

Injection-Induced Seismicity: Recent Lessons from Oklahoma

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Background

- **Hydraulic fracturing** (fracking) very rarely causes earthquakes of significance ($M > 3$)
 - Typically performed at shallow depths
 - Short-term activity
 - Low rate and volume of injection
 - Materials and fluids are subsequently extracted
- Most induced seismicity of concern is caused by **waste water injection** (waste water being a by-product of fracking)
 - Typically deeper wells (below ground water reservoirs)
 - Longer-term activity
 - Higher rate and volume of injection
 - Can significantly increase pore-pressure and alter state of stress in subsurface geologic materials

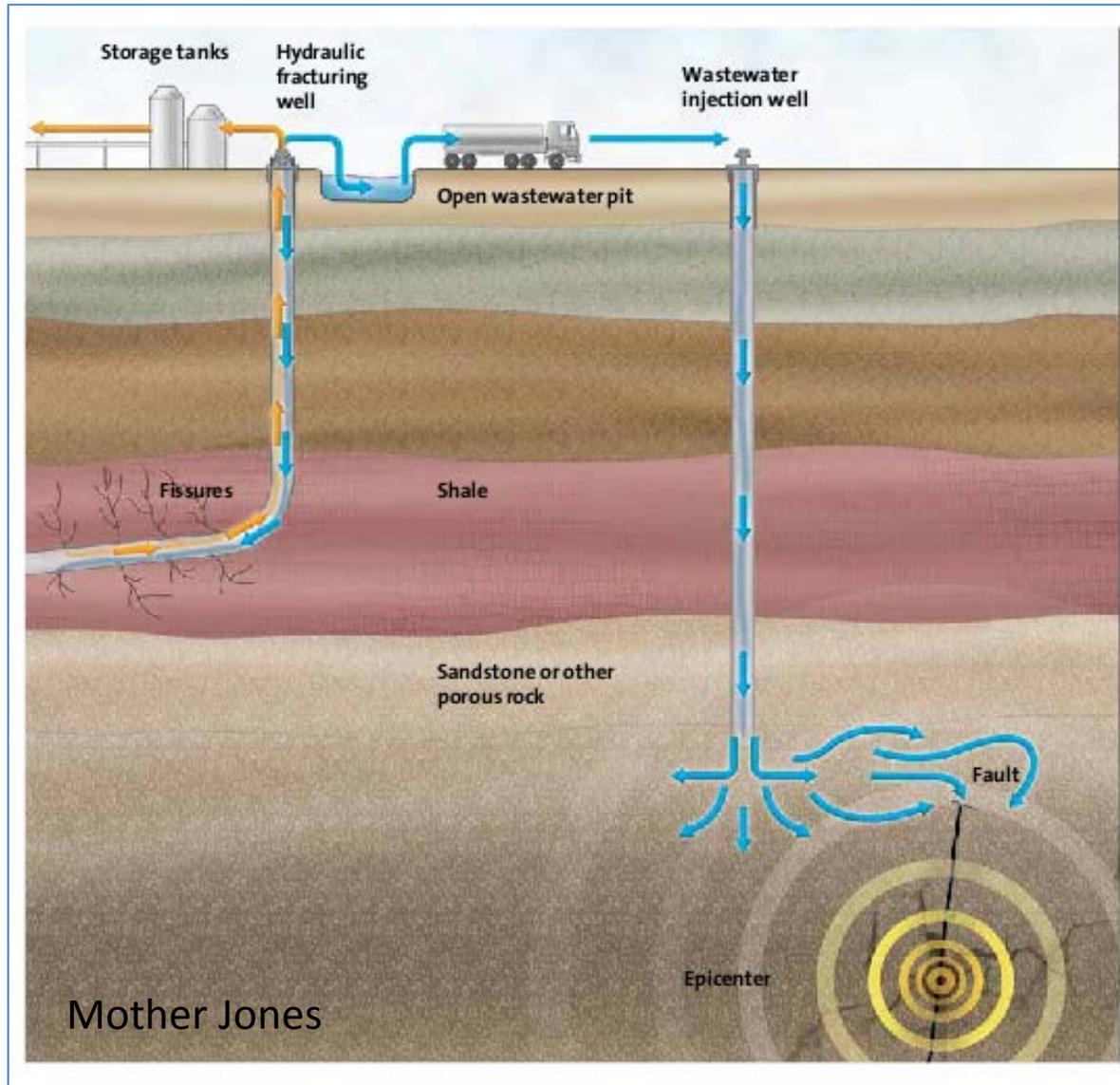
Background (cont.)

- Oil & fluid extraction can cause subsidence, ground deformation and faulting
 - For example, it has been postulated that the 1933 Long Beach earthquake was related to oil extraction and subsidence in Long Beach fields
 - Can be mitigated by re-injection of fluids to balance pressure, but must be closely monitored to maintain stable pressure gradients (e.g., Baldwin Hills 1963).
- In southern California, oil extraction activity *pre-dates* earthquake monitoring
 - First oil wells in 1890's
 - Systematic locating and cataloging of earthquakes using Caltech seismic network began in 1932
 - Lack of “pre-extraction” baseline for seismic activity rates makes delineation of possible causal relationship difficult

State of Knowledge

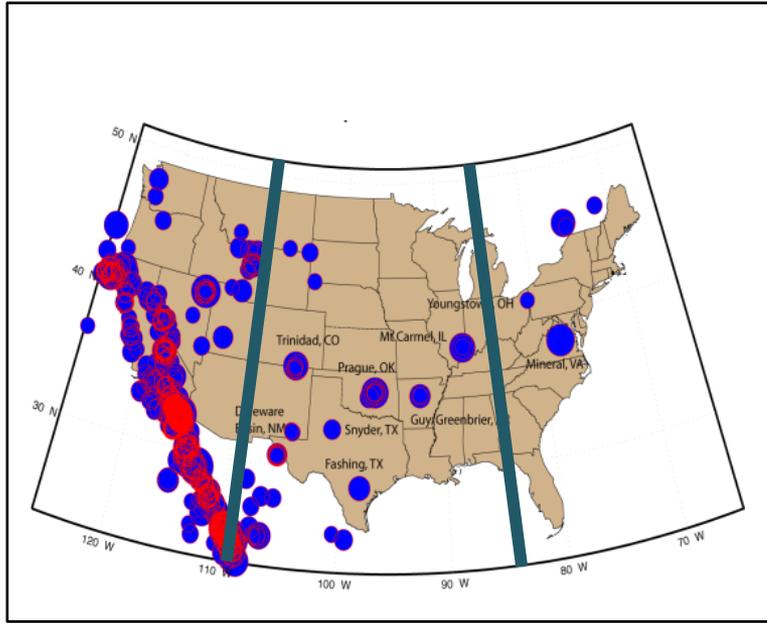
- Mechanisms relating fluid injection and induced seismicity are currently not all that well understood
- Strongest evidence supporting a causal relation (e.g., Oklahoma) occurs with very high rates and volumes of fluid injection
- However, a number of injection wells with high rates/volumes do not exhibit induced seismicity
- Suggests importance of other factors, e.g.,
 - Rock porosity
 - Underlying state of stress
 - Pre-existing fractures
 - Fluid diffusion rates
- Complex problem!

How does Wastewater Injection Induce Earthquakes?



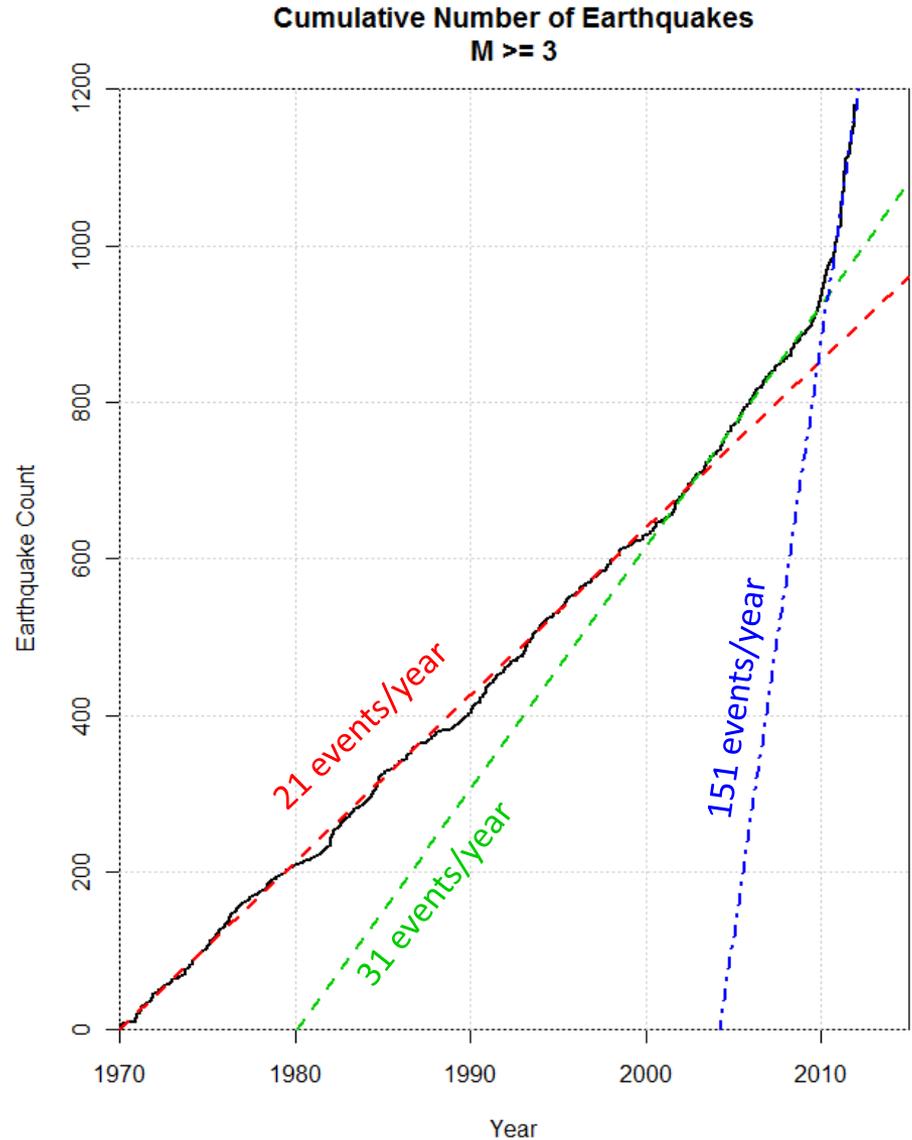
Why are induced earthquakes suddenly an issue?

Rate of Earthquakes in the Midcontinent

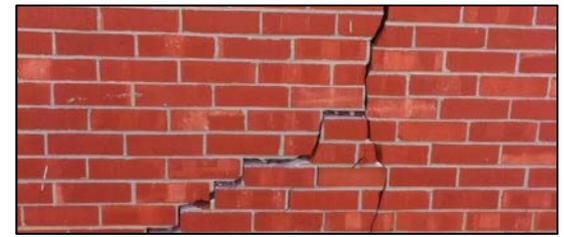
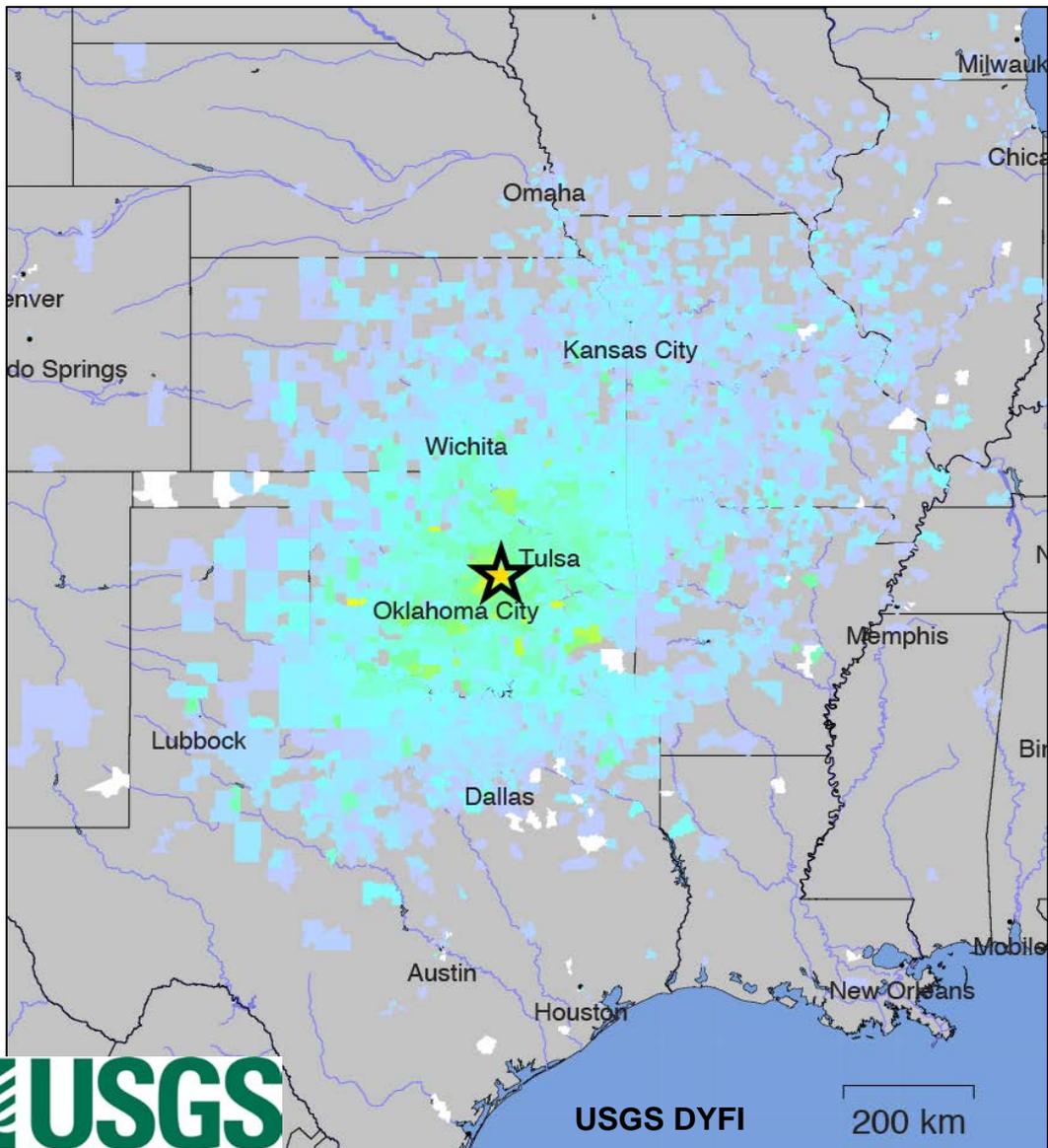


Significant earthquakes linked to injection

- 2011 M5.7 Prague, OK
- 2011 M5.3 Trinidad, CO
- 2012 M4.8 Timpson, TX
- 2012 M4.7 Guy, AR



Largest injection induced event: M_w 5.6 Prague, OK Nov. 6, 2011



Photos by K. Keranen, The Oklahoman (<http://newsok.com/record-5.6-magnitude-earthquake-shakes-oklahoma/article/3620706>), and B. Sherrod

Timeline ↑

OU, RAMP, USGS stations deployed

M4.7

11082011

4 OU stations deployed

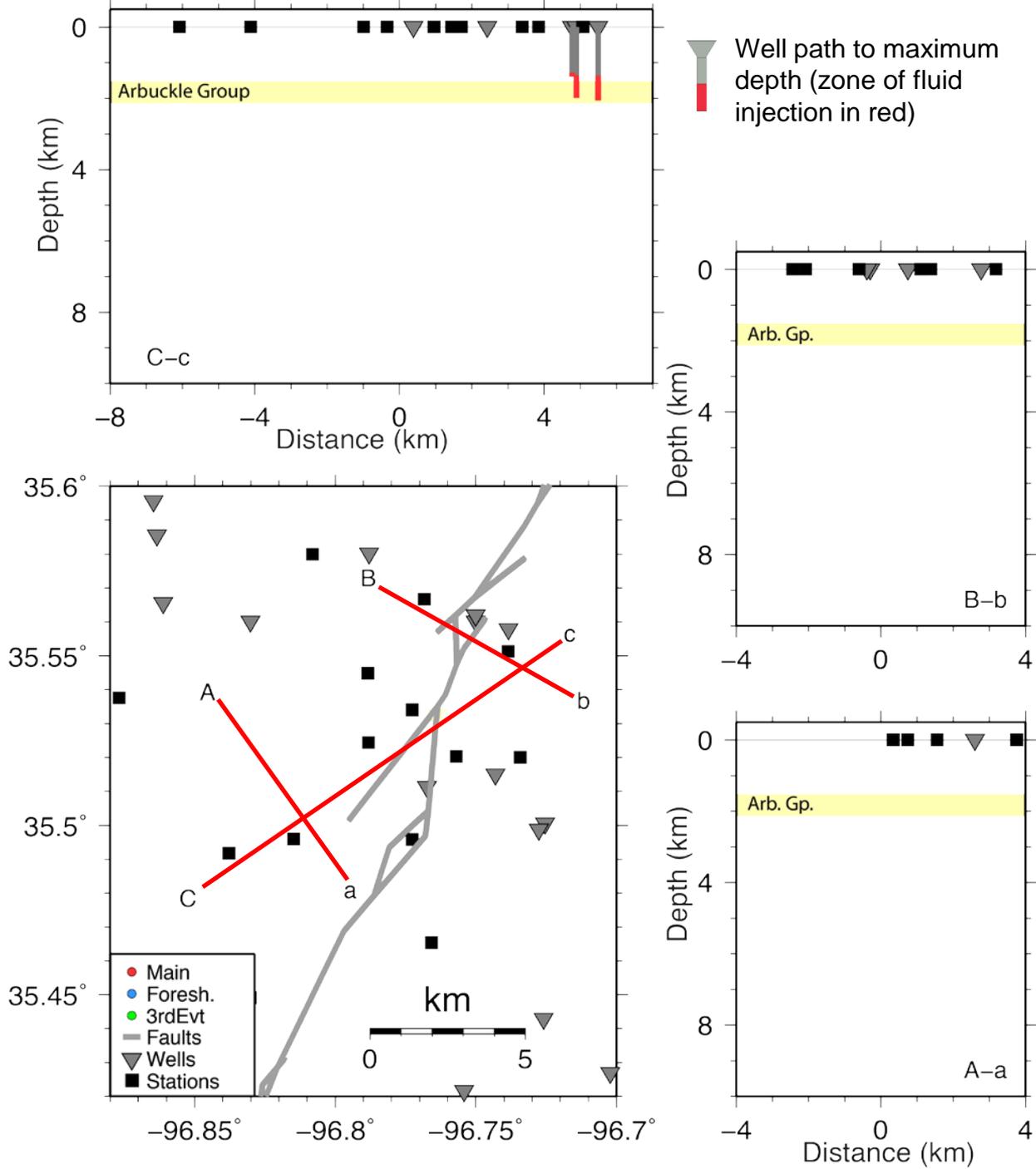
M5.6

11062011

3 OU stations deployed

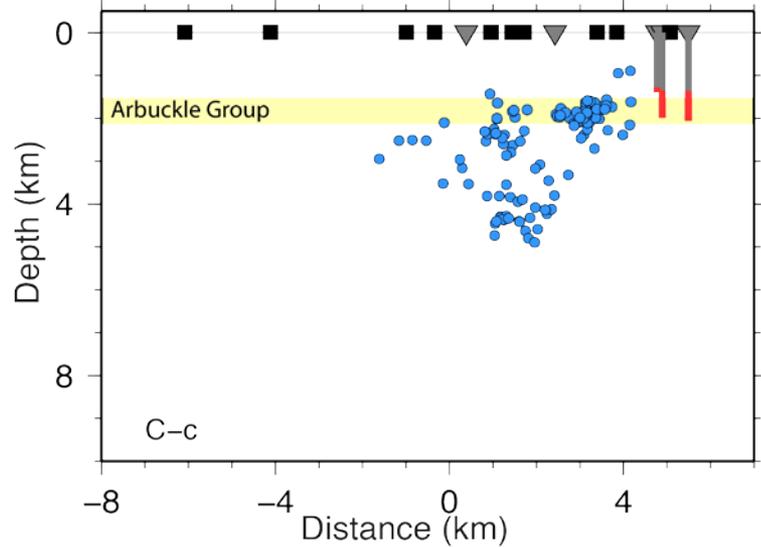
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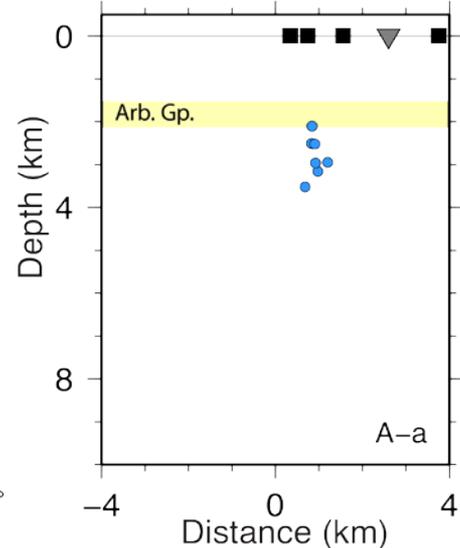
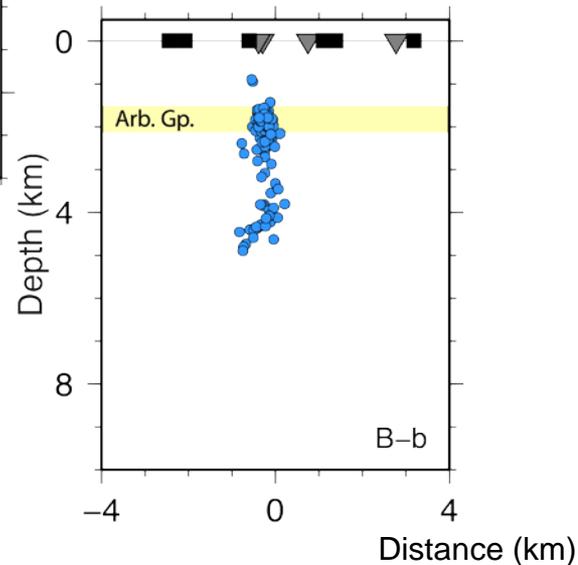
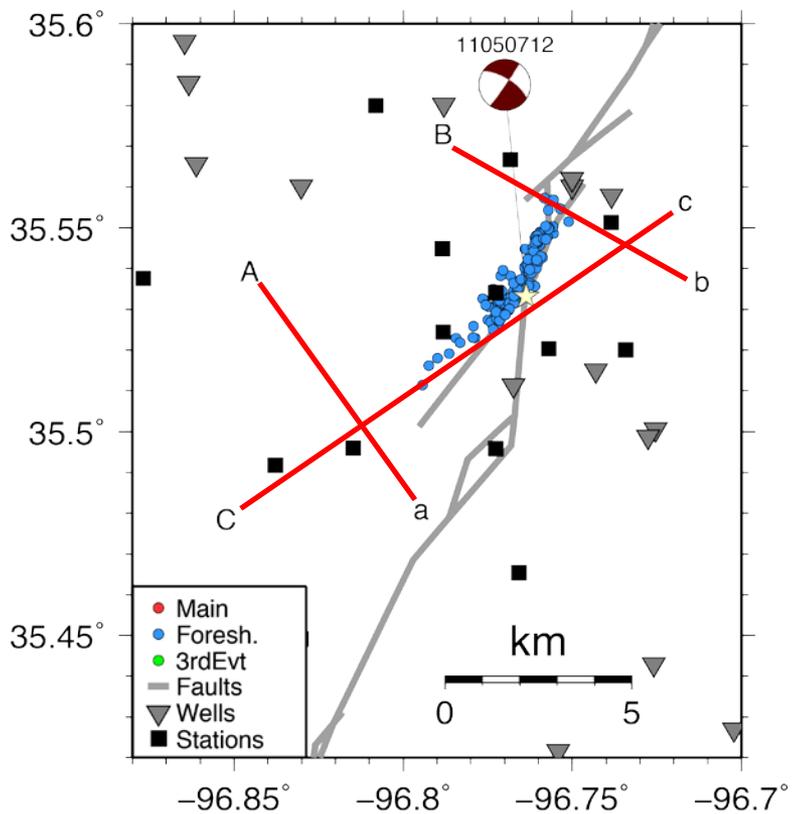


Template

Timeline



Well path to maximum depth (zone of fluid injection in red)



Timeline

OU, RAMP, USGS
stations deployed

M4.7

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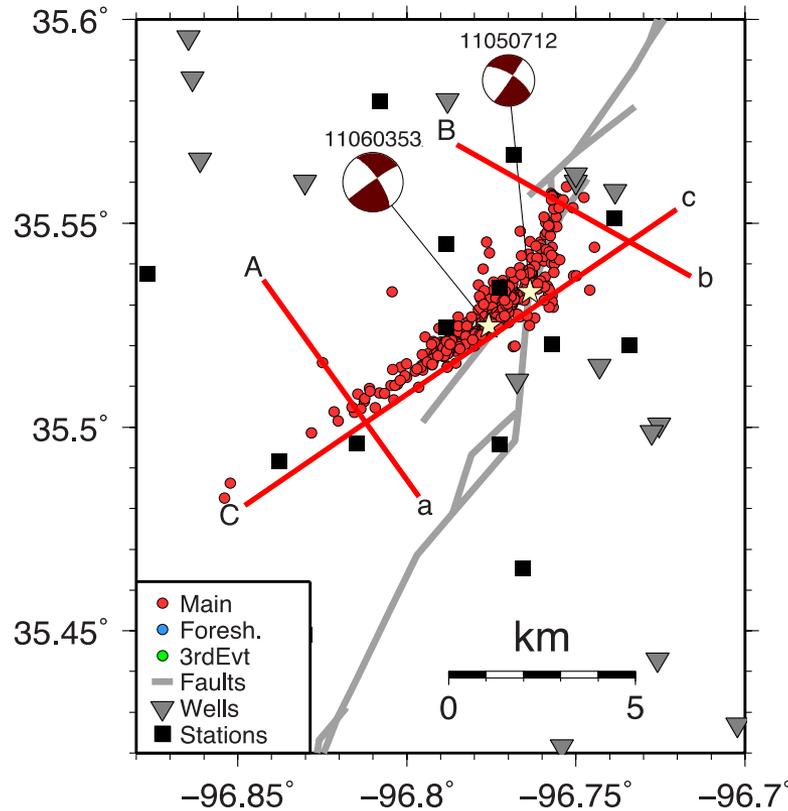
11052011



Arbuckle Group

Well path to maximum
depth (zone of fluid
injection in red)

Arb. Gp.



pth (km)

Arb. Gp.

Distance (km)

Timeline

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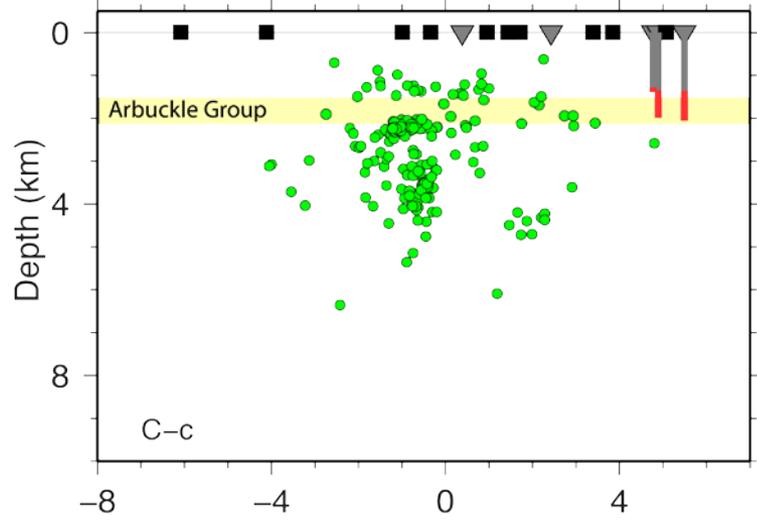
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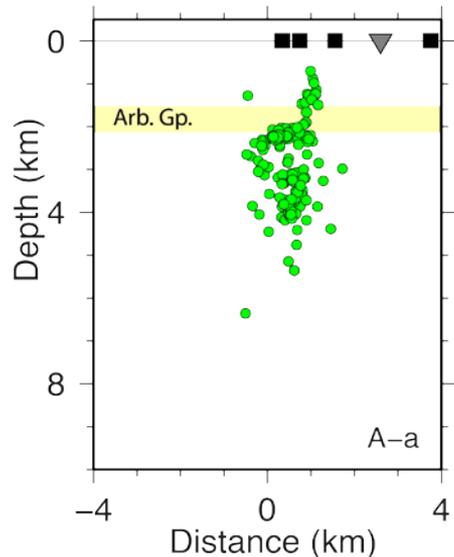
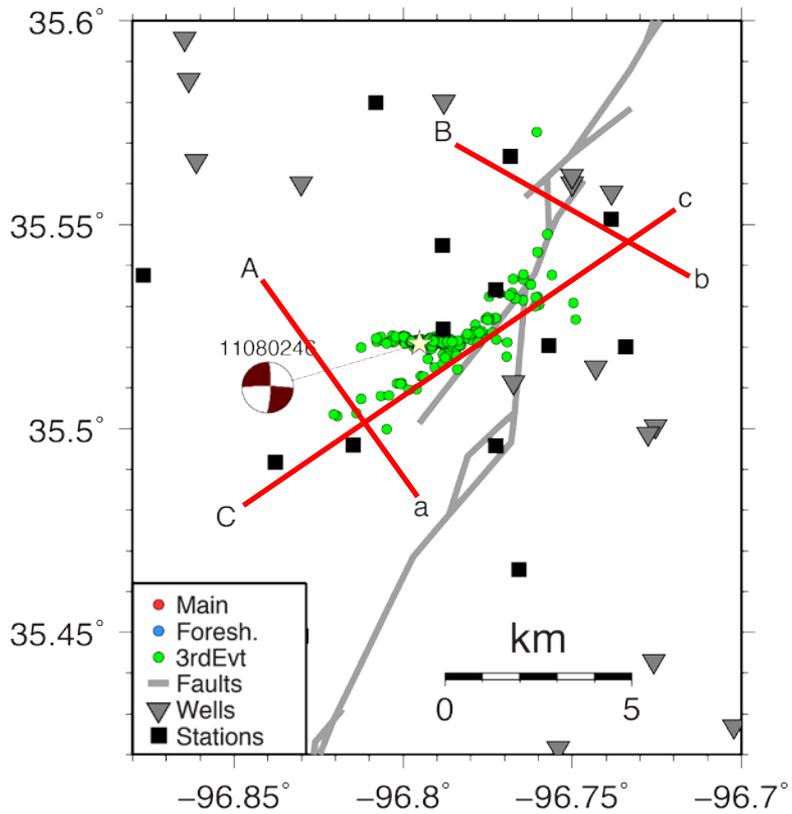
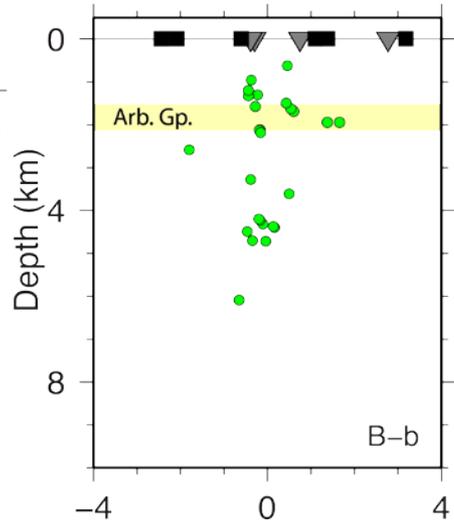
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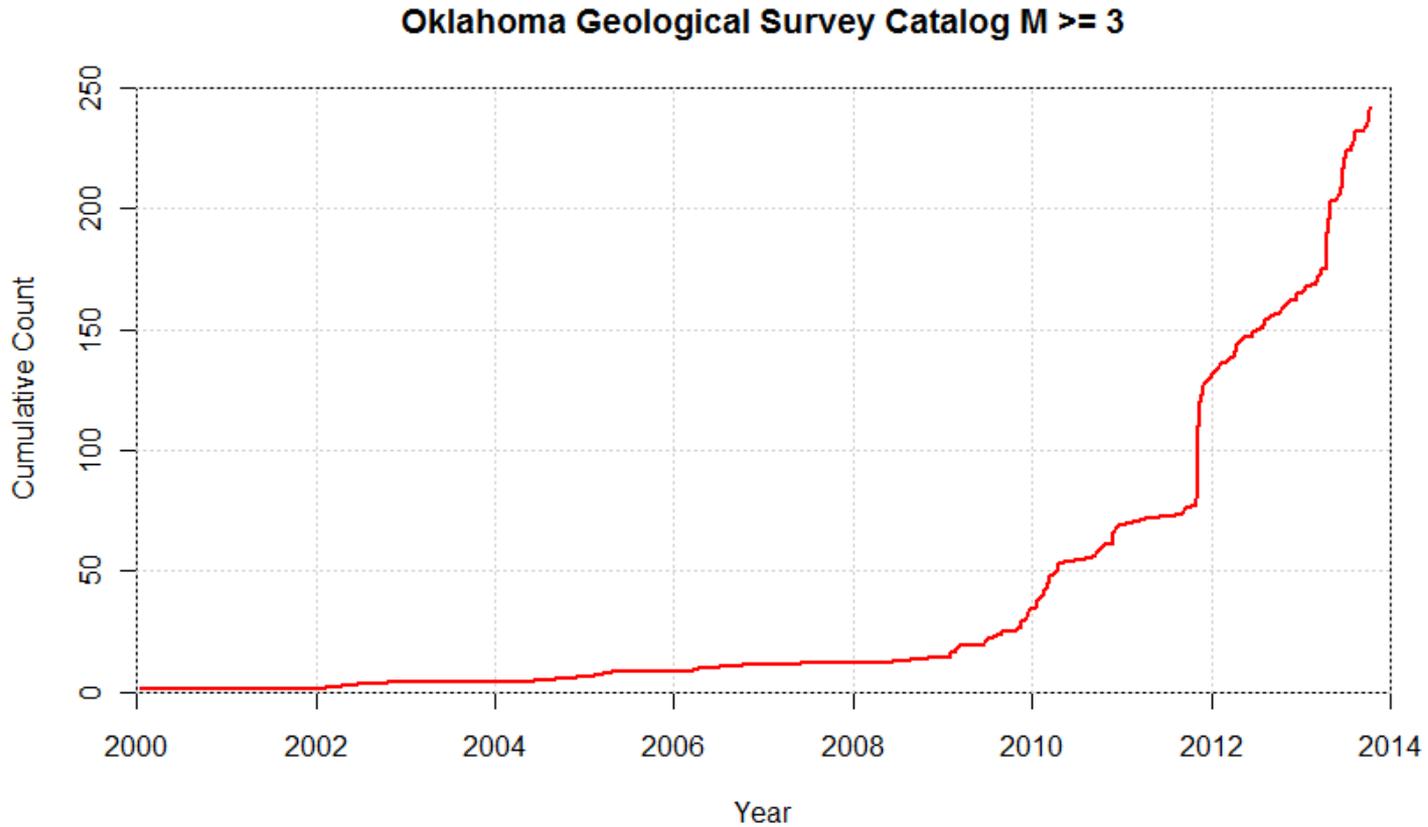
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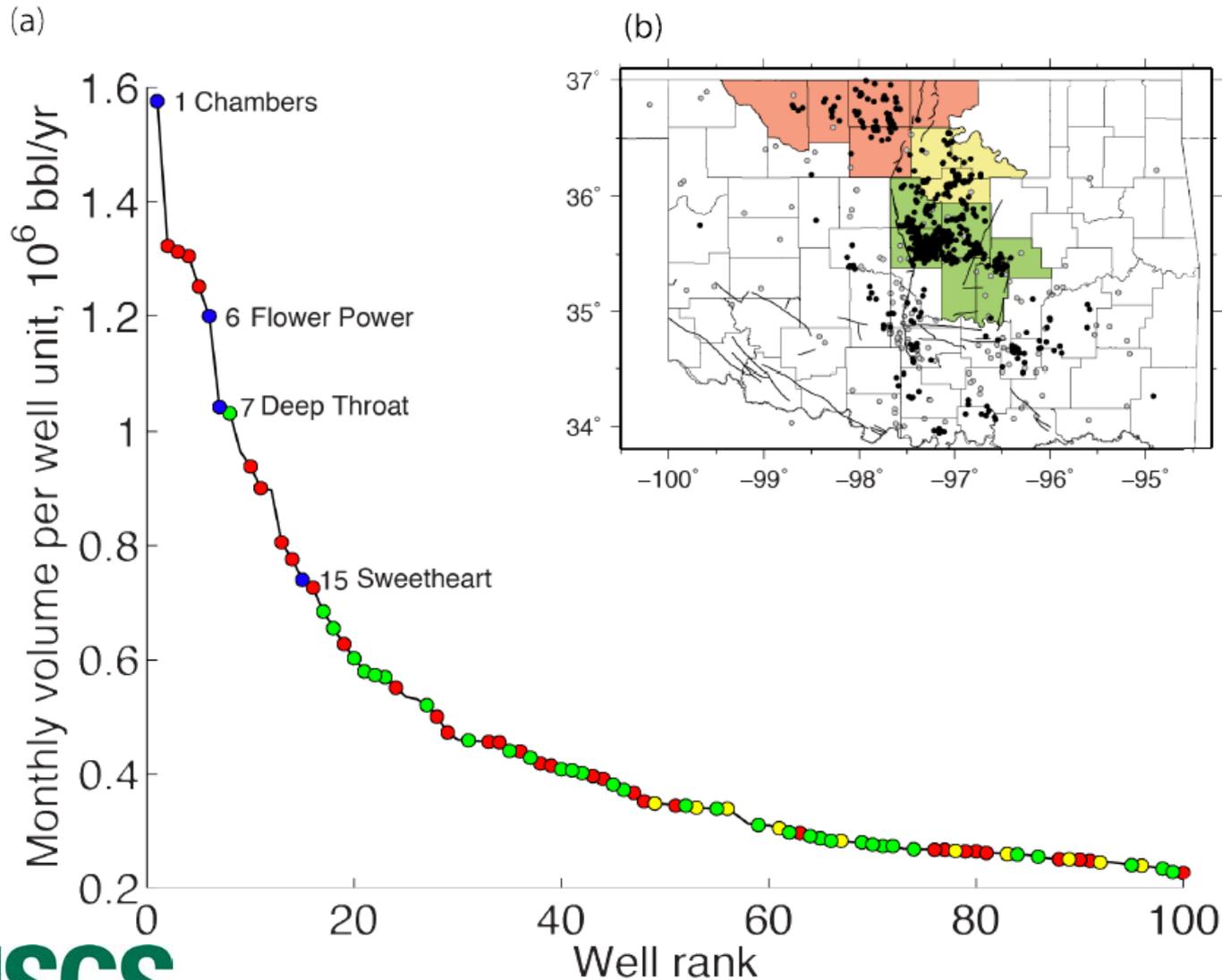
Implications: Prague, OK Earthquake

- Sequence suggests that a long temporal delay (10-20 years) is possible
 - Permeability barriers can delay pressure relaxation; cause a gradual increase in pore pressure
- We should not always expect a correlation between short-term fluctuations in wellhead injection data and seismicity
- Significant tectonic stress release
 - The volume of fluid injected near Prague is orders of magnitude below that predicted for the M5.0 event
- Injection-induced events may trigger nearby faults to fail
 - Injection may cause cascade of failures that occasionally result in larger events

Earthquakes in Oklahoma 2000-2014



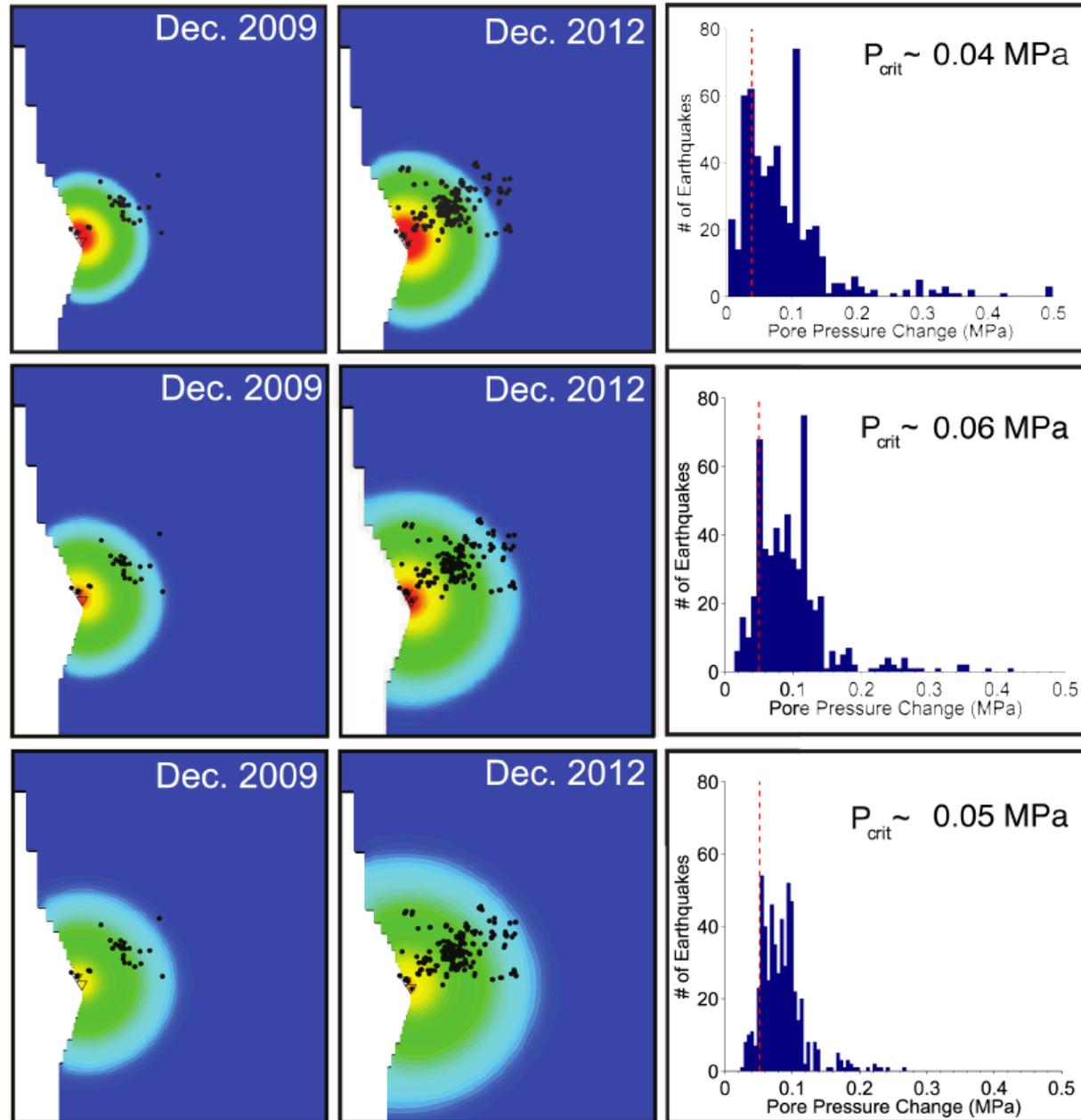
Oklahoma: Very Large Volumes



Pore pressure modeling

- Pressure changes over large distances
- Not always a clear spatial migration of seismicity

4 SE OKC WELLS



Keranen et al., 2014

How do we tell if seismicity is induced?

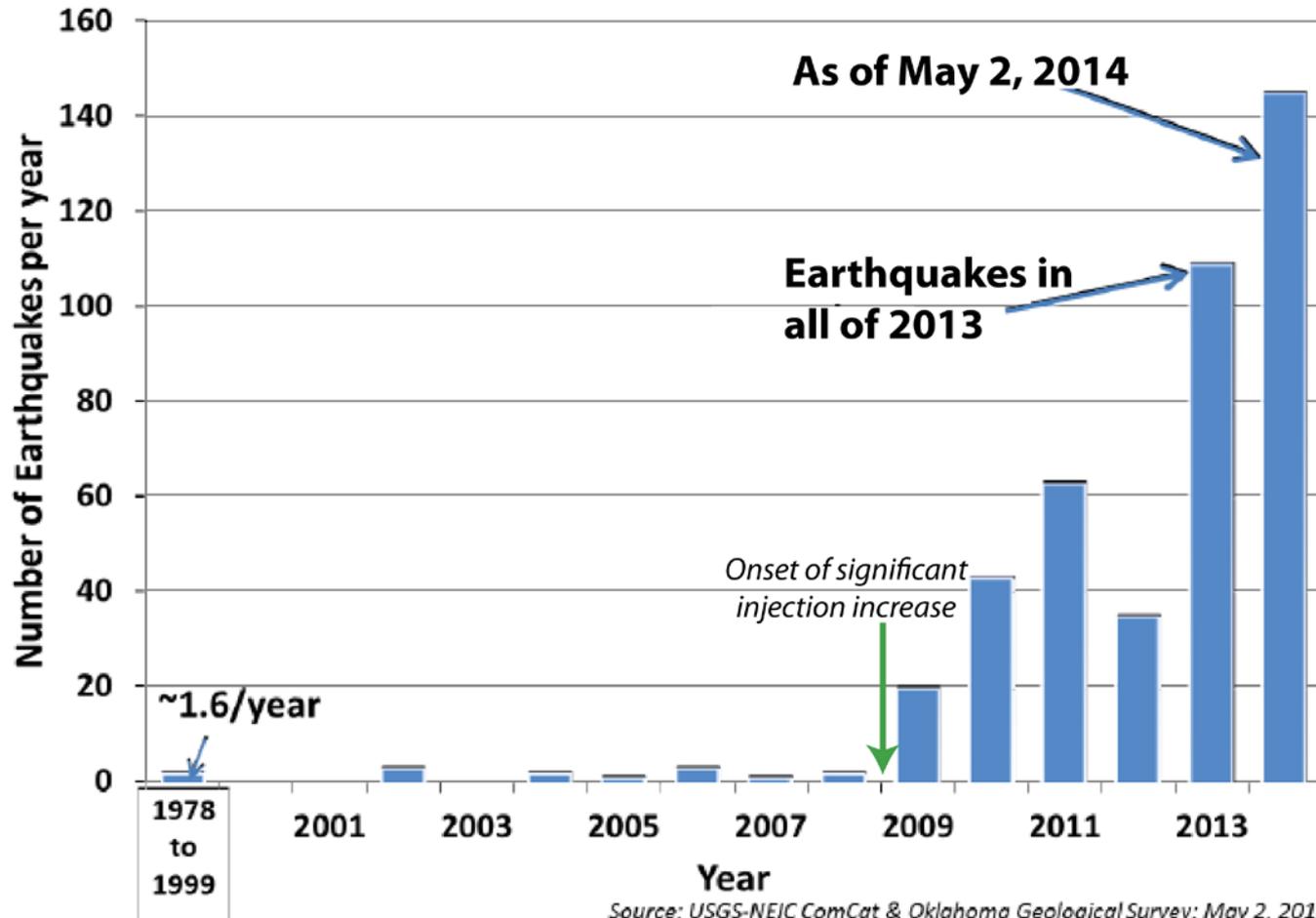
1. Deviation from background seismicity
2. Spatial correlation of seismicity with injection wells
3. Seismicity within the depth intervals of fluid injection
4. Temporal correlation to injection practices (injection pressure, injection rate)
5. Increased fluid pressure in the subsurface beyond a critical threshold

Modified from Davis and Frohlich, 1993

Not hard and fast rules!

Southern California is *not* like Oklahoma: So Far

Oklahoma Earthquakes Magnitude 3.0 and greater



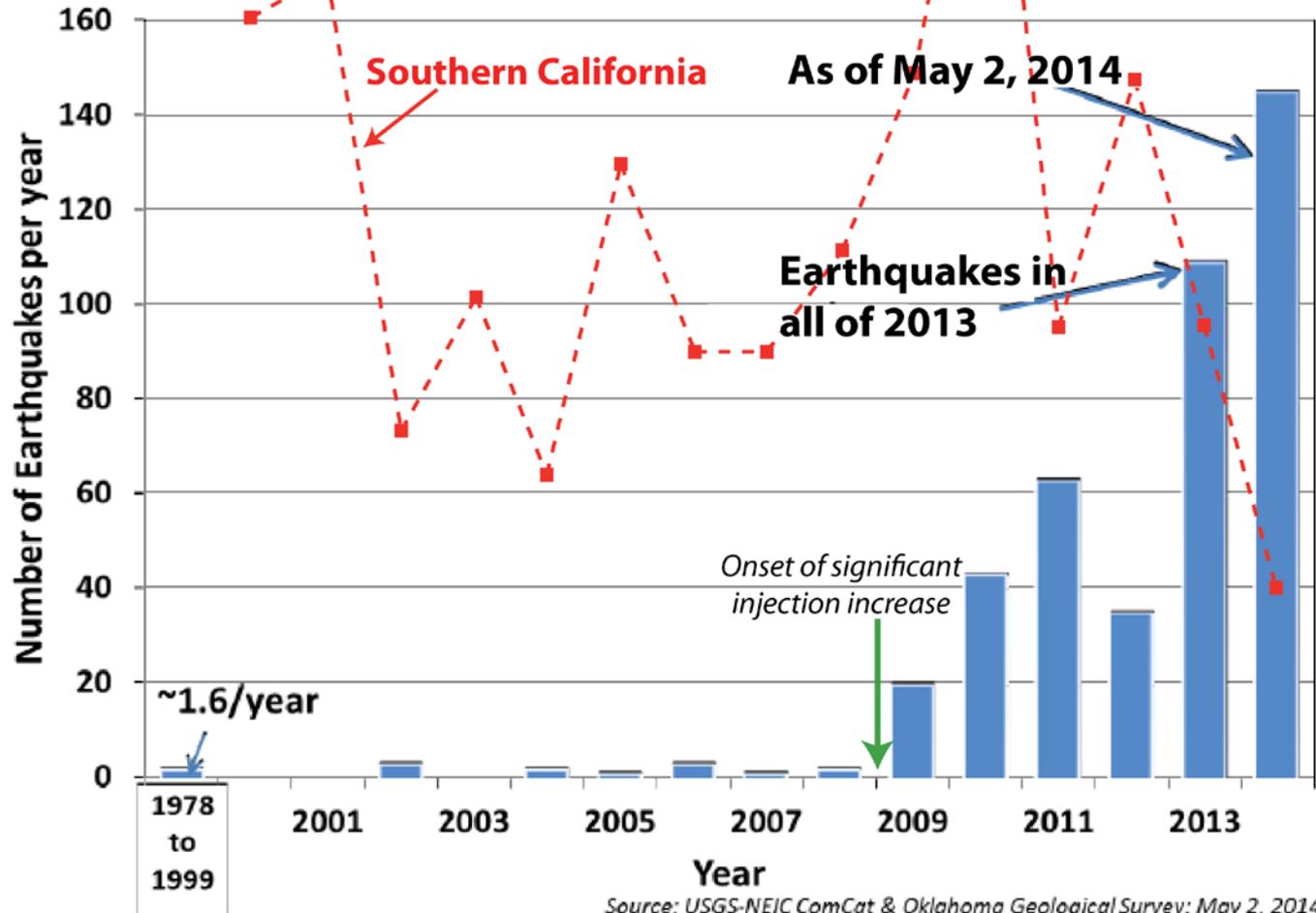
Source: USGS-NEIC ComCat & Oklahoma Geological Survey; May 2, 2014

In Oklahoma:

- Injection rate & volume much higher than CA
- Seismicity very close to wells
- Strong correlation between onset of injection and increased seismicity

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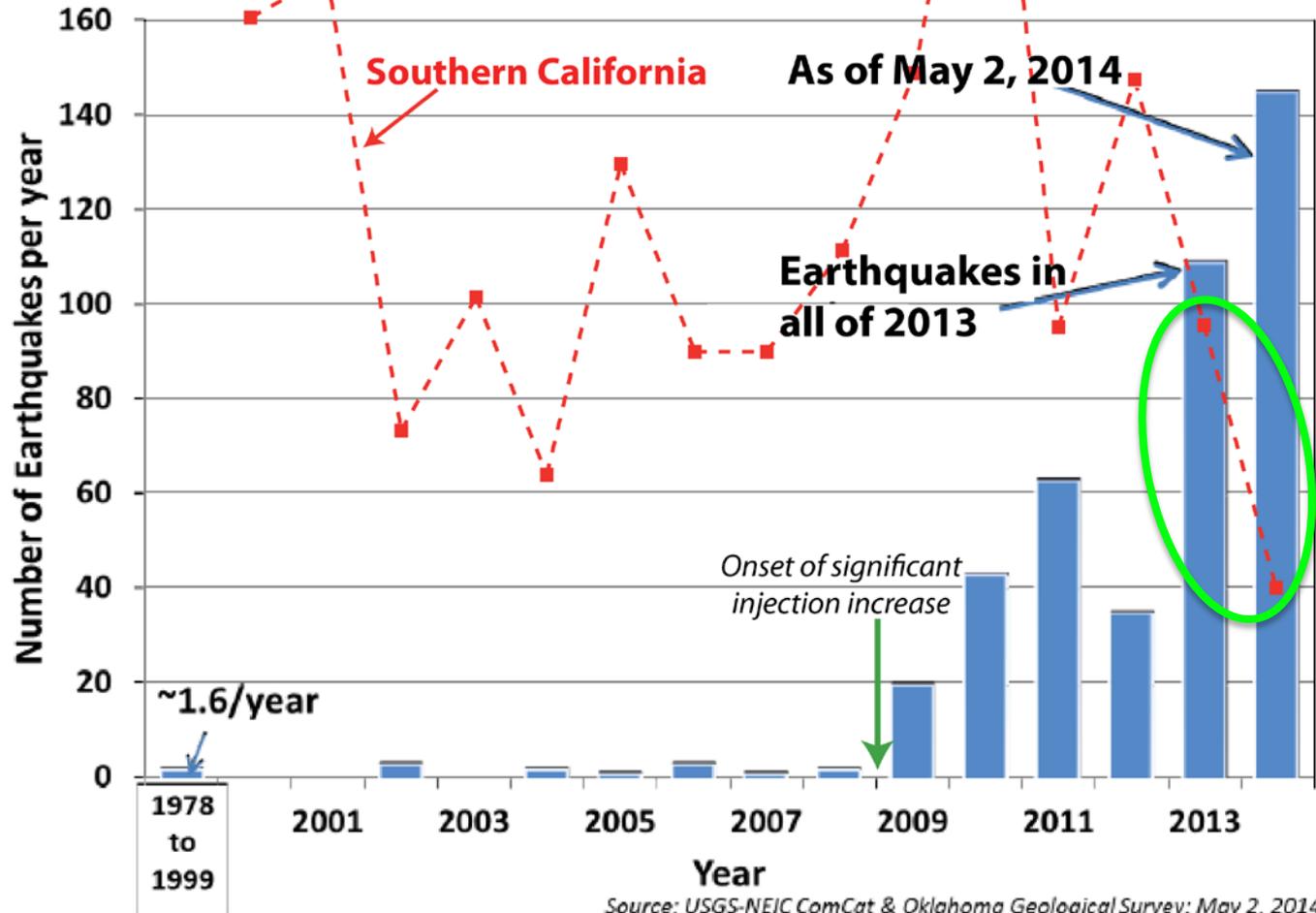
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Summary

- **Wastewater injection and hydraulic fracturing can cause seismicity**
 - Large increase in seismicity in Central and Eastern US. Injection tends to cause a greater number of events, including damaging earthquakes.
 - Link between larger volumes and induced earthquakes, but the problem is complex
 - Not always clear migration of seismicity away from injection sites
- **The key to improved understanding of these processes requires increased monitoring and cooperation**
 - Densify seismic instrumentation in areas of large scale extraction activities (e.g., central California)
 - Provide more access to injection data (rates, volumes and locations)
 - Develop industry, government and academic collaborations to work together in addressing these problems