# Remotely induced seismicity and the effects of regional earthquakes on **open-vent** systems

AB Clarke, A Magee, MJ Fouch, JF Smekens, L Vanderkluysen, H Hartnett

# Outline

- Background and examples of remotely induced seismicity
- Induced seismicity associated with M6.4 Oaxaca EQ in the Western US – USArray Transportable Array data (TA)
- Effects of regional EQs on open-vent systems
- Proposed methods for future work at LUSI and Eastern Java open-vent volcanoes

# Motivation

- Documenting where and when seismicity and eruptions are influenced by regional earthquakes is one part of understanding earthquake and volcanic hazards

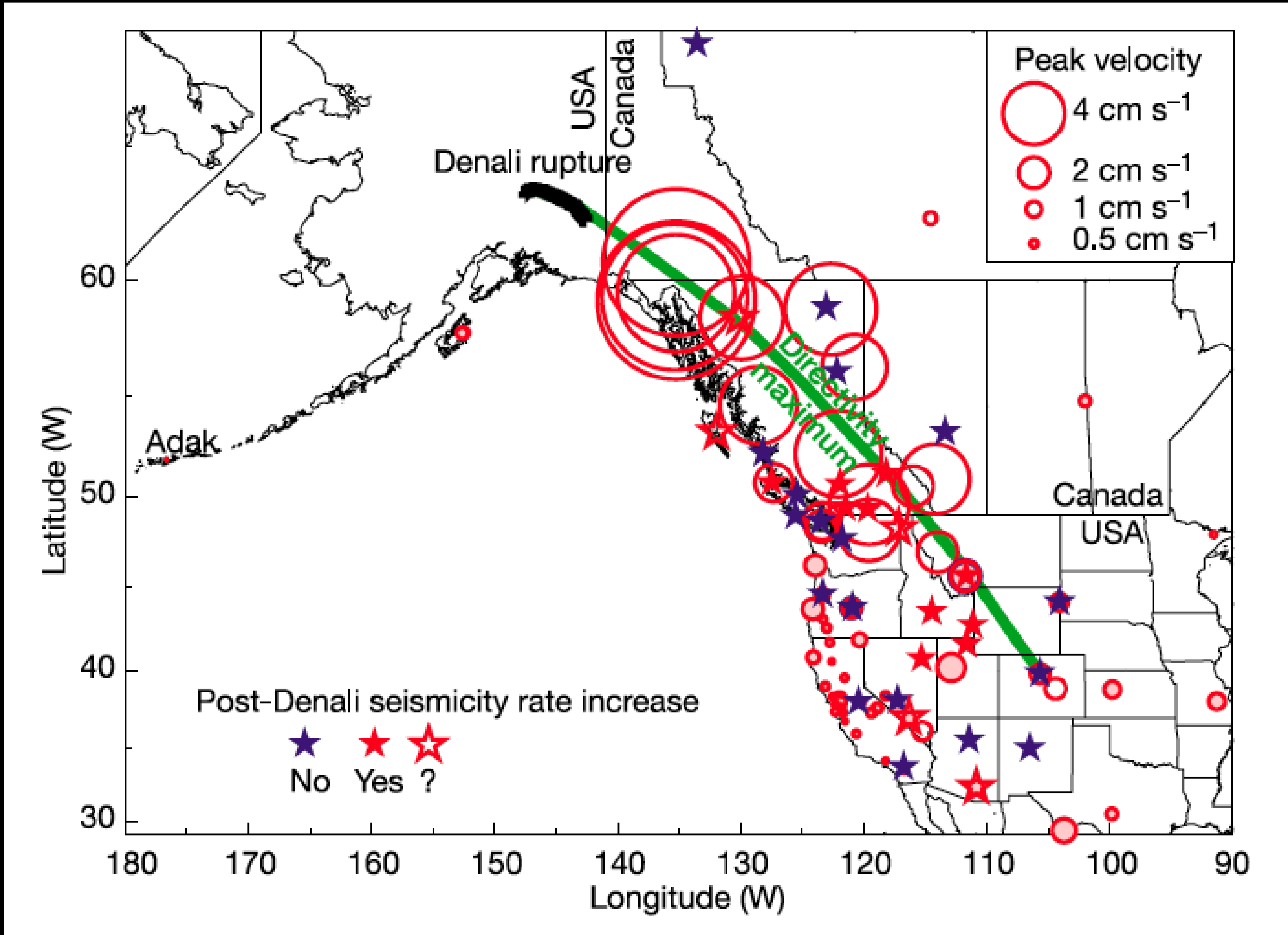
- Regional earthquakes may change LUSI's source region at depth and influence its flow rate at the surface.

# Example

- 28 June 1992 $M_W$ 7.3 Landers, California
  - First example noticed
  - Induced seismicity (Hill et al. 1993, Anderson et al. 1994):
    - Boundary of Basin and Range / Sierra Nevada
    - Geysers geothermal field
    - Southern Cascades
    - Western Idaho
    - Yellowstone National Park

# Example: 2002 Denali Fault

- Mw 7.9
- Depth 5 km
- Strike-slip
- Several studies found that several stations in western U.S. exhibited higher seismicity rates after the earthquake
- Directivity inferred as major influence




Gomberg et al. (2004)

# Mechanisms: static stress change vs. dynamic stresses

**Static stress change** is defined as the "difference in the stress field from just before an earthquake to shortly after the seismic waves have decayed."
(for example at 50 km ~3kPa; decays as $1/r^3$; no effect beyond 100km )

**The dynamic stresses** are those induced "by the seismic waves from a large earthquake."
(for example, at longer distances multiple cycles of 10's of kPa; decays as $1/r^{1.66}$)

Hill et al. [2002]

# Mechanisms?

- Unclogging of fractures

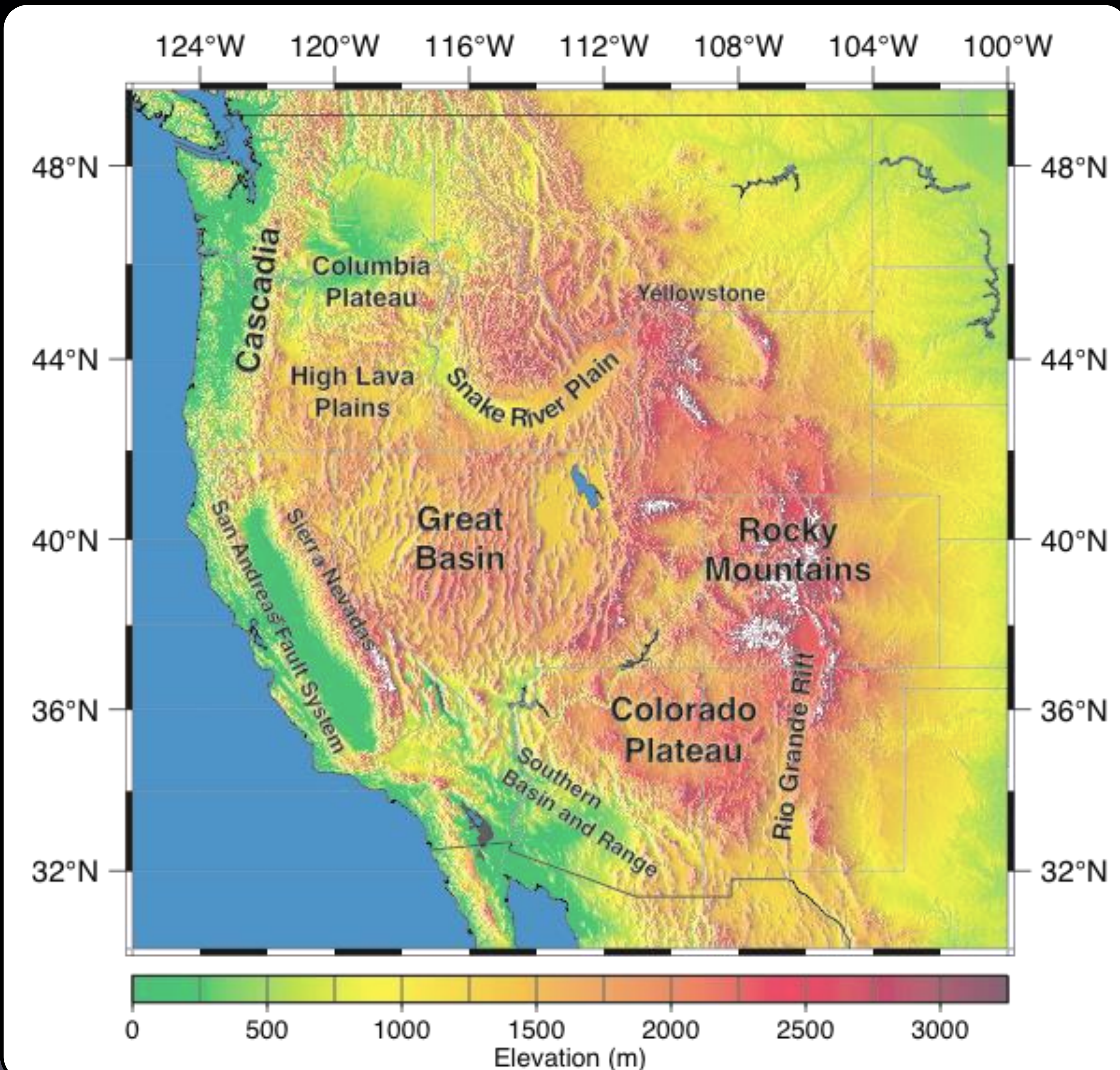
- Increased bubble pressure or enhanced degassing (Linde et al.., 1994; Brodsky et al. 1998)

- Fluid pumping through pathways

- Open-systems tend to be more susceptible to changes due to the passing of seismic waves

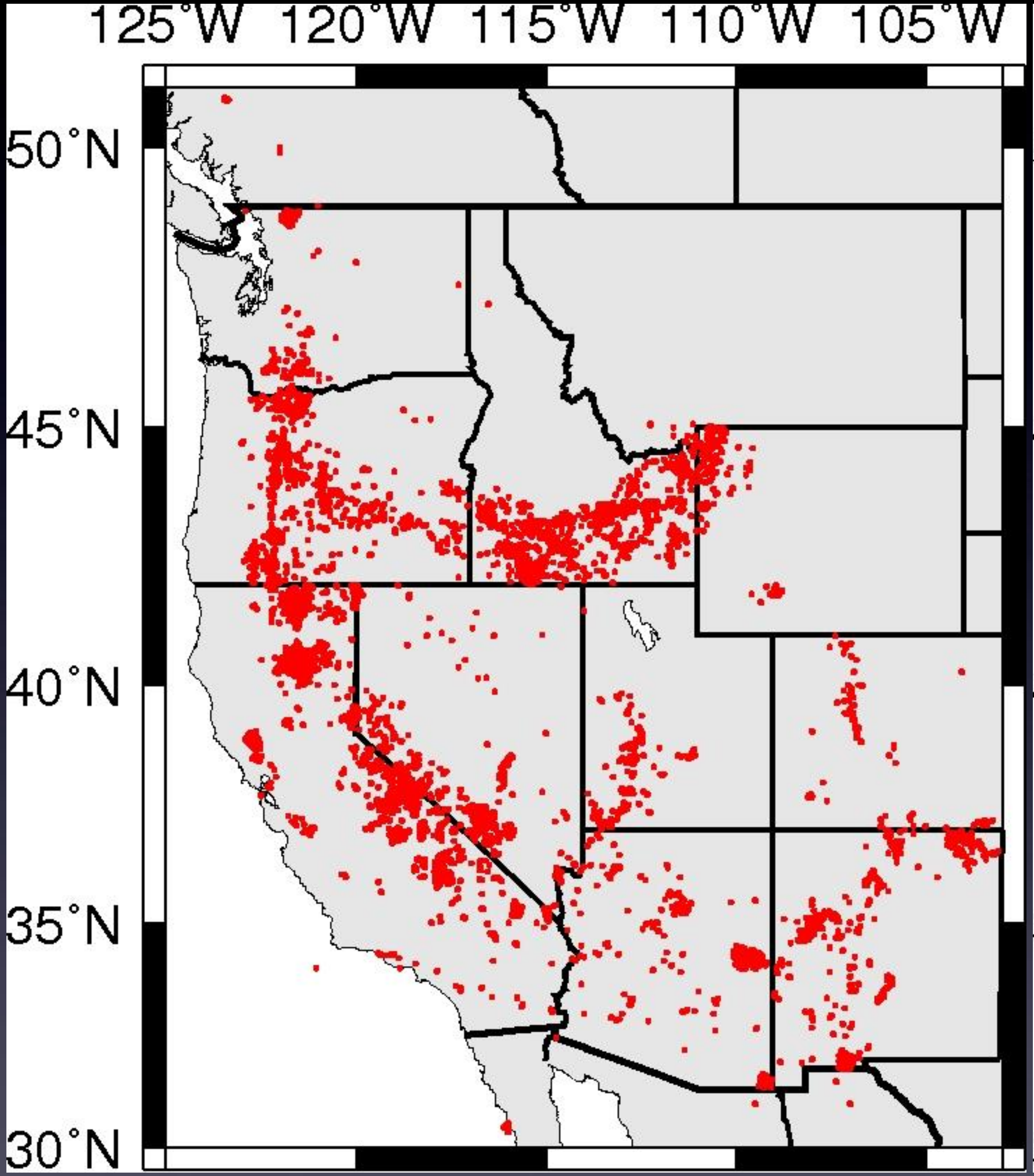
Brodsky et al, 2003; Linde et al., 1994; Brodsky et al., 1998; West et al. 2005; Harris and Ripepe, 2007

# Our Recent Study: Examining Induced Seismicity in the Western U.S.

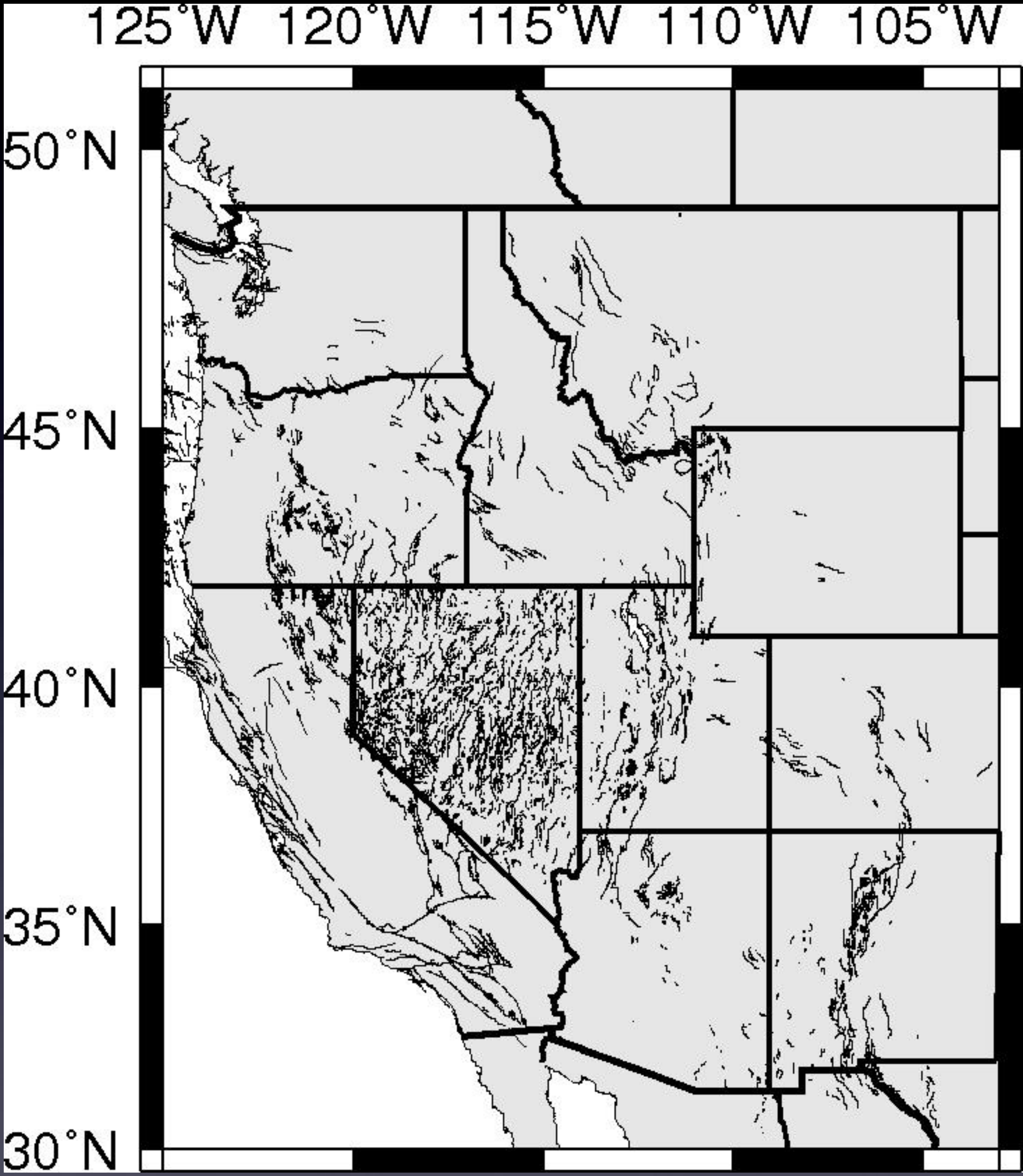



- Broad range of active tectonic and volcanic settings across entire region

# Tectonic Setting

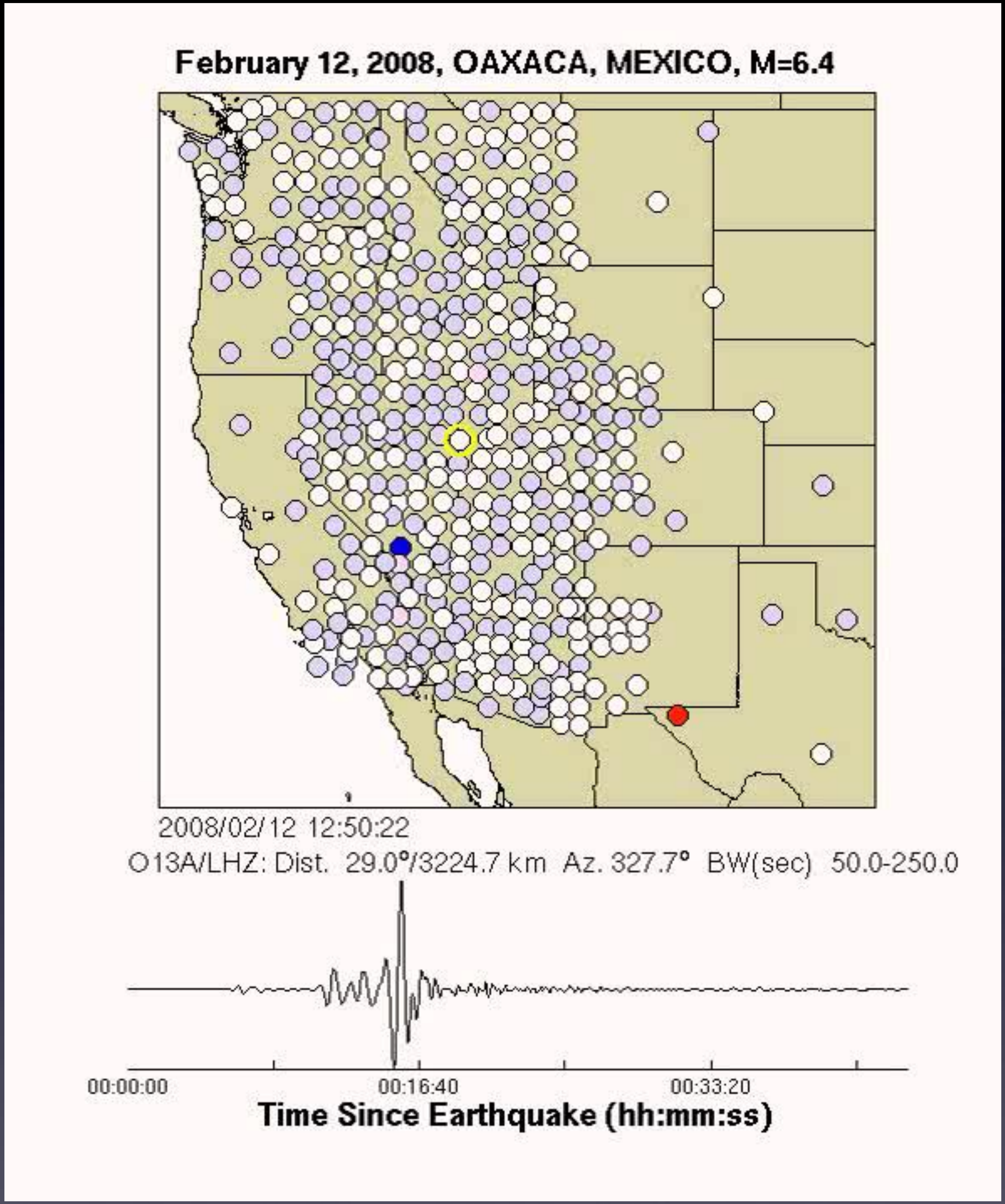



Post - 10 Ma volcanism



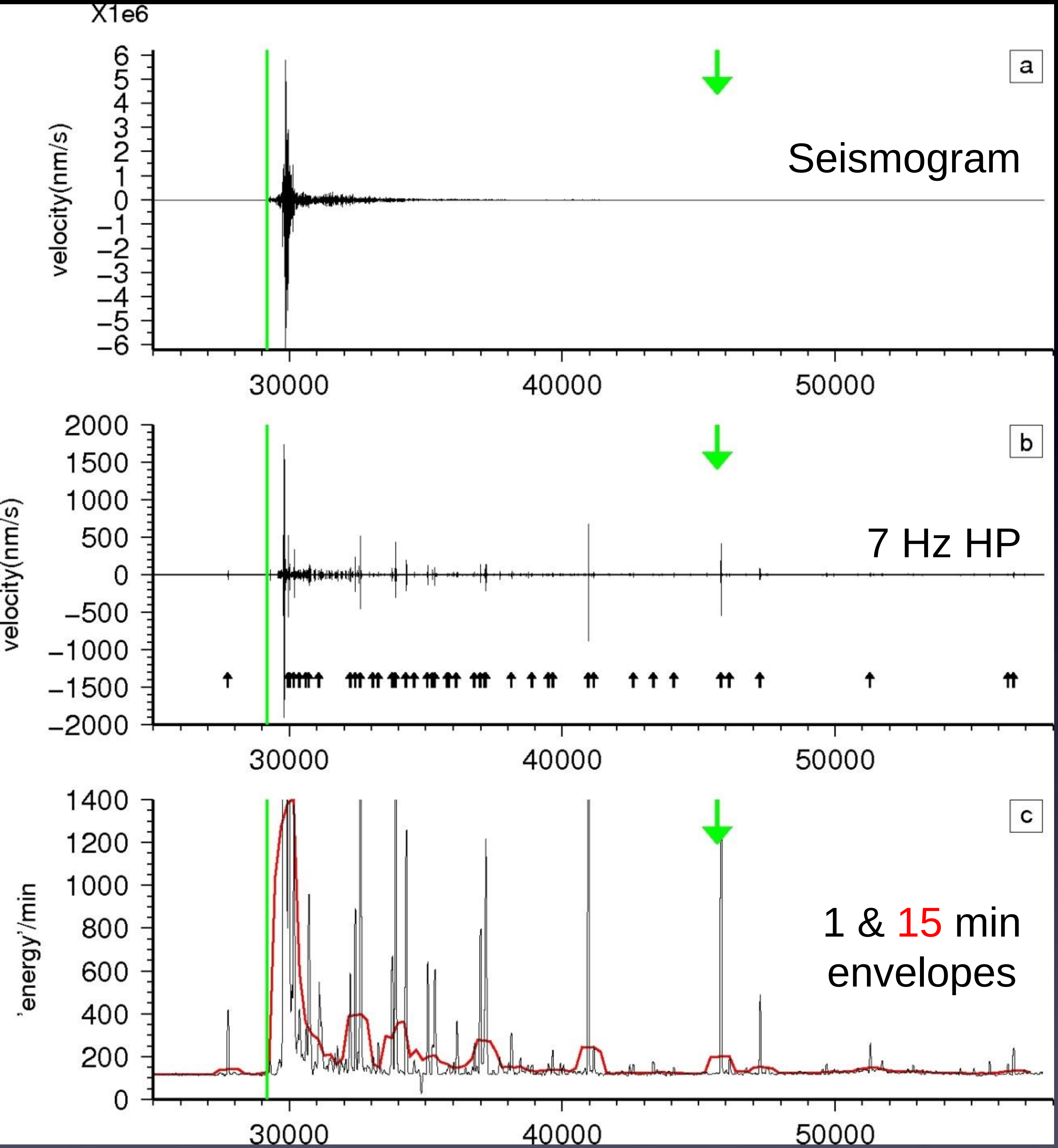

Post-130 Ky active faults

# Regional Event: 2008 Oaxaca, Mexico




- Mw 6.4
- Depth 116 km
- ~3200 km from center of study area (Western US)
- USArray provides dense spatial coverage
- Supplemented by Berkeley and Caltech stations

# Data Processing

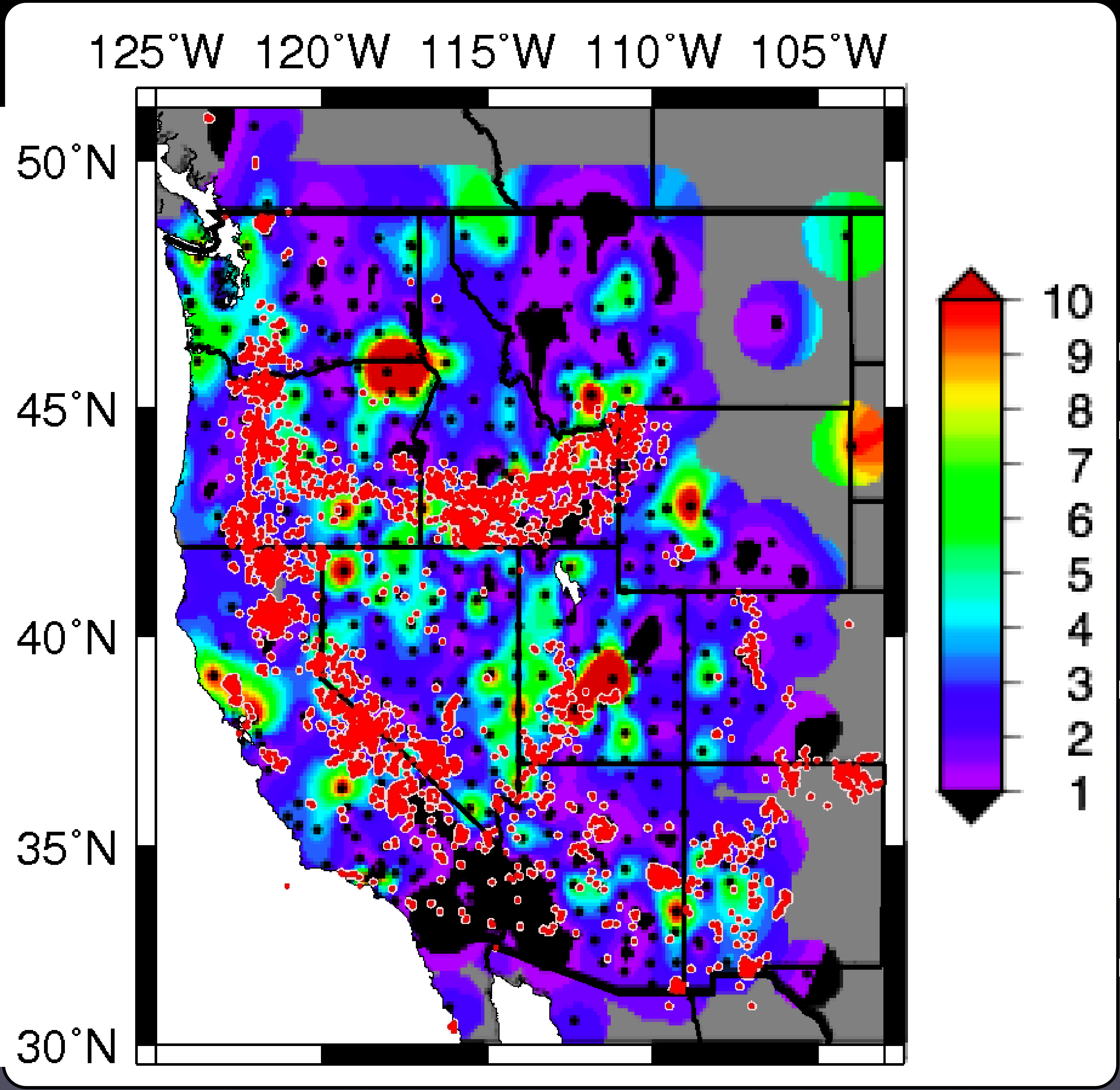



1) Count every local earthquake

2) Envelope-based method

- High-pass filter at 7 Hz to find events <200km away.
- Envelope, integrate, divide by time
- Compare post-event to pre-event integrated ground motion (**IGM ratio - proxy for energy increase**)

# Patterns of Large IGM ratios

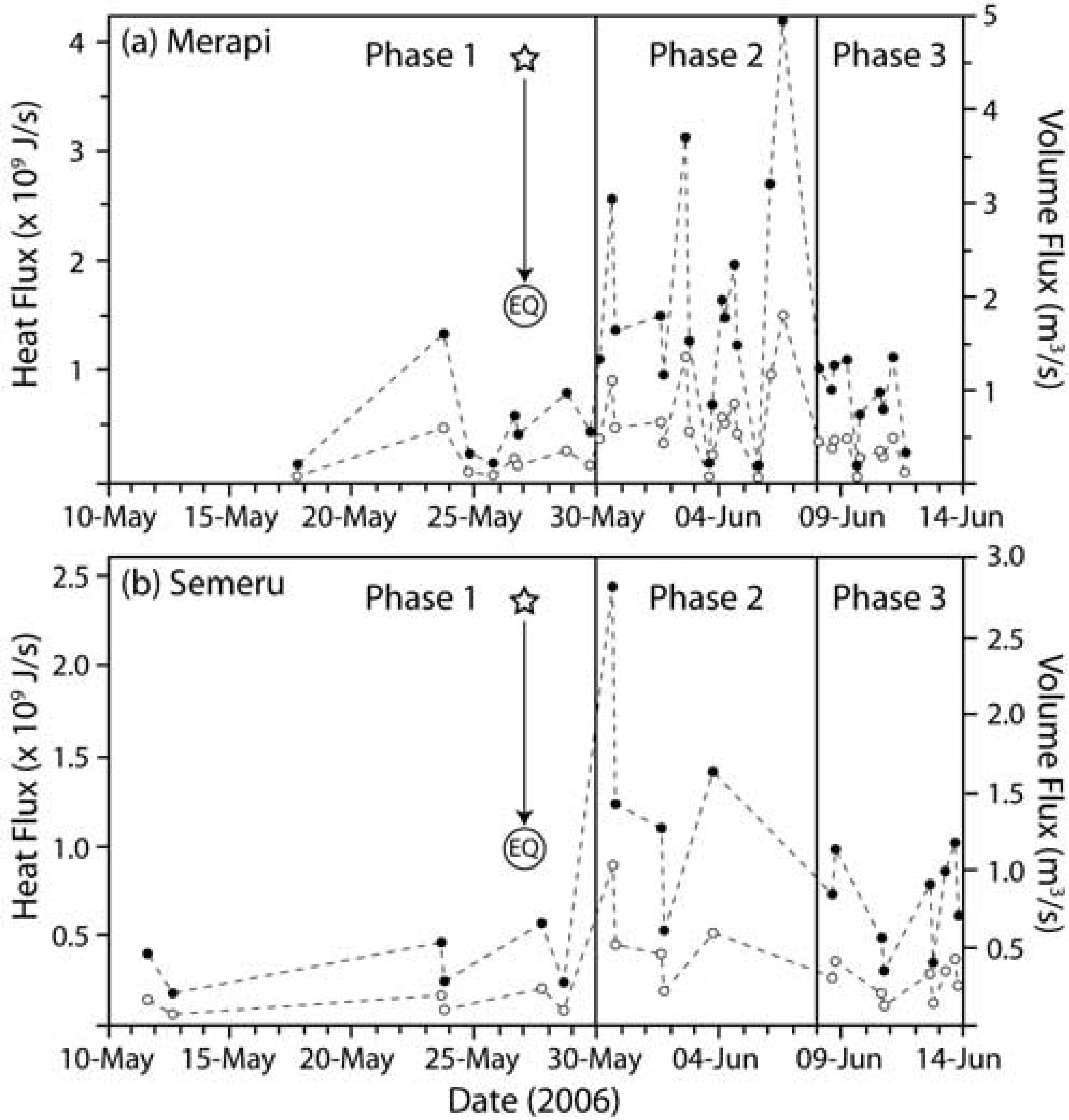


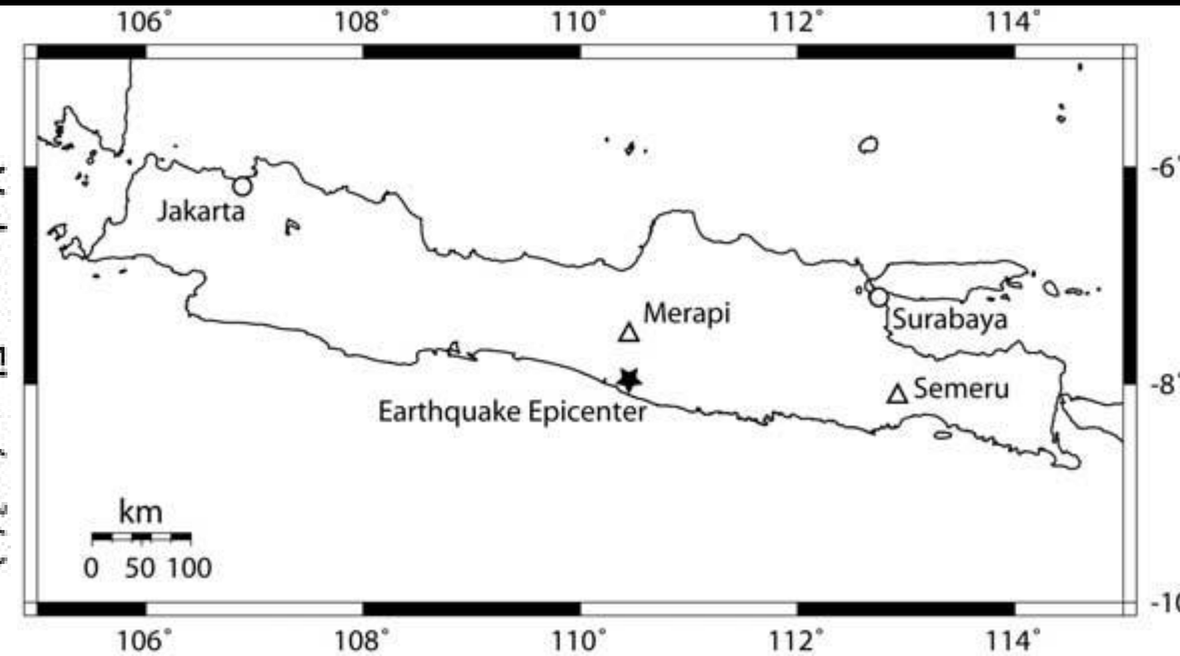

- Wallowas
- High Lava Plains / Snake River Plains / Yellowstone
- Wasatch Front / western Utah
- Bay area
- Seattle area

# Preliminary conclusions: Oaxaca

- Oaxaca event appeared to induce a lot of seismicity in the western US, although it was small (Mw 6.4) and far away (~3200km)
- Best correlation for the Oaxaca event is with young volcanism suggesting that weak zones (hydrothermally altered, fluid-rich, magmatic zones, faults) are susceptible to induced seismicity
- Station density may in part explain why we detect more induced seismicity than for the Denali EQ
- Is this sort of response happening all the time, but we just aren't detecting it, or was there something special about Oaxaca?

# Earthquakes and open volcanic systems: Merapi & Semeru (Short-lived) increase in thermal and volume flux




Harris and Ripepe (2007), GRL 34; From Walter et al. (2007) GRL, 34

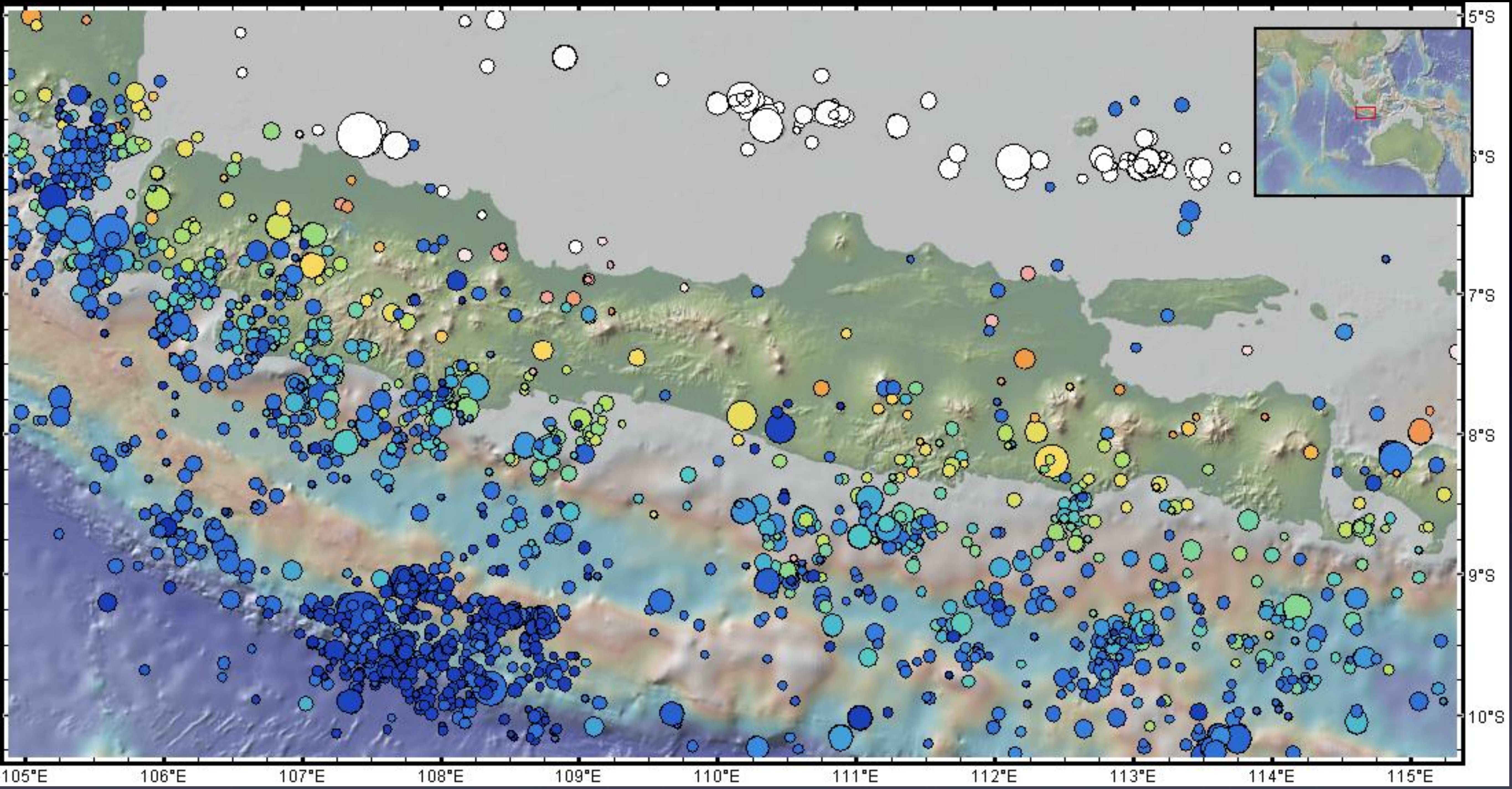
**Merapi** –
Static Stresses ~3kPa, Dynamic Stresses: 5 -10 cycles of ~30 – 60 kPa

**Semeru –**
Dynamic stresses: multiple cycles of a few kPa

**Causes?** - simple pumping or induced gas exsolution

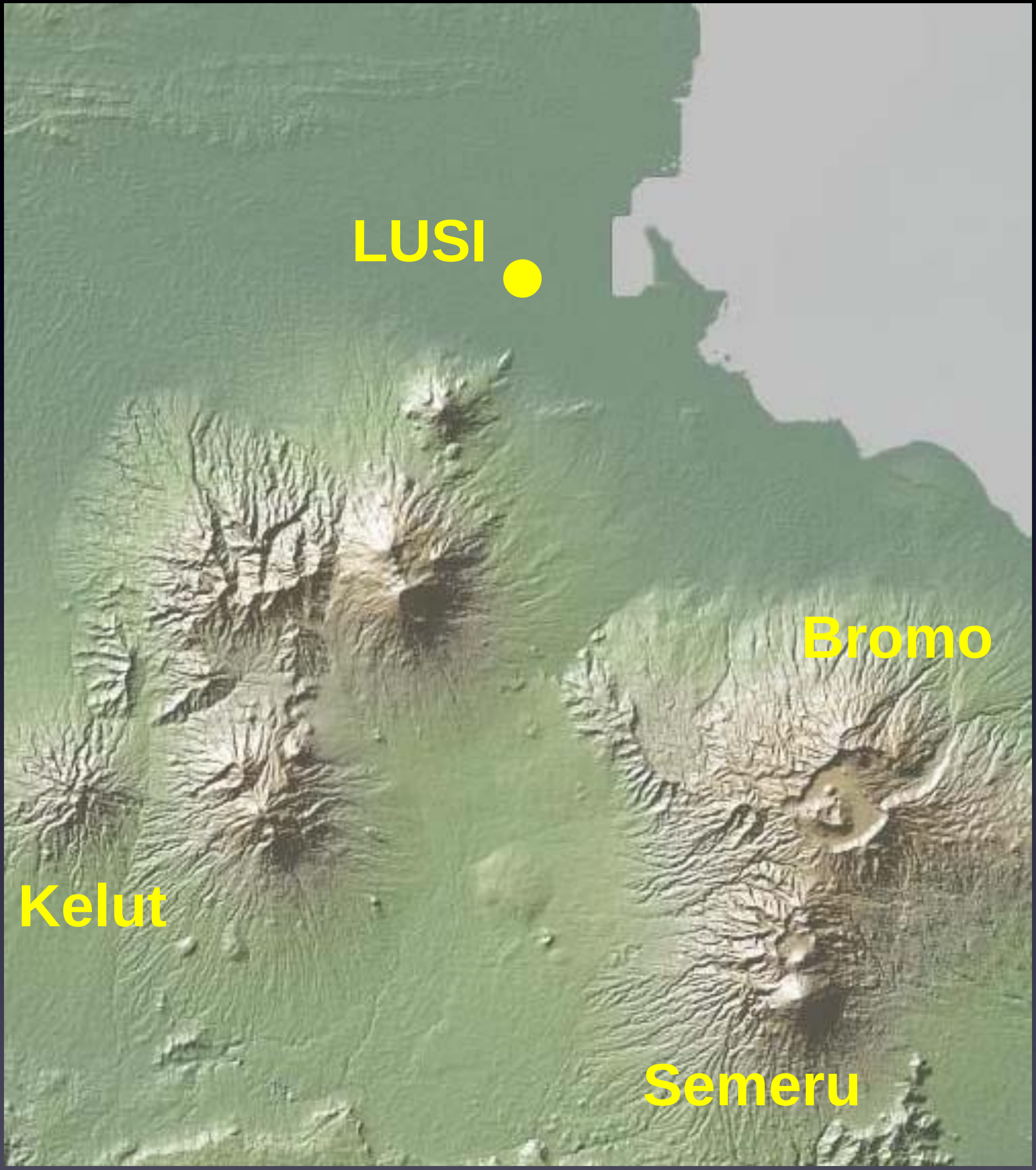
**Lag time –** controlled by ascent rates and compressibility of fluid

# Seismicity near Java

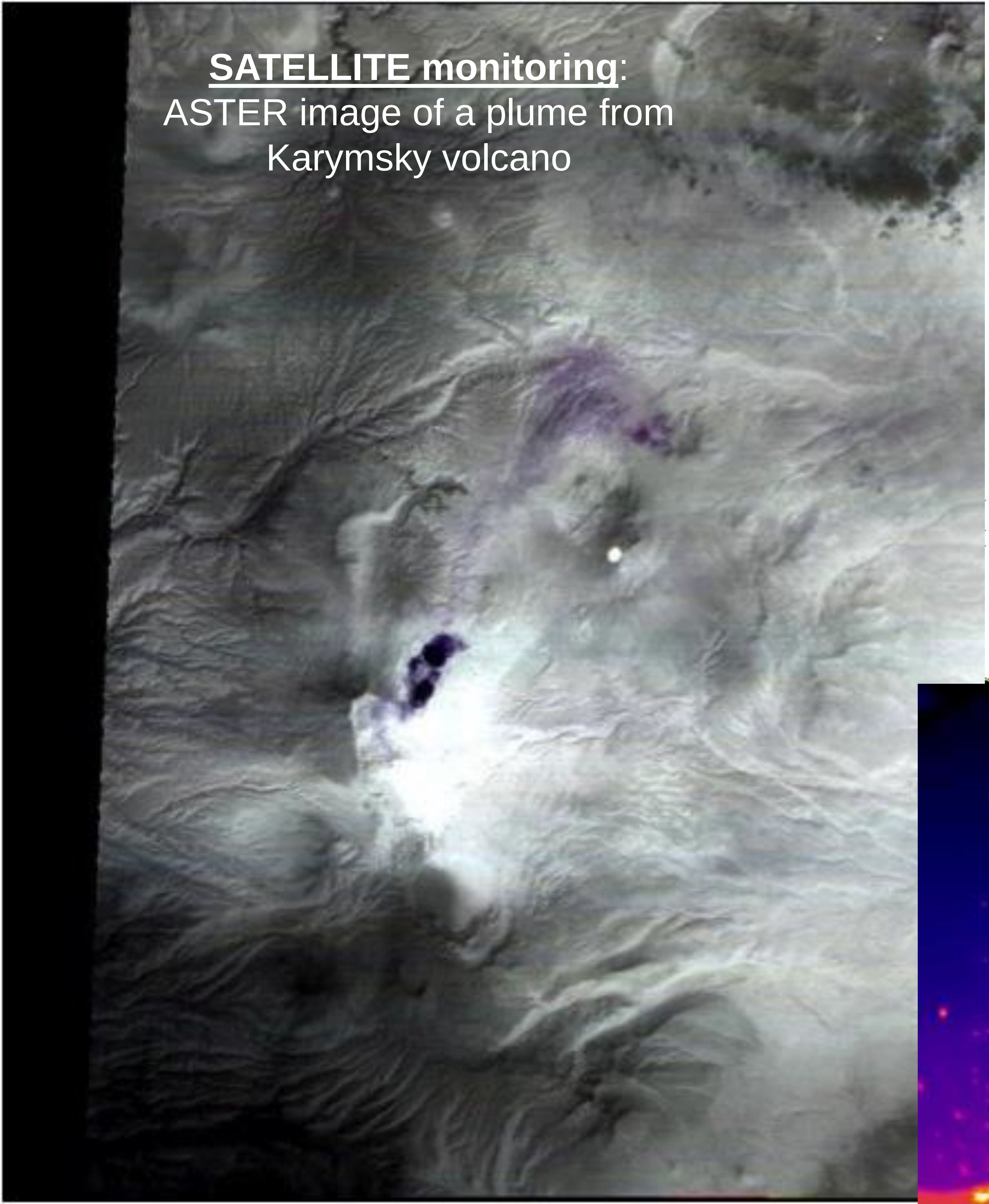


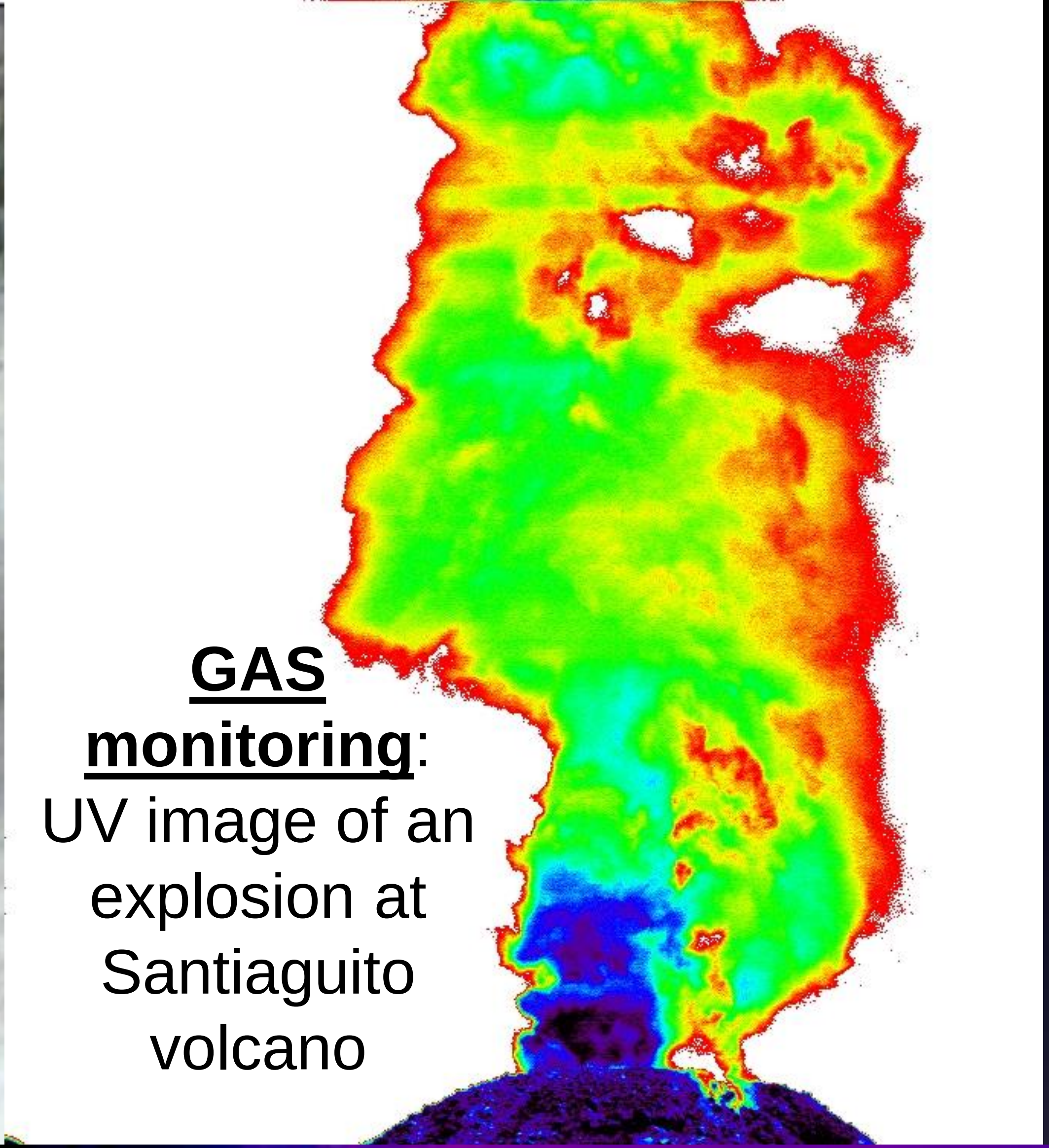

EQs of M4.5 and greater, 1973 to present, scaled with circle size
Color=depth to 200 km, blue=deep, red=shallow, white= >200km

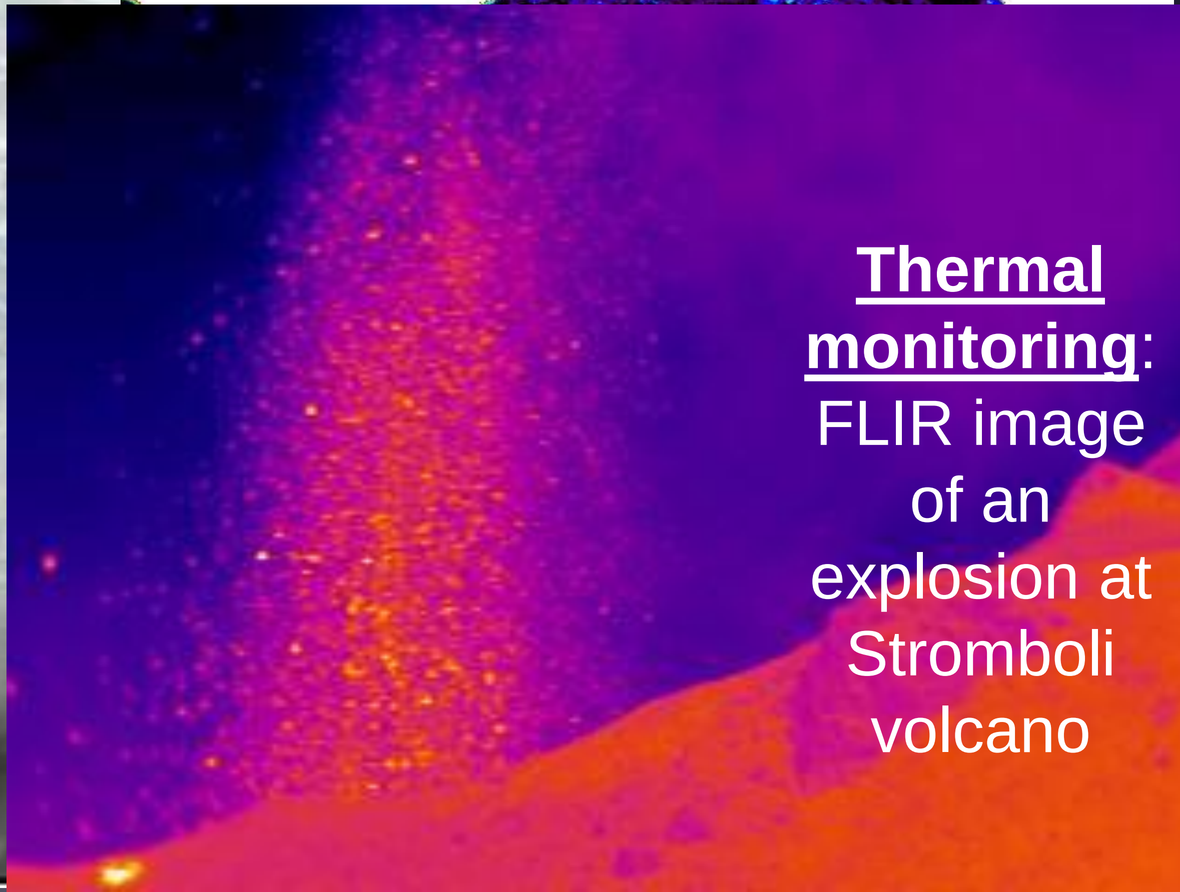
# Continuous Monitoring of Open-systems

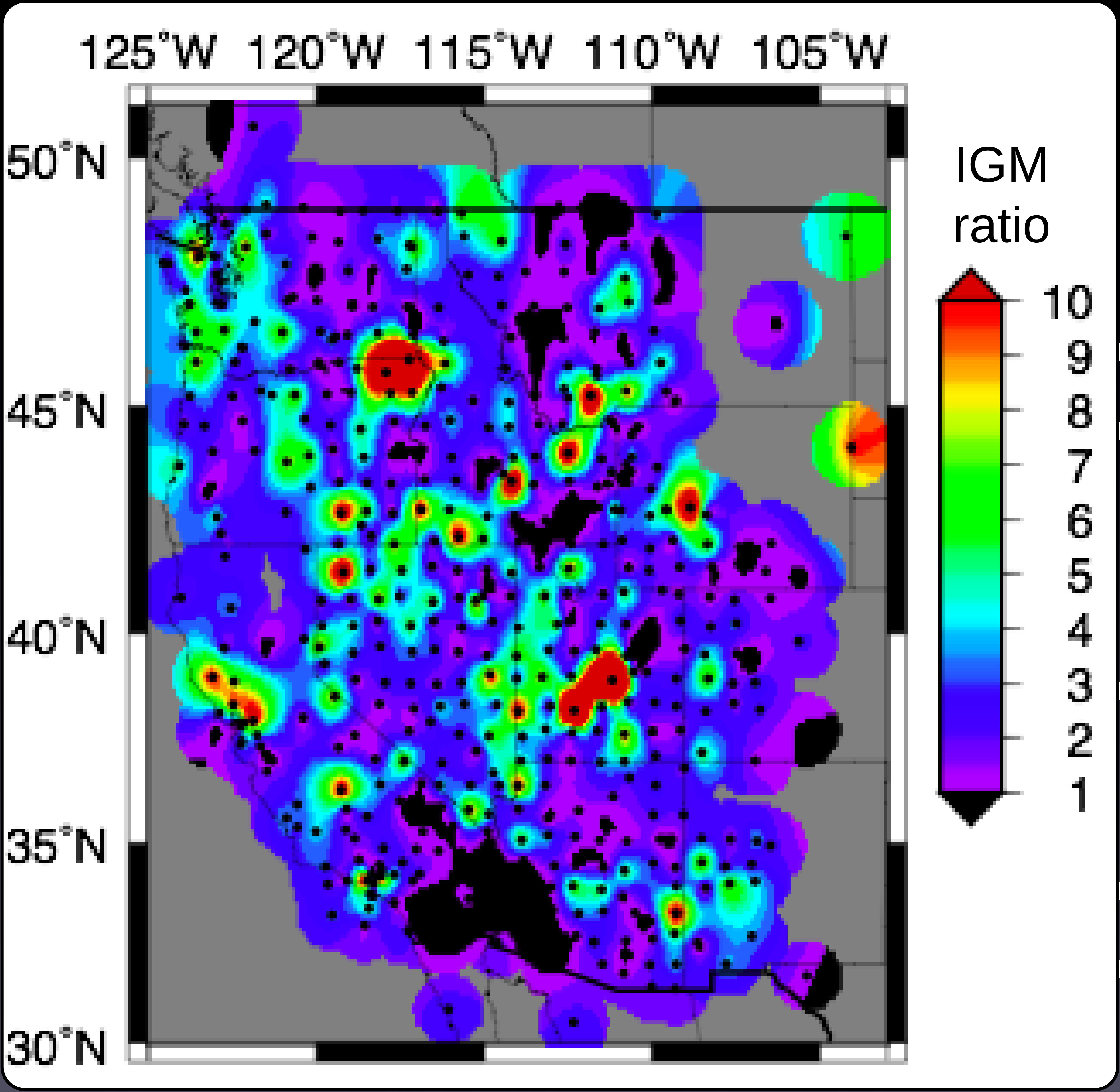



- We propose to look for correlations between regional seismicity and thermal, gas and mass flux from open systems in Eastern Java
- Seismic data is already continuous; we will collect continuous data for blocks of time - using FLIR, UV, and video cameras. To be supplemented by ASTER & MODIS data
- These campaigns may allow us to a) document an interesting phenomenon; **b) understand how susceptible the LUSI source region is to external forcings**


SATELLITE monitoring:
ASTER image of a plume from
Karymsky volcano


GAS monitoring:
UV image of an explosion at Santiaguito volcano


Thermal monitoring:
FLIR image of an explosion at Stromboli volcano




# Patterns of Large IGM ratios

- Wallowas
- High Lava Plains / Snake River Plains / Yellowstone
- Wasatch Front / western Utah
- Bay area
- Seattle area

| | | Stress (Mpa) | | Period |
|---|---|---|---|---|
| Solid Earth tides | | $10^{-3}$ | | 12h |
| Ocean tides | | $10^{-2}$ | | 12h |
| Hydrological loading | | $10^{-3}$-$10^{-1}$ | | days-years |