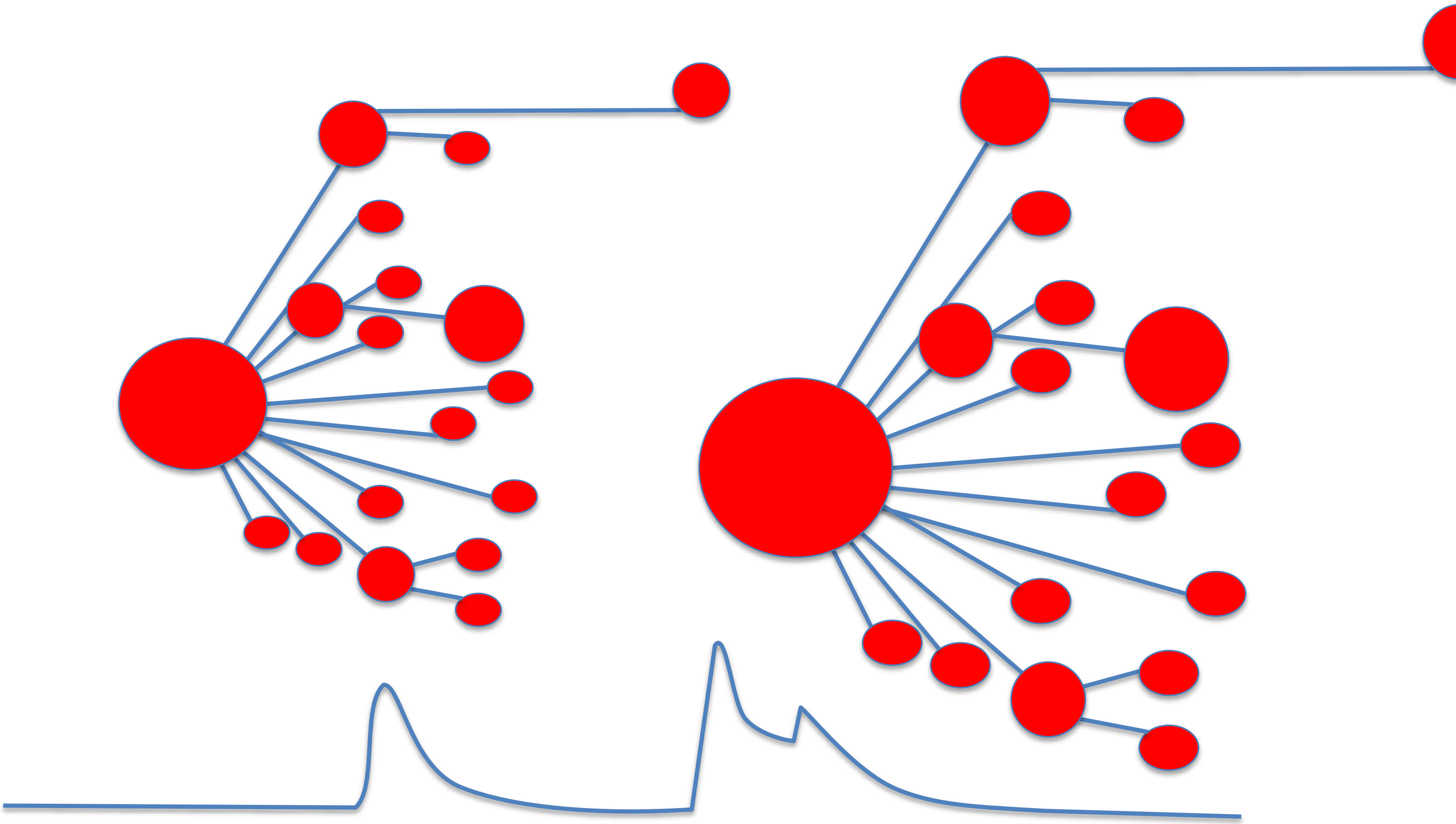


Brodsky & Lajoie, *Science*, 2013

Raw Earthquake & Operational Data

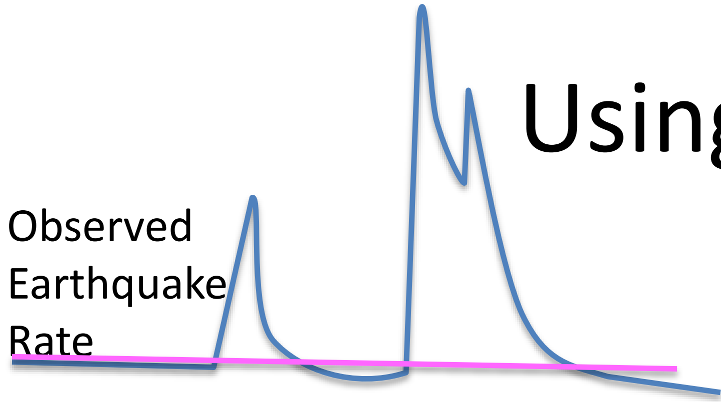


Epidemic-Type Aftershock Sequence (ETAS) Model



Ogata, 1988 ++

Using ETAS to Determine the Background Rate



$$\text{Earthquake Rate at Time } t_E = \mu + \sum_{i;\, t_i < t_E} \frac{K_E 10^{\alpha(M_i - M_c)}}{(t_E - t_i + c)^p}$$

Where:

- μ=background rate,
- Number of aftershocks = $K_E\ 10^{\alpha(Mi\text{-}Mc)}$

  Given completeness magnitude M_c

  & mainshock magnitude M_i
- Aftershock rate from mainshock at time $t_i \sim 1/(t_E - t_i + c)^p$

Fit K_E, p, μ and track μ

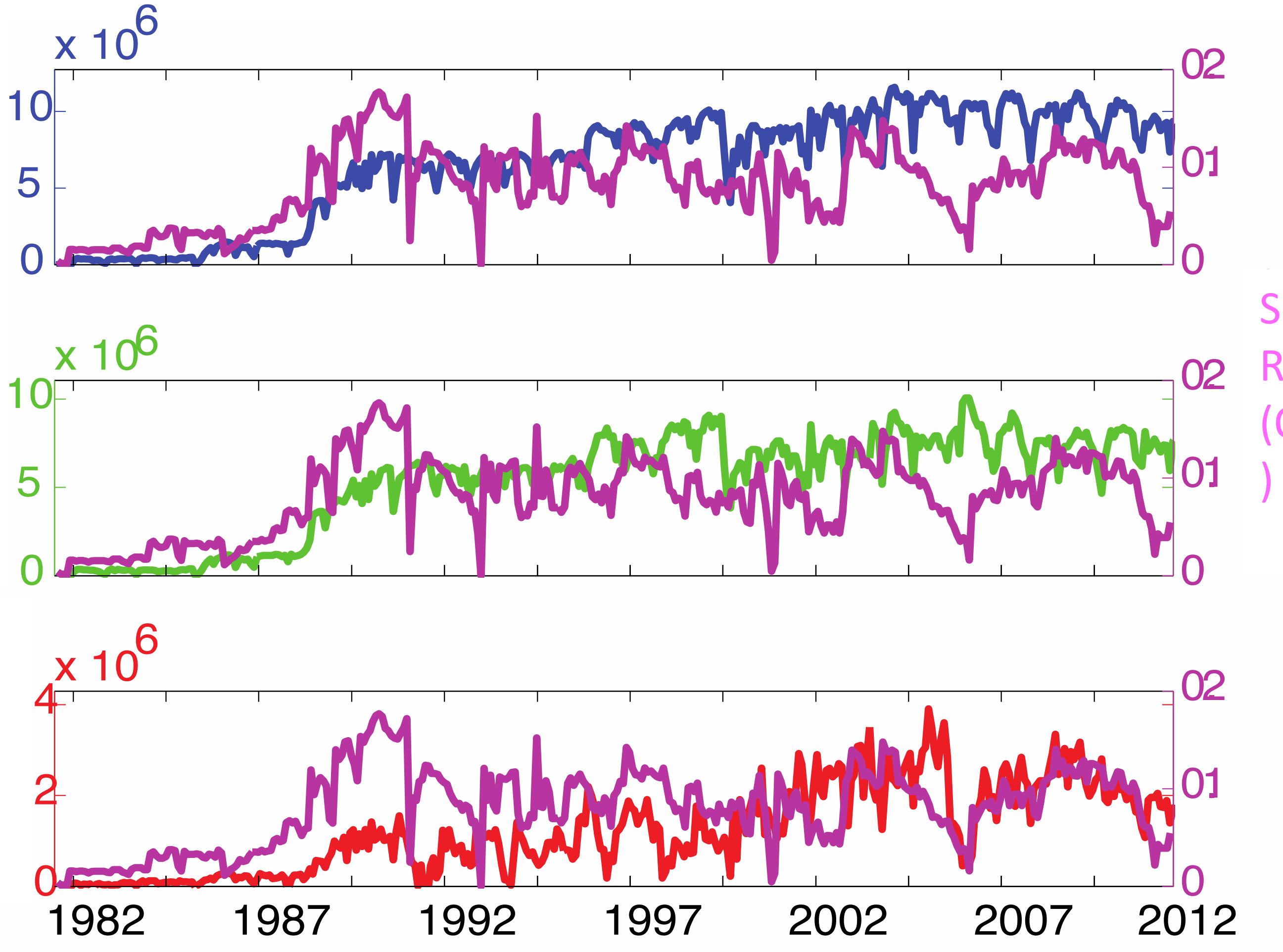
Ogata, 1988 ++

Background (non-aftershock) rate and operations

Production Rate (m^3/month)

Injection Rate (m^3/month)

Net Extraction Rate (m^3/month)



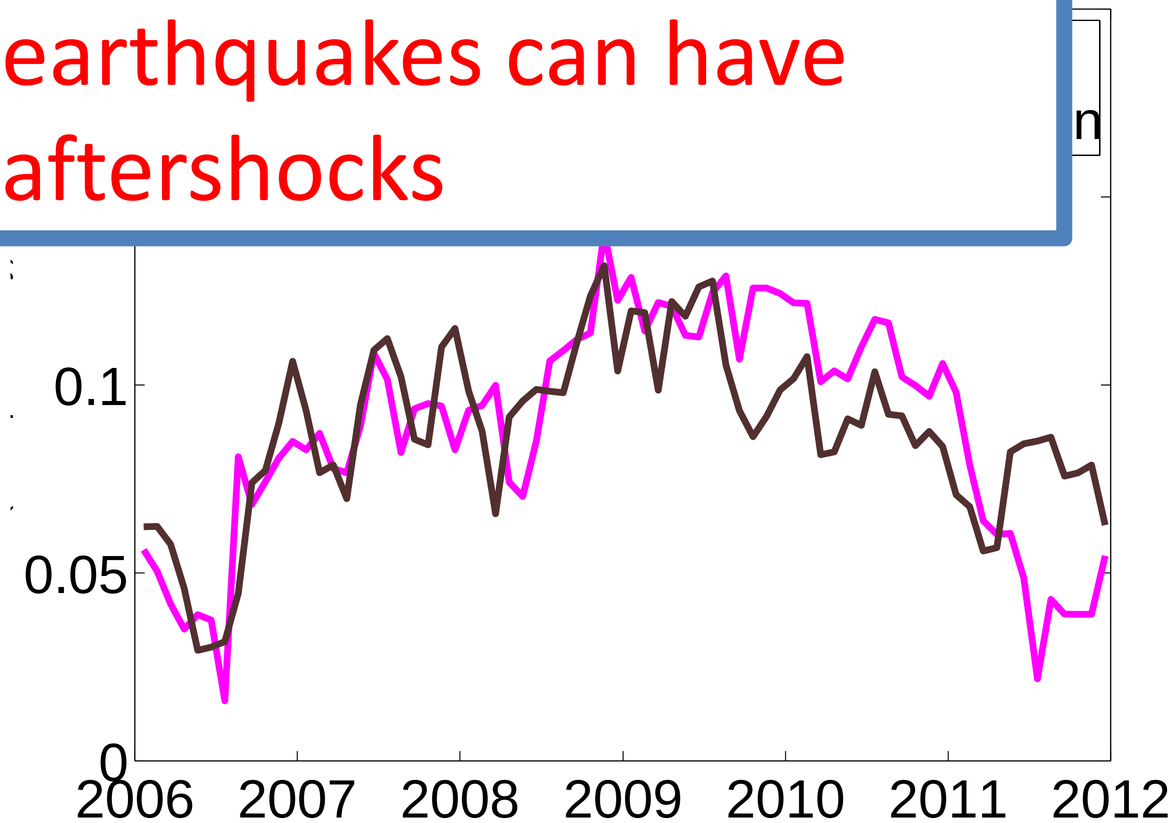
Seismicity Rate (Quakes/Day)

Brodsky & Lajoie, *Science*, 2013

Best-Fit Linear Combination of Injection and Net Production

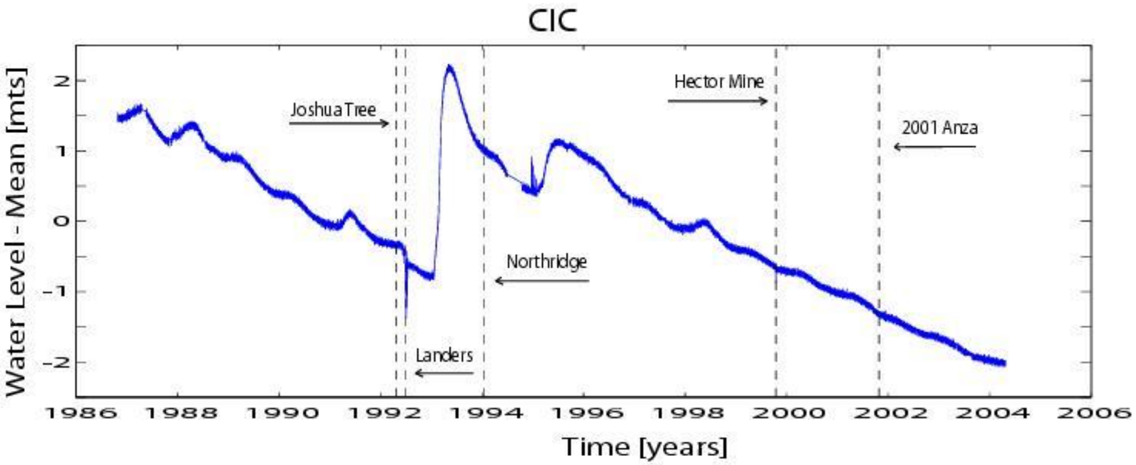
Anthropogenic earthquakes can have aftershocks

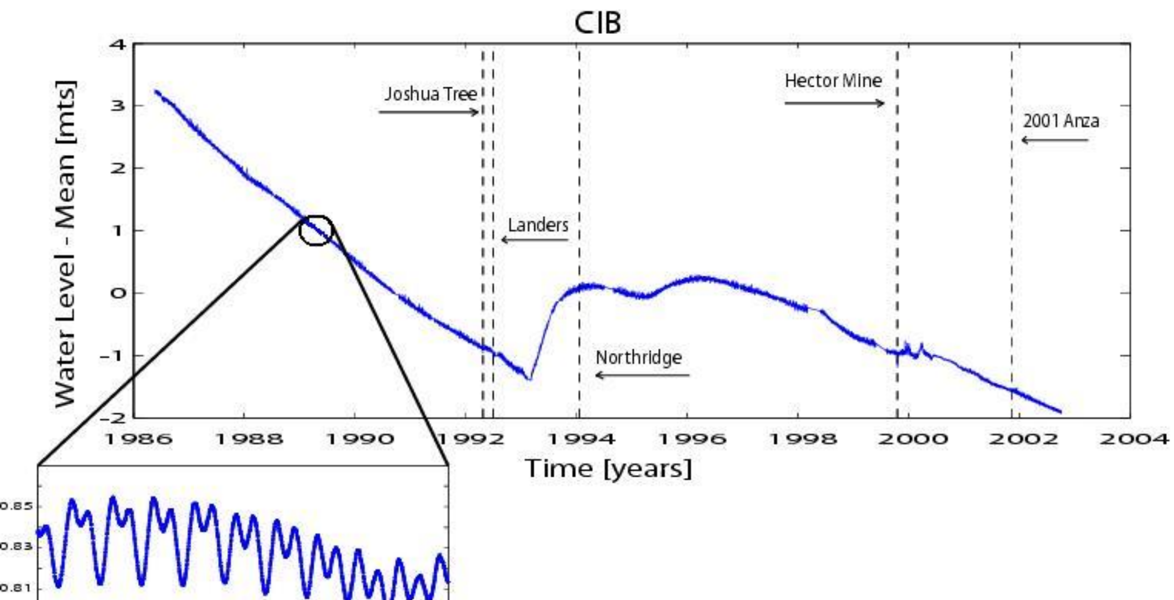
Seismicity Rate (Quakes/Day)

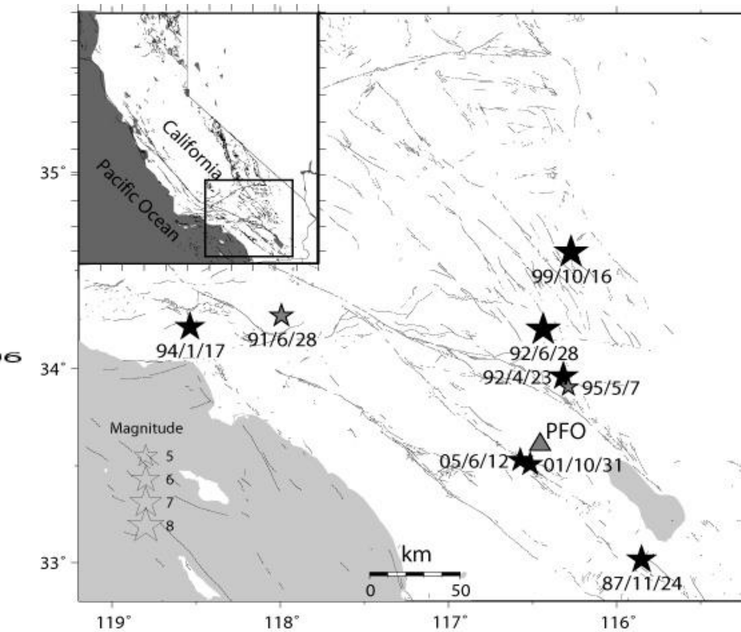


Brodsky & Lajoie, *Science,* 2013

Part III: Dynamic Permeability Enhancement



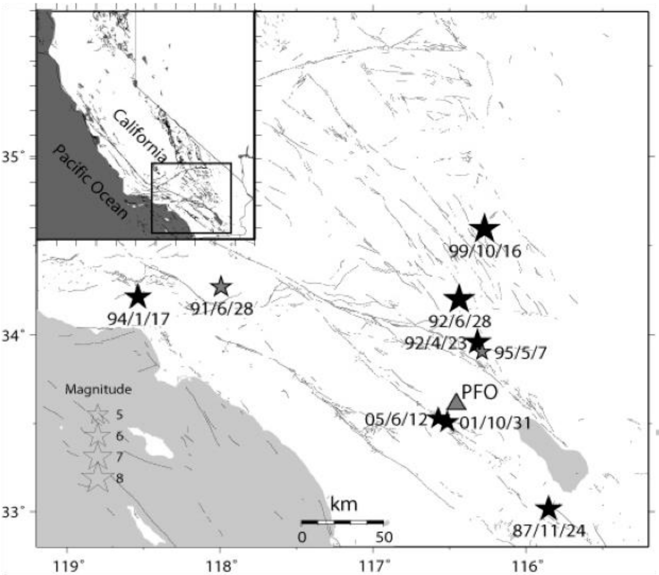


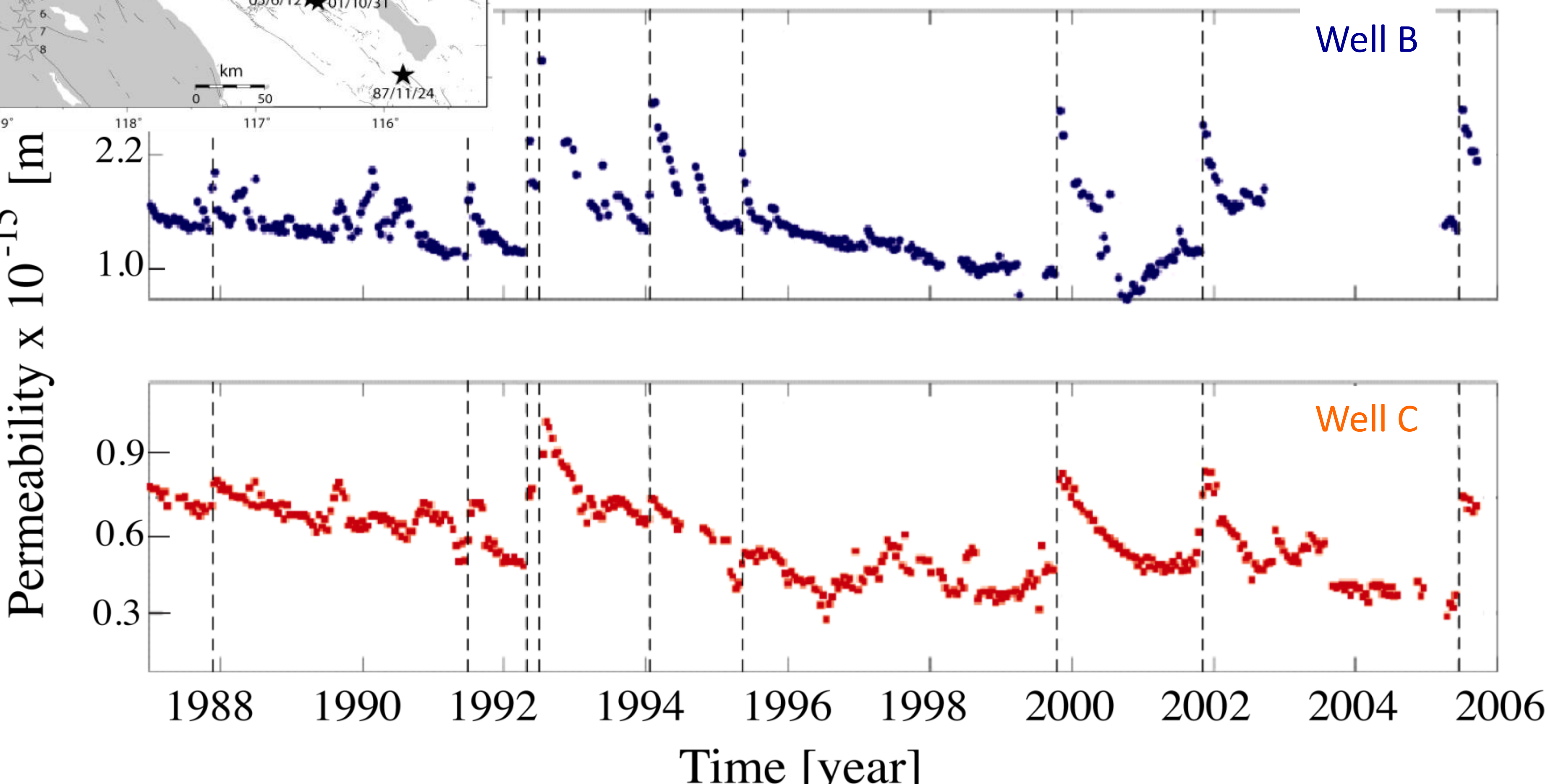


Elkhoury, Brodsky and Agnew, *Nature*, *2006*

Permeability Records: Permeability increases at the Time of Earthquakes

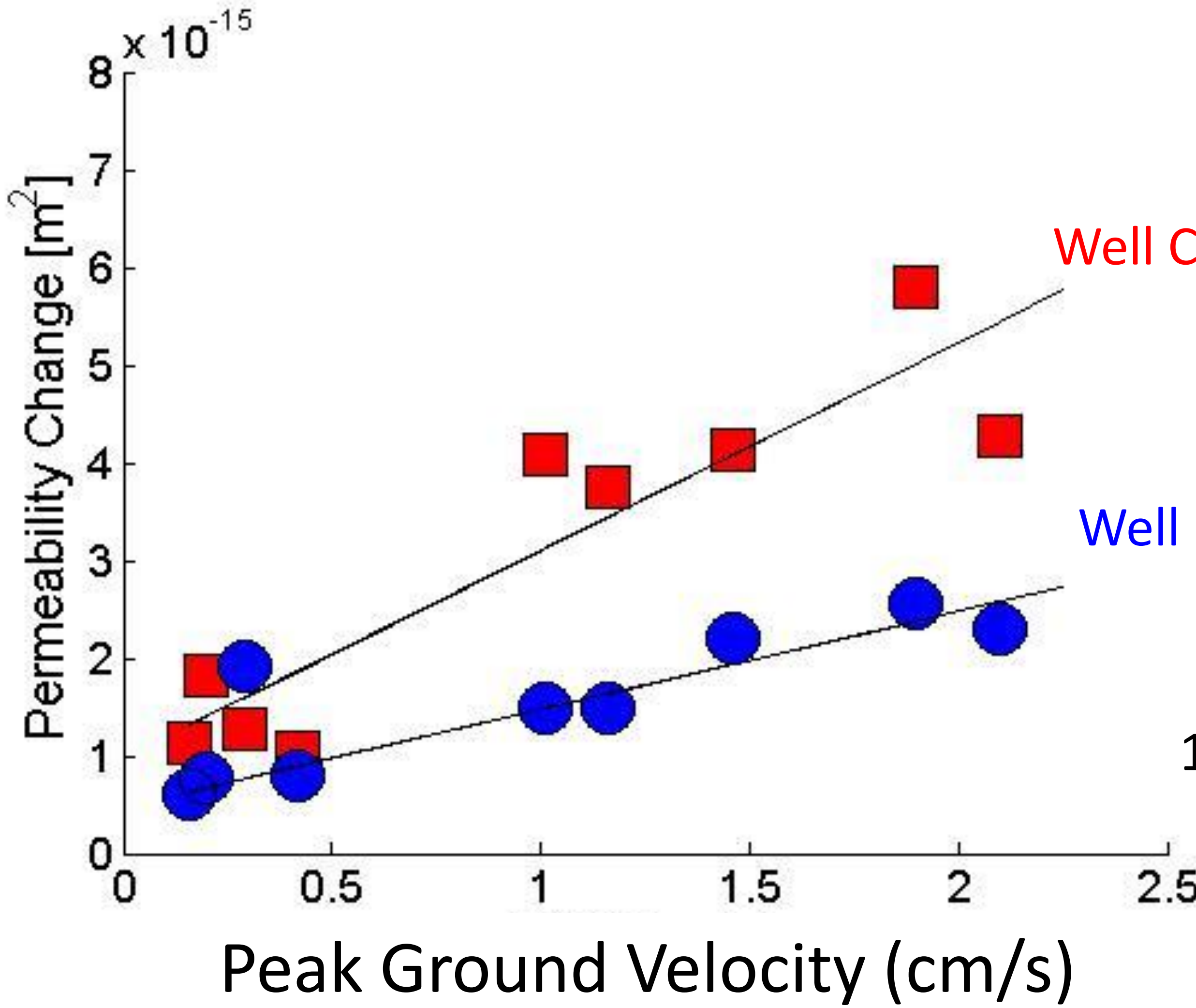
Assuming a homogenous, isotropic flow following Hsieh et al., 1987





Elkhoury, Brodsky and Agnew, *Nature, 2006*

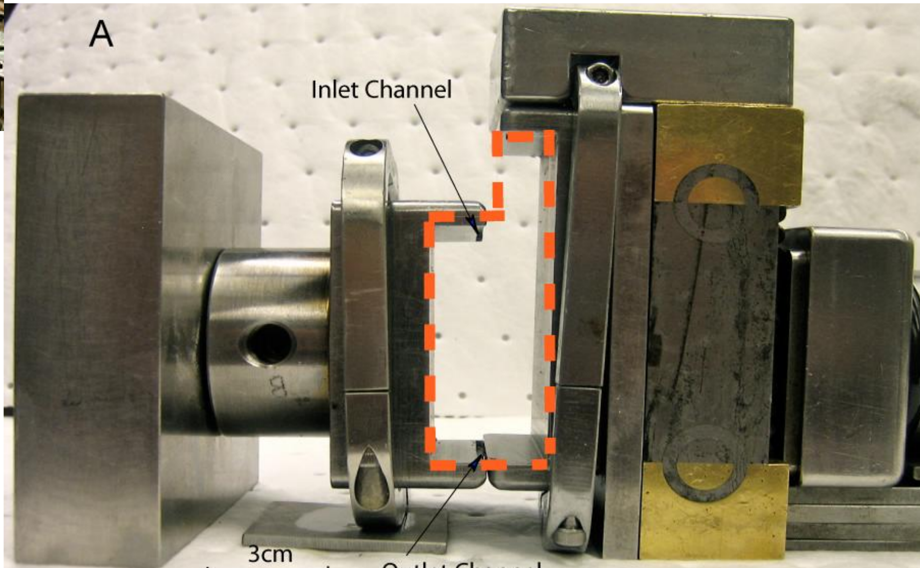
Permeability Increases with Shaking



1 cm/s ~0.1 MPa

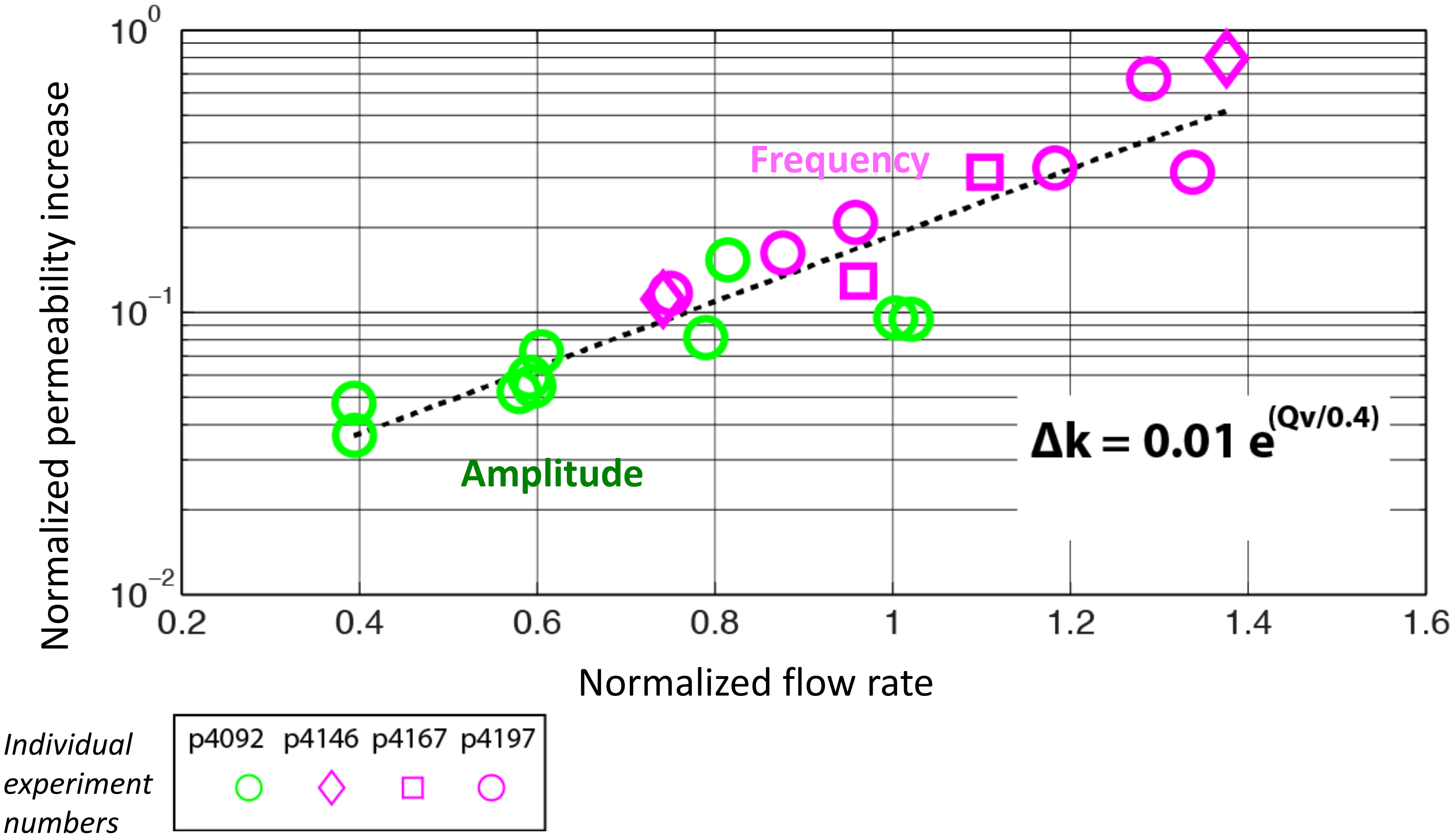
Elkhoury, Brodsky and Agnew, *Nature*, *2006*

Laboratory Experiment



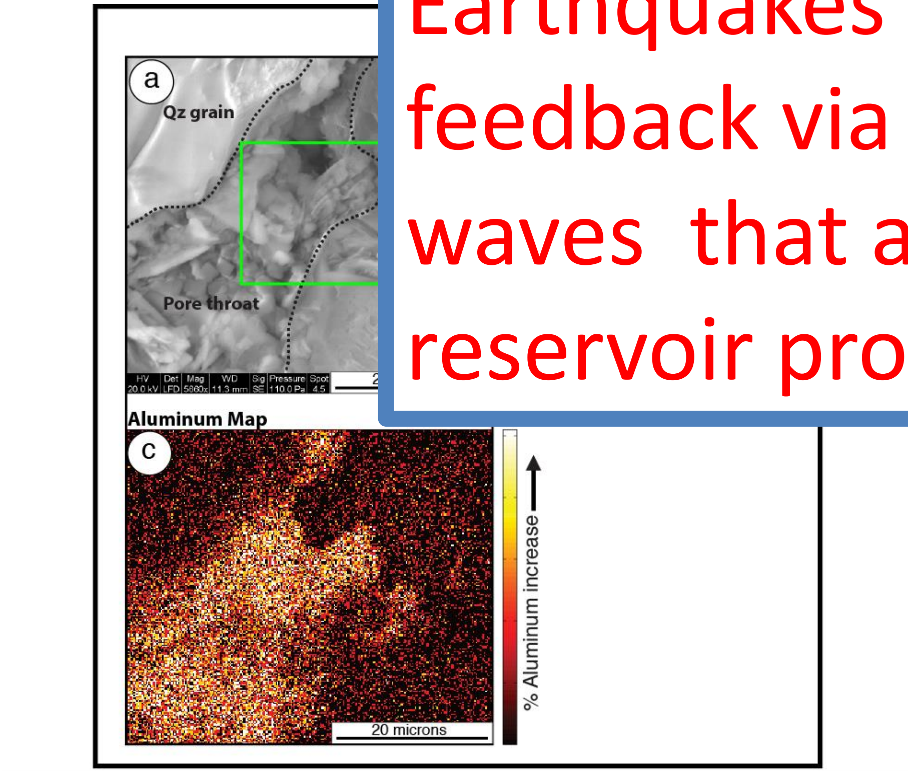
Elkhoury et al., *J. Geophys. Res.*, 2011
Candela et al., *Earth & Planet. Sci. Let,* 2014
Candela et al.*, J. Geophys. Res.*, 2015

Permeability Increases Generated in the Lab

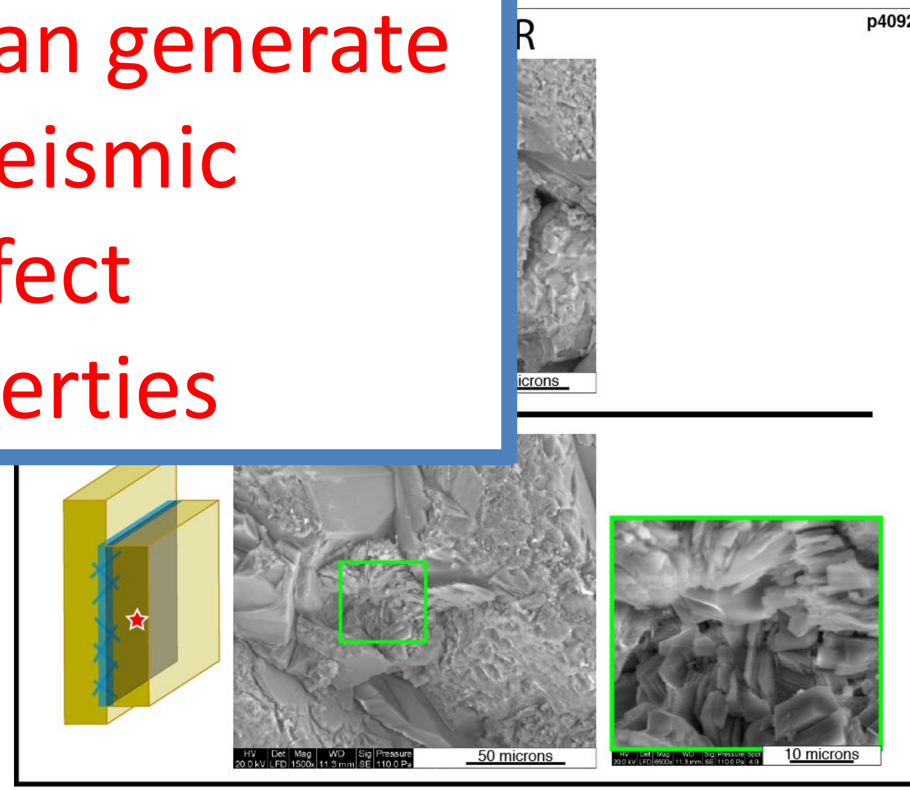


Candela et al., *J. Geophys. Res.*, 2015

Imagery of throat clearing



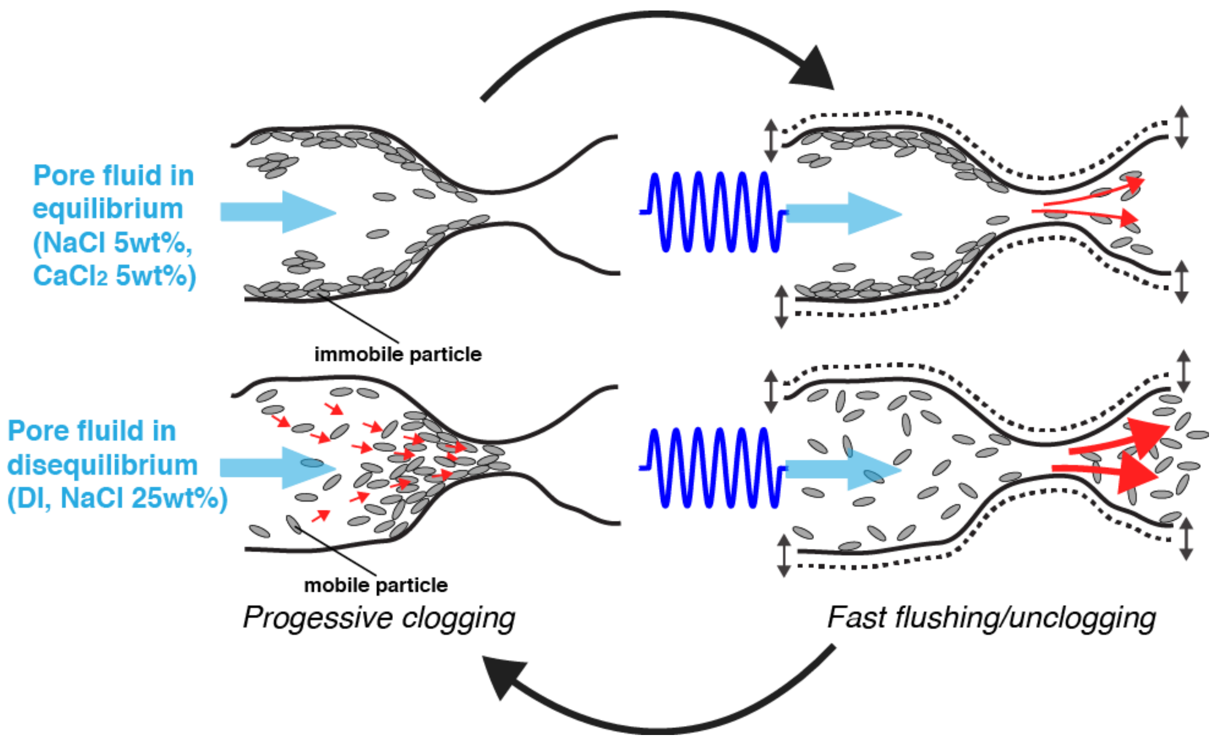
Earthquakes can generate feedback via seismic waves that affect reservoir properties



Candela et al., *EPSL*, 2014.

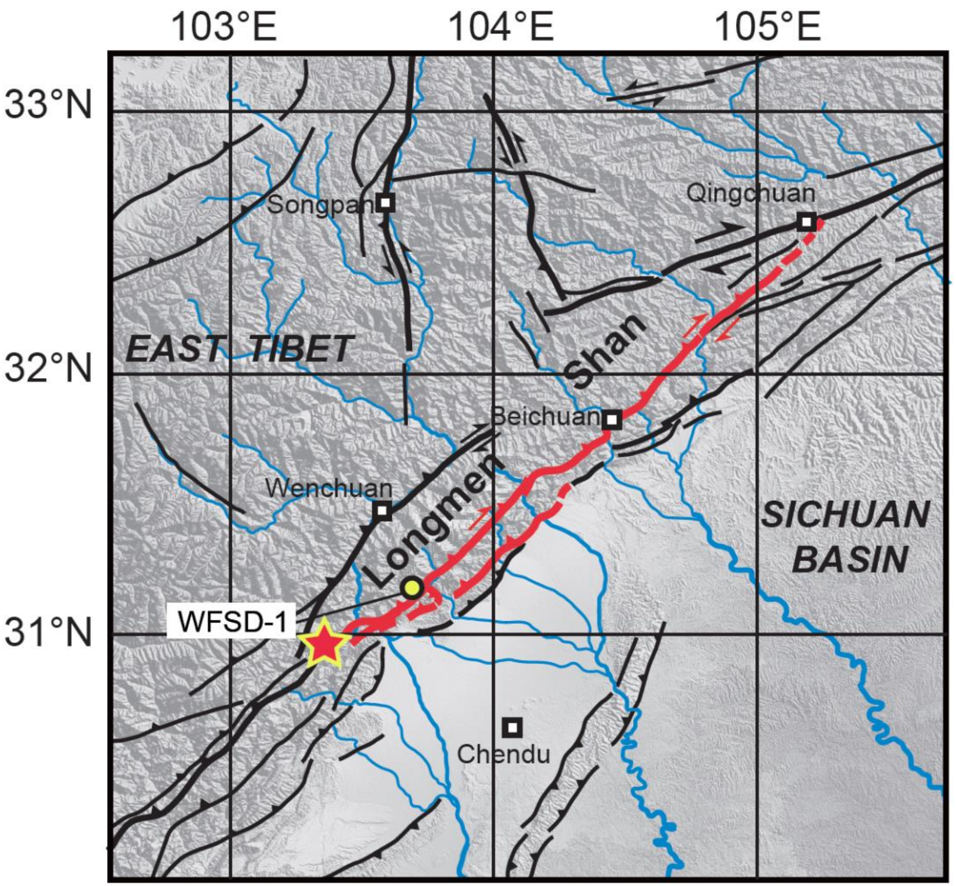
Conclusions

- From dynamic triggering:
  - The distinction between “induced” and “triggered” is a continuum
- From aftershock statistical models:
  - Anthropogenic earthquakes can have aftershocks
- From dynamic permeability:
  - Earthquakes can generate feedback via seismic waves that affect reservoir properties



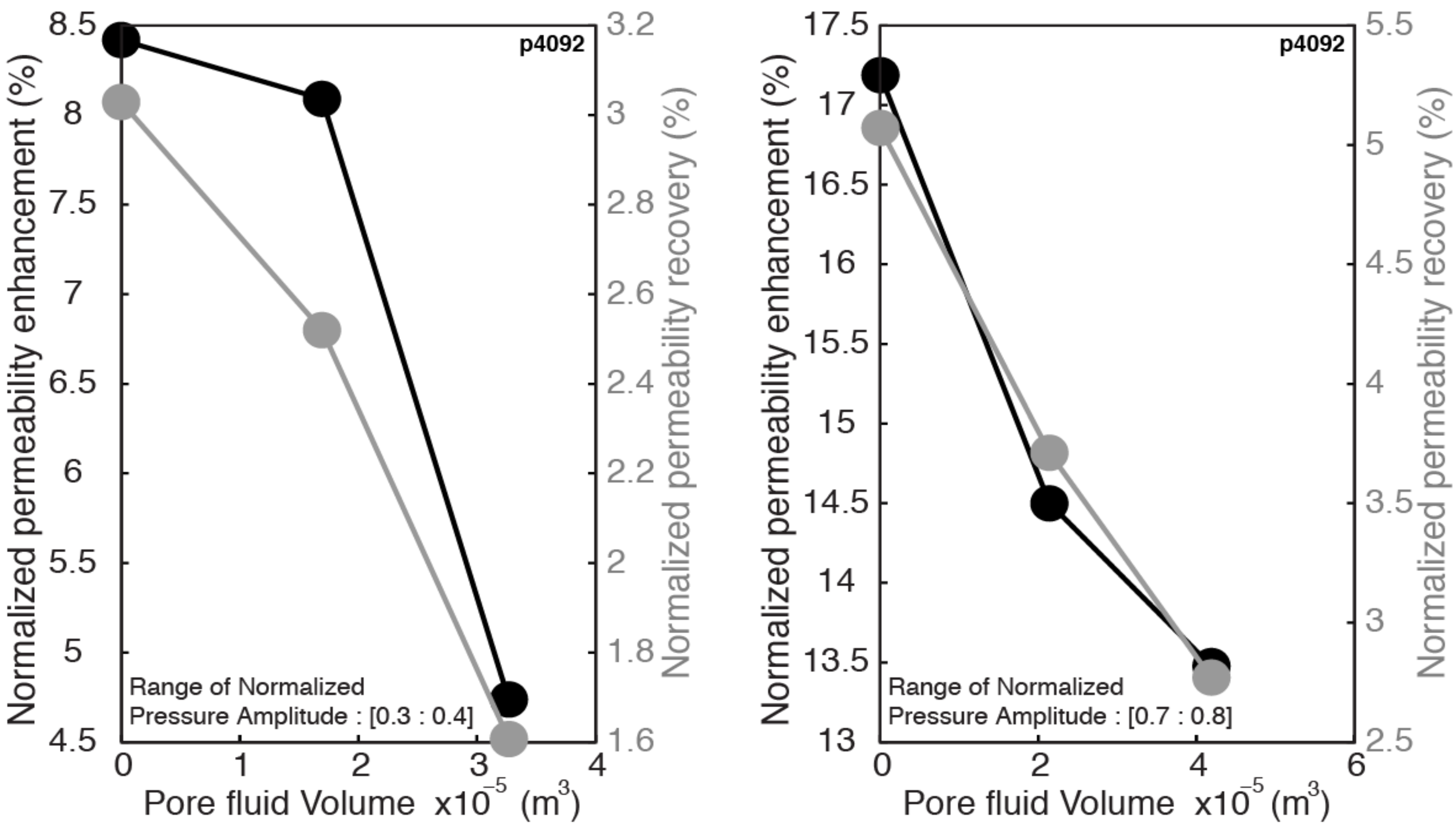
Candela et al., *EPSL*, submitted.

WFSD



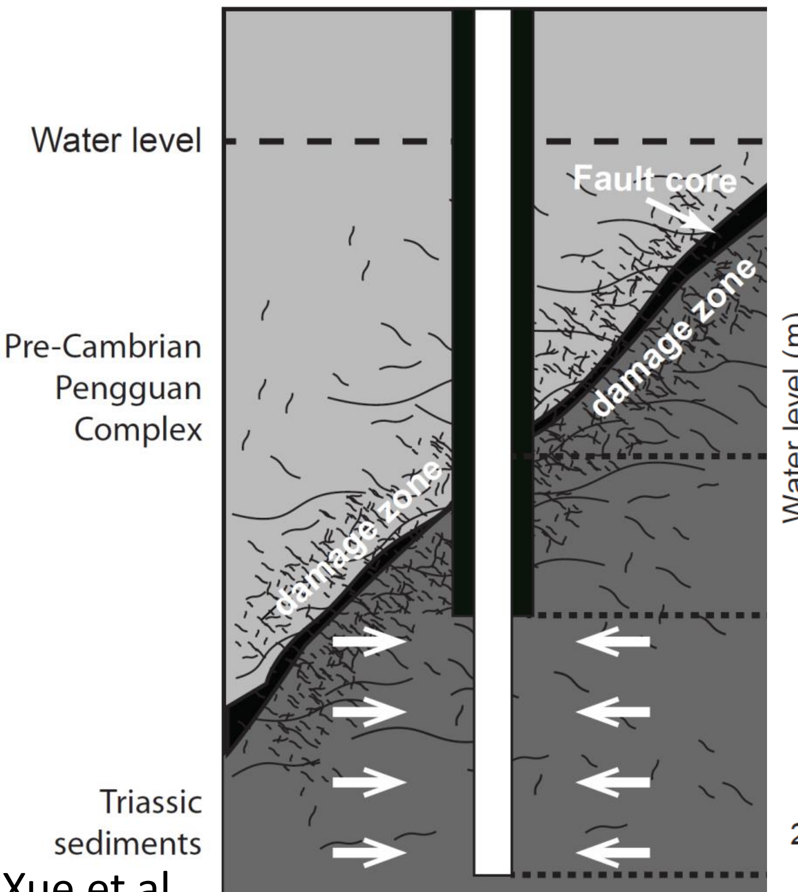
M_W 7.9
May 12, 2008
Wenchuan
Earthquake

Recovery to Original Permeability

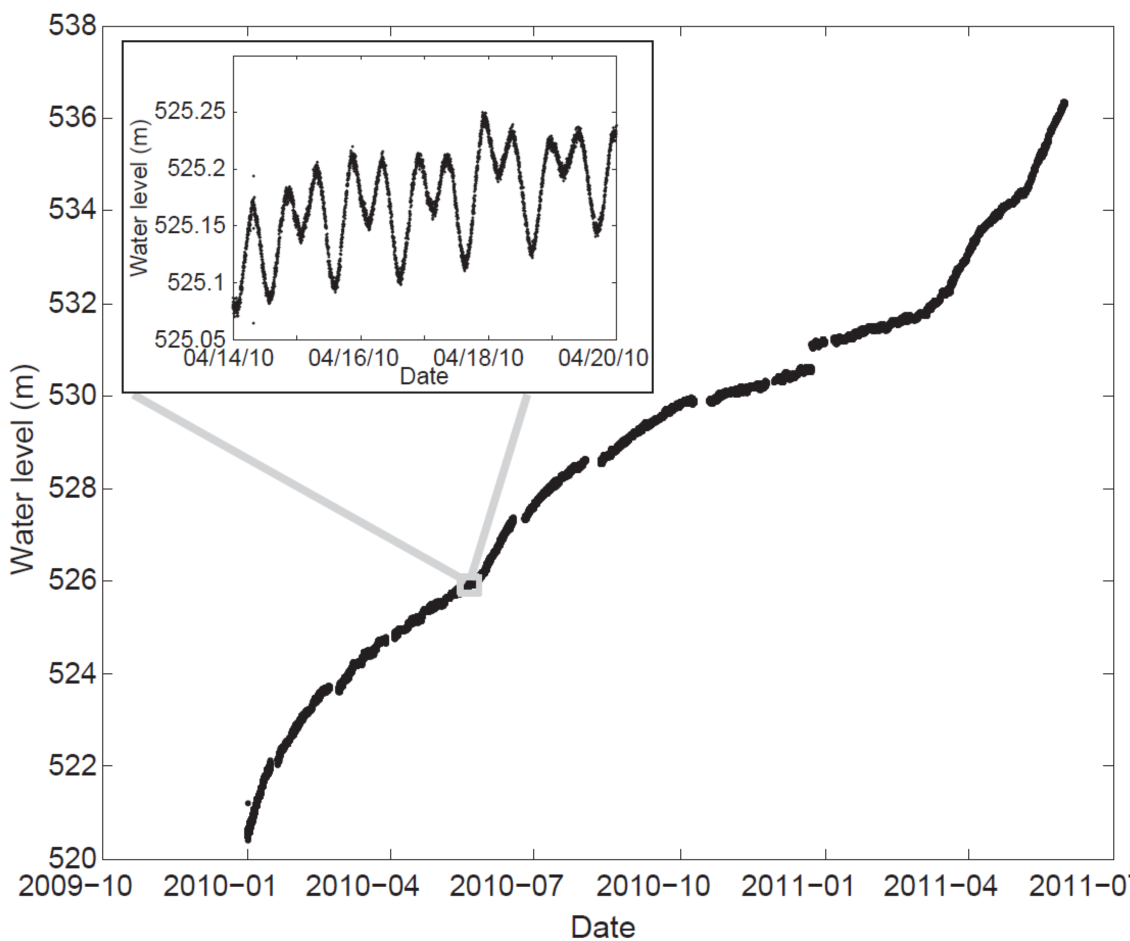


Candela et al., *EPSL*, submitted.

Permeability in the Fault Zone: Wenchuan Fault Zone Scientific Drilling

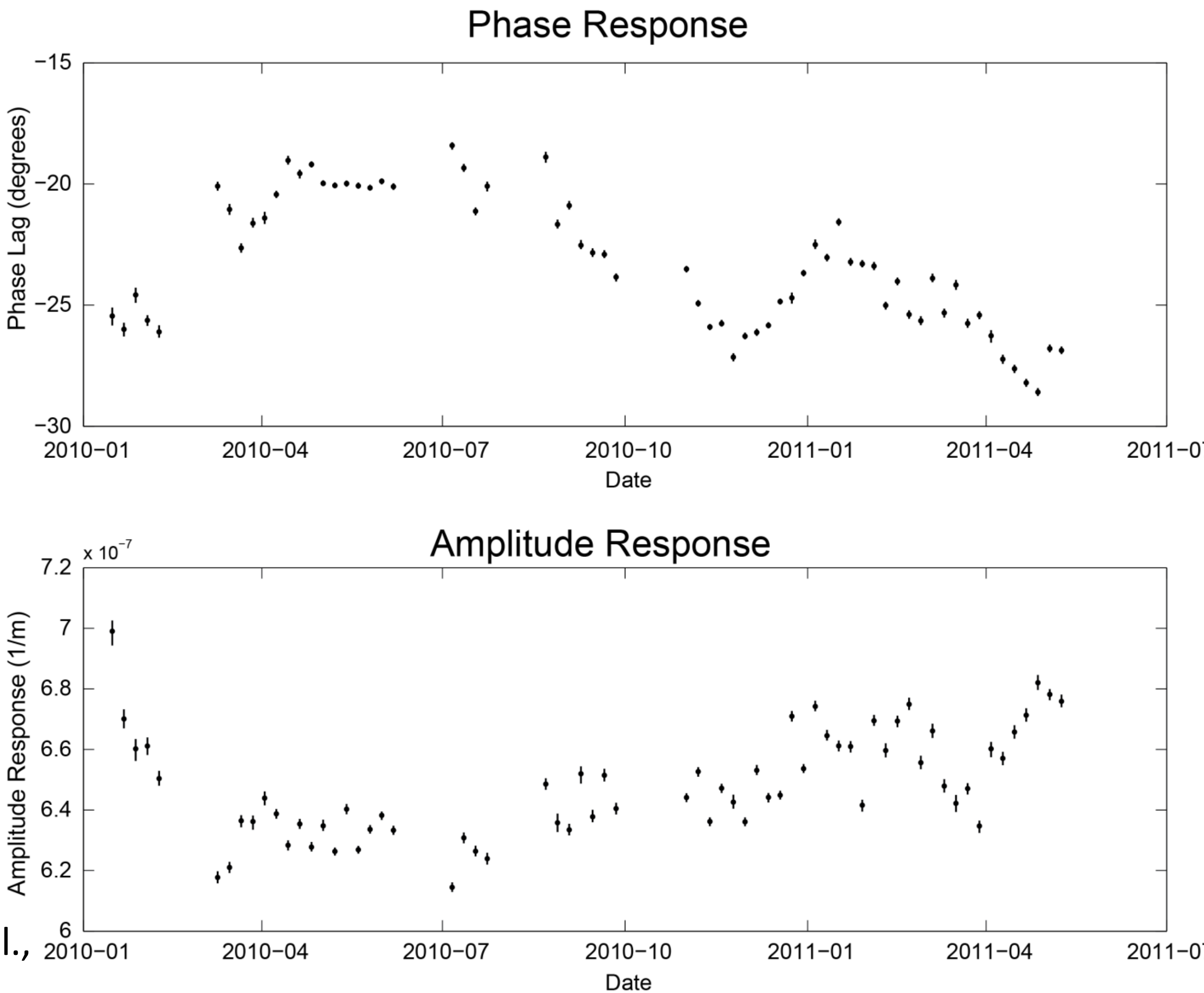


Xue et al., *Science*, 2013



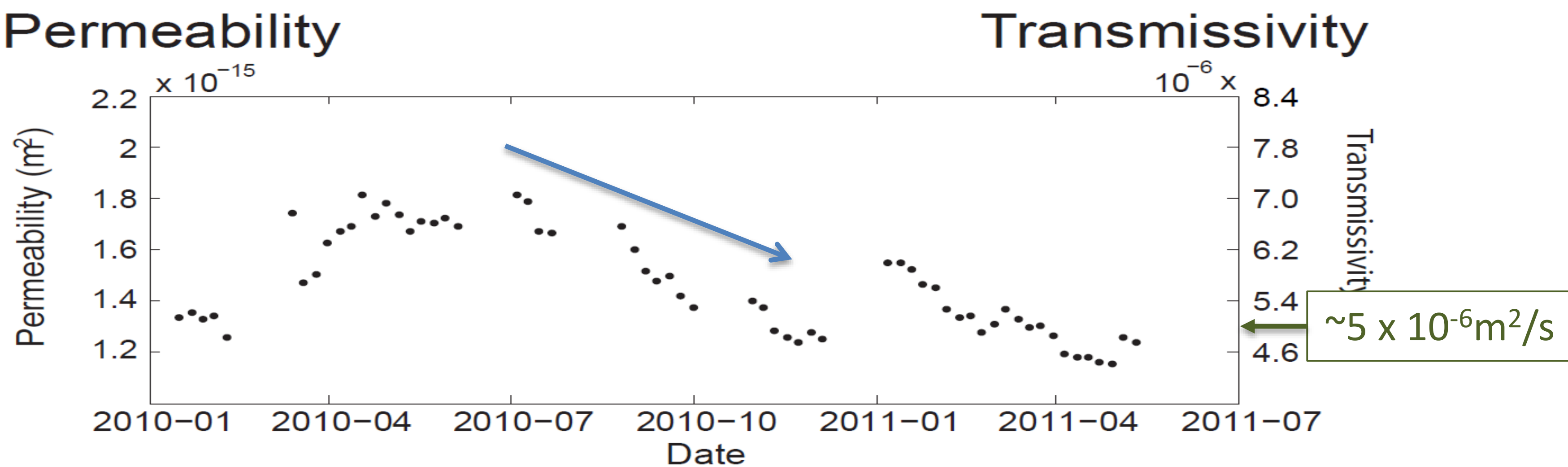
Water level from WFSD-1 borehole

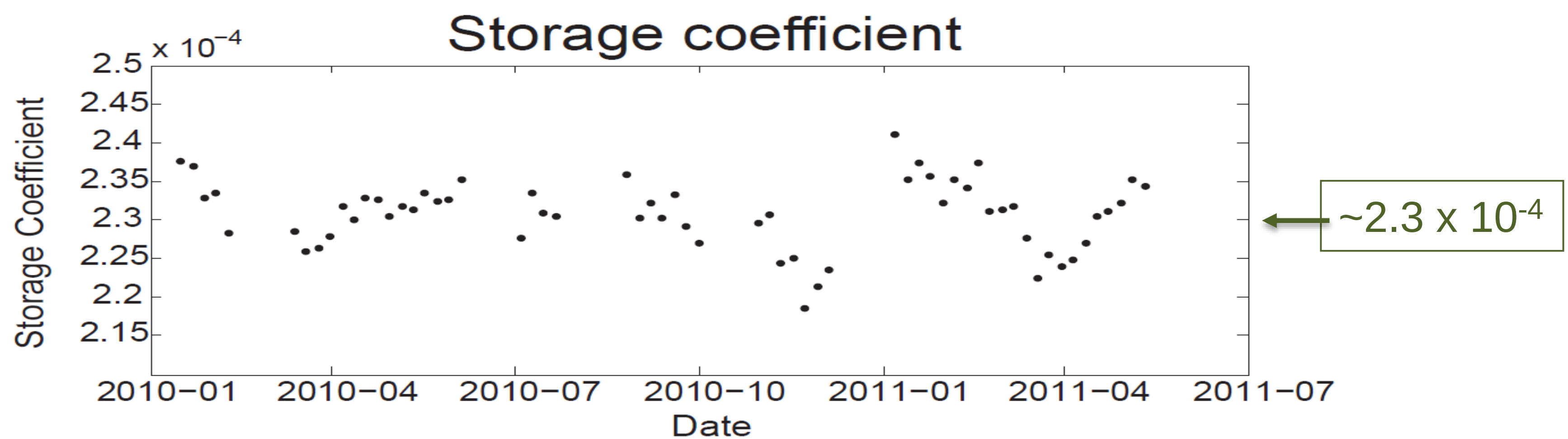
Tidal Response



Xue et al., *Science*, 2013

Permeability and Storage in the Wenchuan Fault

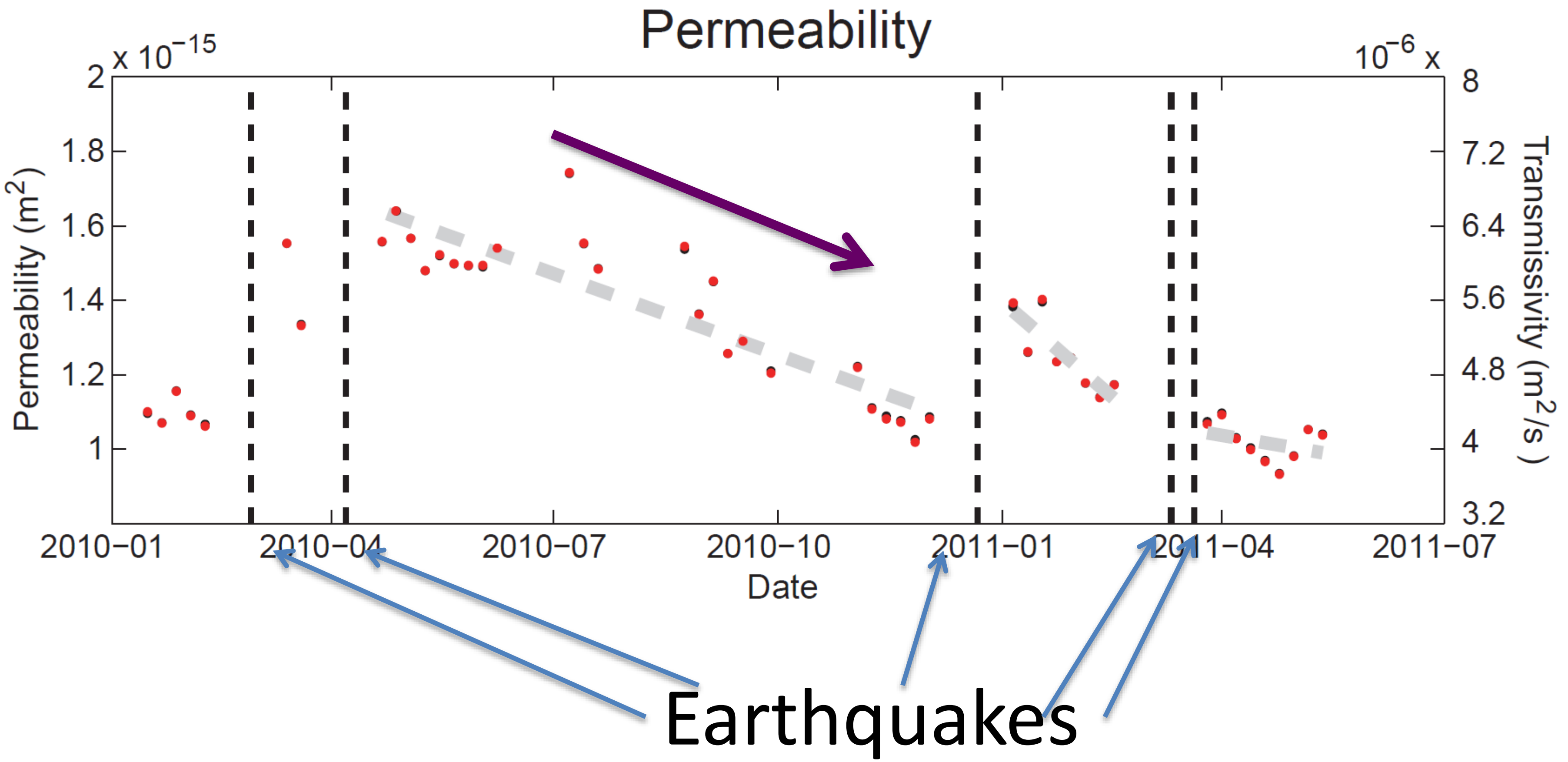




Xue et al., *Science*, 2013

Hydraulic Diffusivity = T/S ≈ 2×10^{-2} m^2/s

Temporal Changes



Xue et al., *Science*, 2013

Permeability changes indicate fast, episodic healing in the fault following a major earthquake

Conclusions

- **Permeability varies over time**
  - Seismic waves can increase permeability by factors up to 3-4
    - In some cases, permeability change correlated to amplitude of dynamic strain
      - Reproduced in the lab
    - Possibly due to opening (unclogging) of fractures
  - Over years, permeability can decrease by similar amounts
    - May be the fingerprint of fault zone healing

- **IMPLICATION FOR HYDROGEOLOGY:**

  Permeability is a dynamically controlled and its steady-state value is governed by the competition of processes.