Concerns About the Potential for Induced Seismicity Associated with the Mississippian Play: Perceived or Real?

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Outline

- Induced Seismicity Background
- Induced Seismicity Regional Context
- Potential for Induced Seismicity in the Mississippian Play
- Possibilities for Risk Mitigation
- Best Practices

Earthquake Triggering

Natural Causes

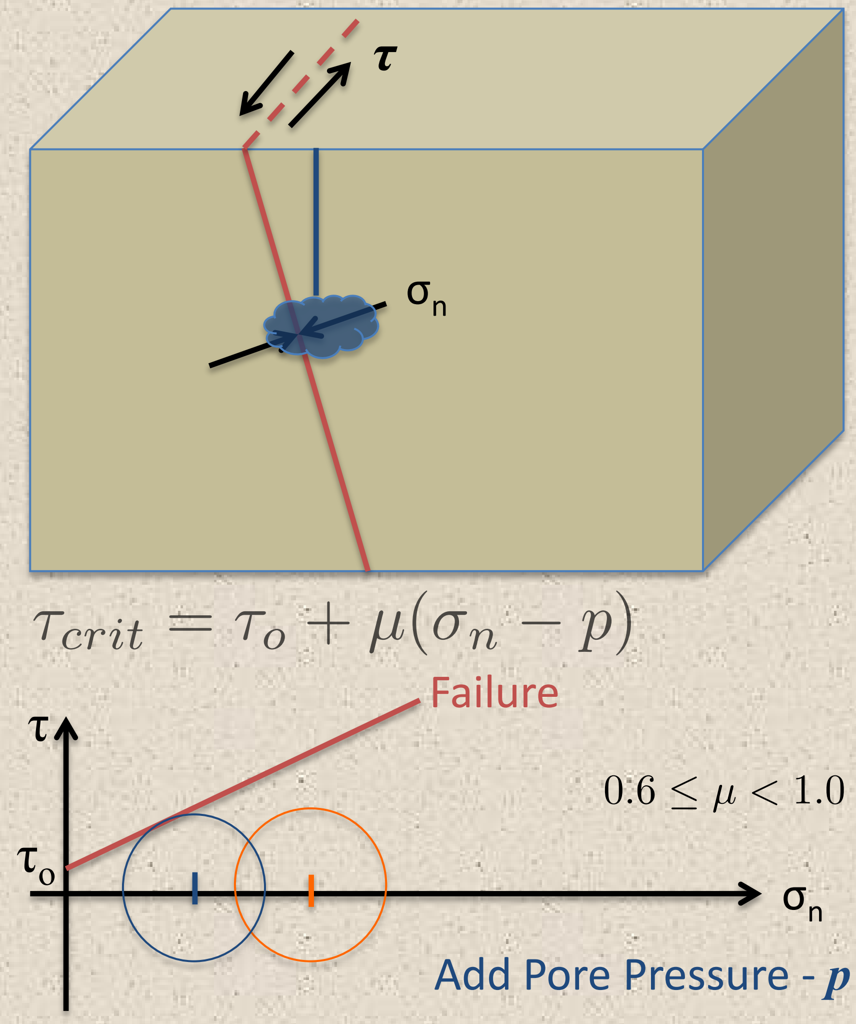
- Dynamically by the passage of seismic waves
  - typically from very large earthquakes distances > 1000 miles
- Statically by local stress changes from previous earthquakes
  - Small amounts of stress changes have been shown to trigger earthquakes
  - as little as 2-7 psi
- Natural fluid movement
  - May be the cause of many aftershocks of large earthquakes
- Hydrologic loads

Anthropogenic

- Reservoir Impoundment
- Mining and Oil Production (Mass Removal)
- Fluid Injection
- Geothermal Production & Thermal Contraction

Induced Seismicity from Fluid Injection

- Most of the Earth's upper crust is near failure
- Increased pore pressure from fluid injection effectively reduces friction on fault
  - or in Mohr-Coulomb space, moves the circle towards failure



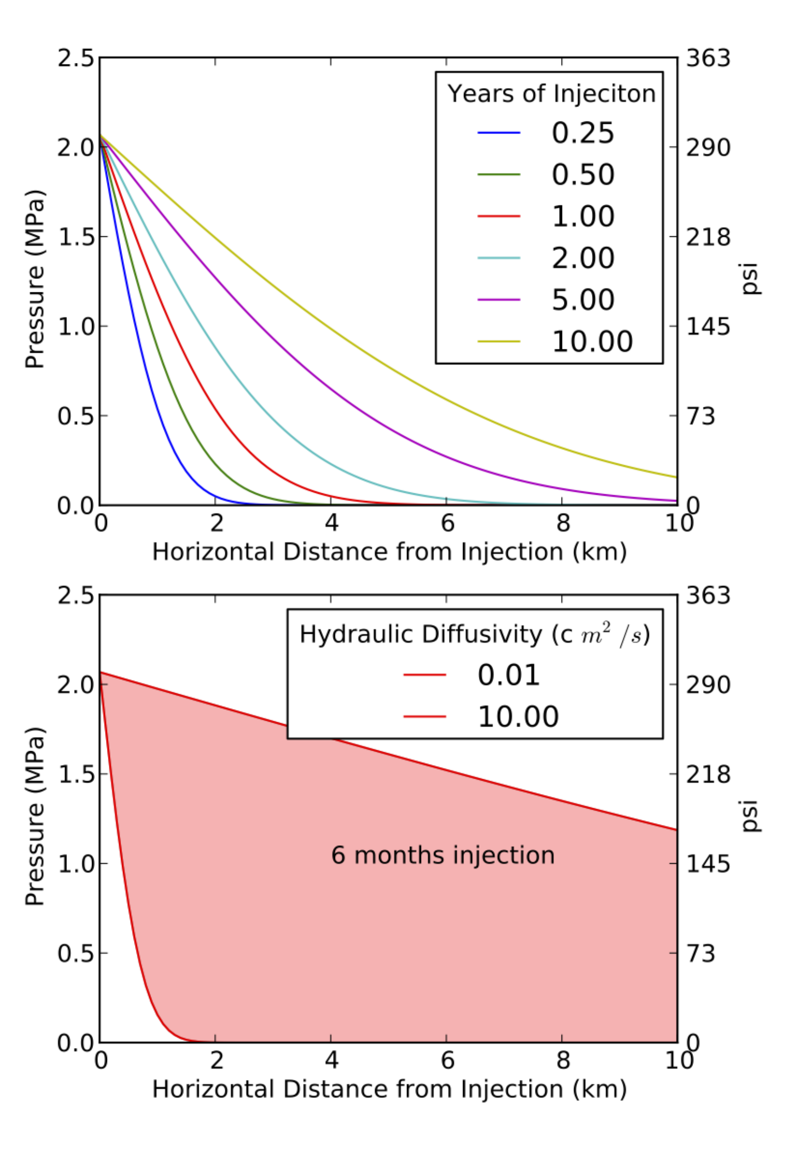
Pressure Diffuses Within the Earth

- Pressure increase is not due to actual fluid flow
  - Can be much more rapid
  - Because water is fairly incompressible it is similar to an elastic response although slower
  - Diffusivity is

    $$c = T/S$$

    T = transmissivity

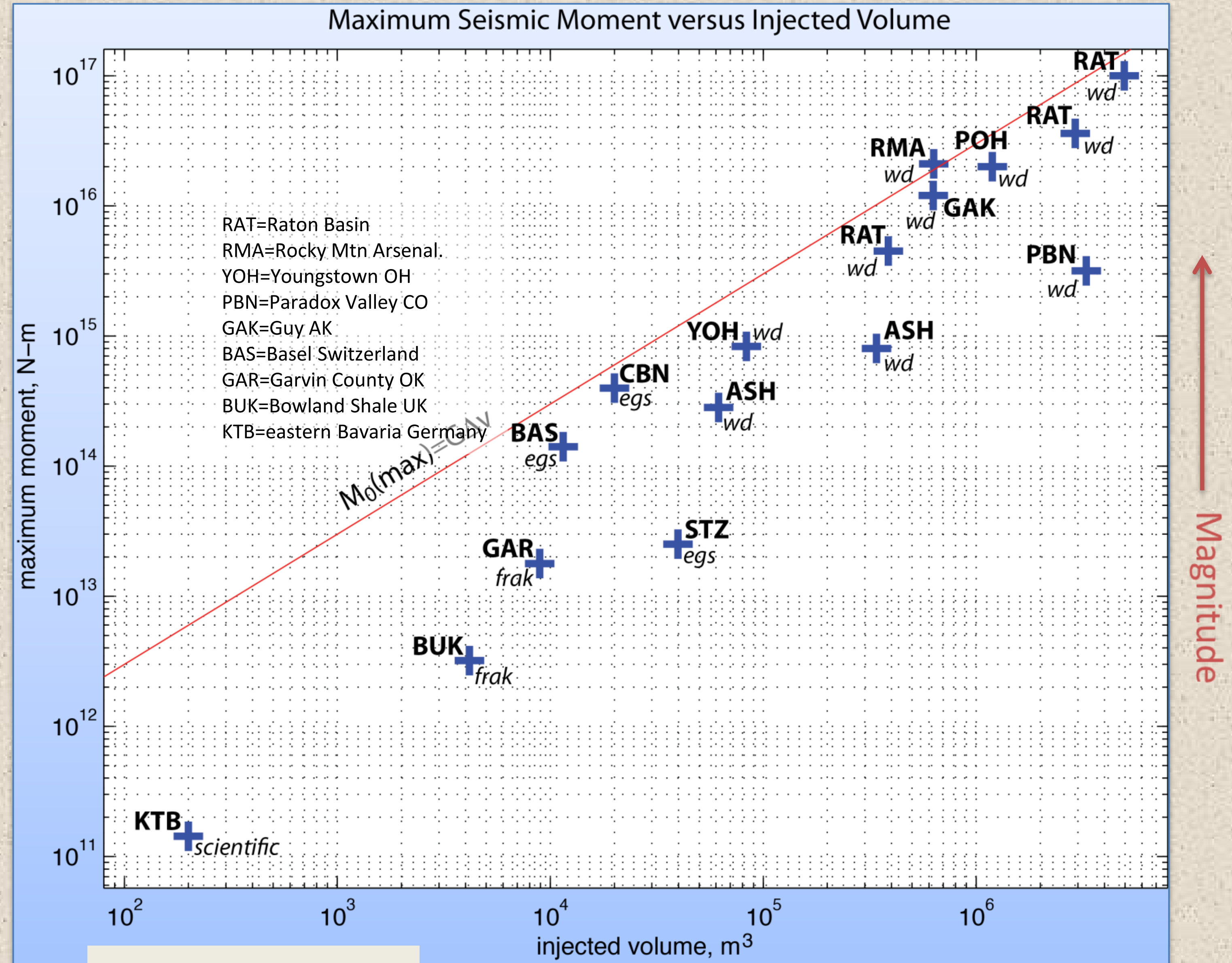
    S = storativity
- Pressure increases over time



Talwani et al. (2007) J. Geophys Res.

Risk from Induced Earthquakes

- Hydraulic Fracturing (Lower Risk)
  - Magnitudes generally less than 0
  - Observed maximum magnitude (M_{max}) 3.1-3.4
  - Injection duration may be weeks
- Water Disposal (Higher Risk)
  - Observed M_{max} 5.3-5.7
  - Damage from some events
  - Injection duration may be decades



Injection Duration

Courtesy of Art McGarr (USGS)

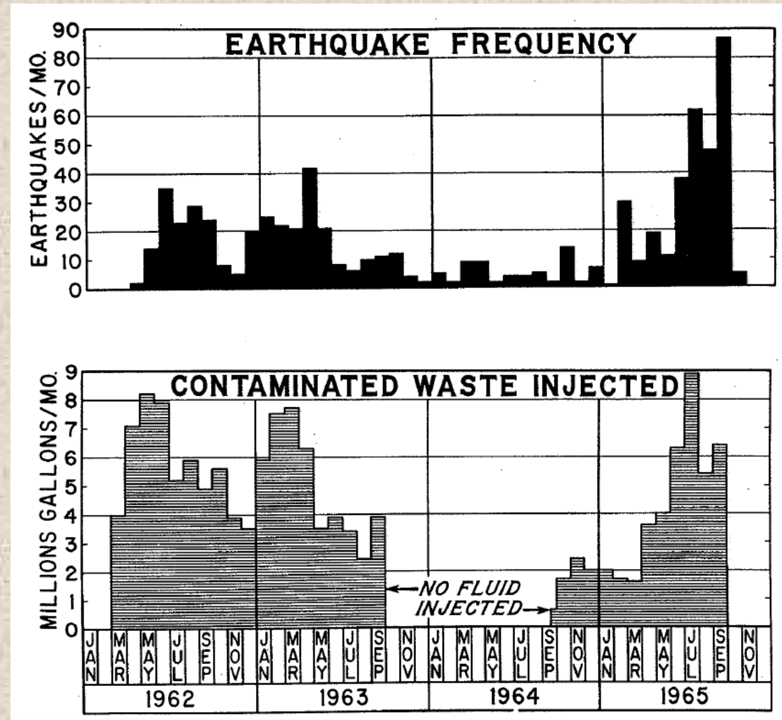
Injection Induced Seismicity

Best Documented Cases

- Rangely, CO – Raleigh et al. (1976) Science
- Paradox Valley, CO, Ake et al. (2005) Bull. Seismol. Soc. Amer.
- KTB, Germany, Baisch et al. (2002) Bull. Seismol. Soc. Amer.
- Basel, Switzerland, Deichmann & Giardini (2009) Seismol. Res. Letters
- Rocky Mountain Arsenal, CO, Hsieh & Bredehoeft (1981) J. Geophys. Res.

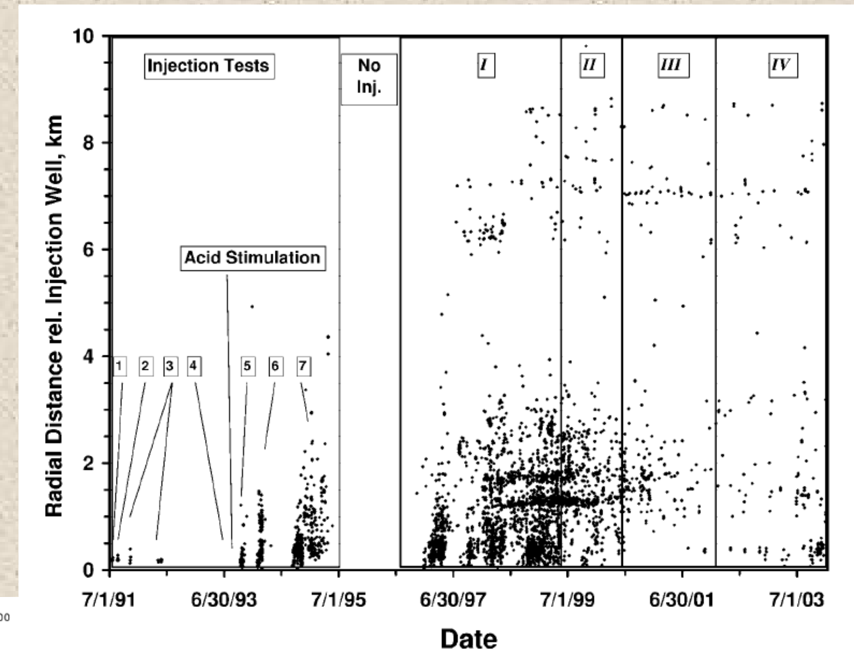
General Observations

- Earthquakes occur first near the well and migrate away from the well with time
- Earthquakes have a clear temporal correlation to injection
- Time and spatial distribution of earthquakes can generally be related to diffusion of pore pressure
- Earthquakes can occur over long distances >20 km
- Modifying injection parameters alters earthquake production



RMA, Healy et al. (1968)

Paradox Valley, Ake et al. (2005)



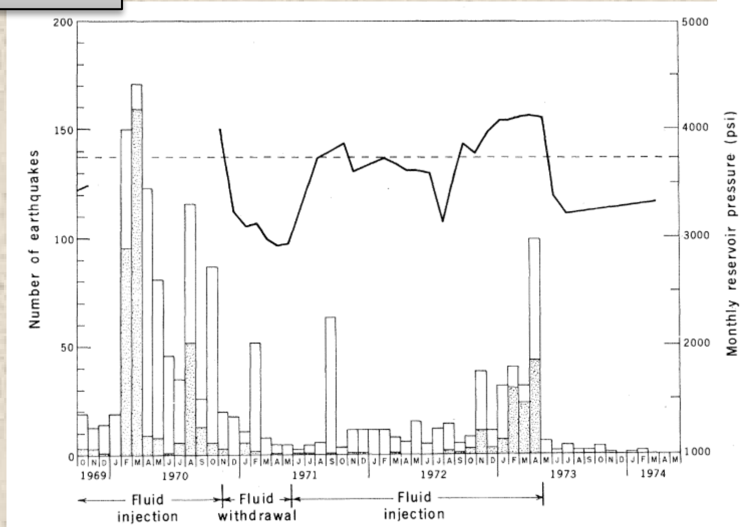
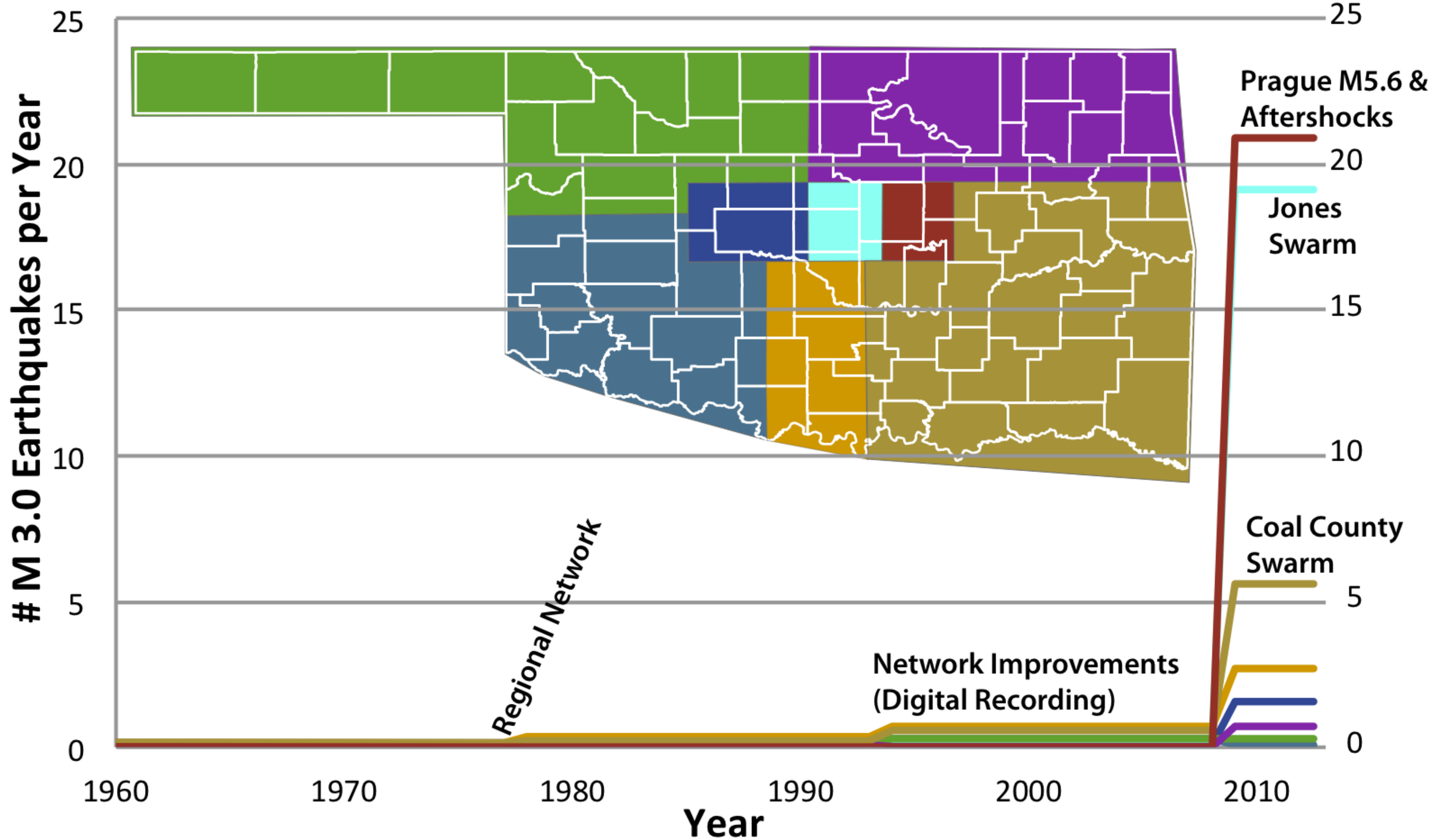


Fig. 7. Frequency of earthquakes at Rangely. Stippled bars indicate earthquakes within 1 km of experimental wells. The clear areas indicate all others. Pressure history in well Fee 69 is shown by the heavy line; predicted critical pressure is shown by the dashed line.

Rangely, Raleigh et al. (1976)

Earthquake Rate Changes in Oklahoma By Region



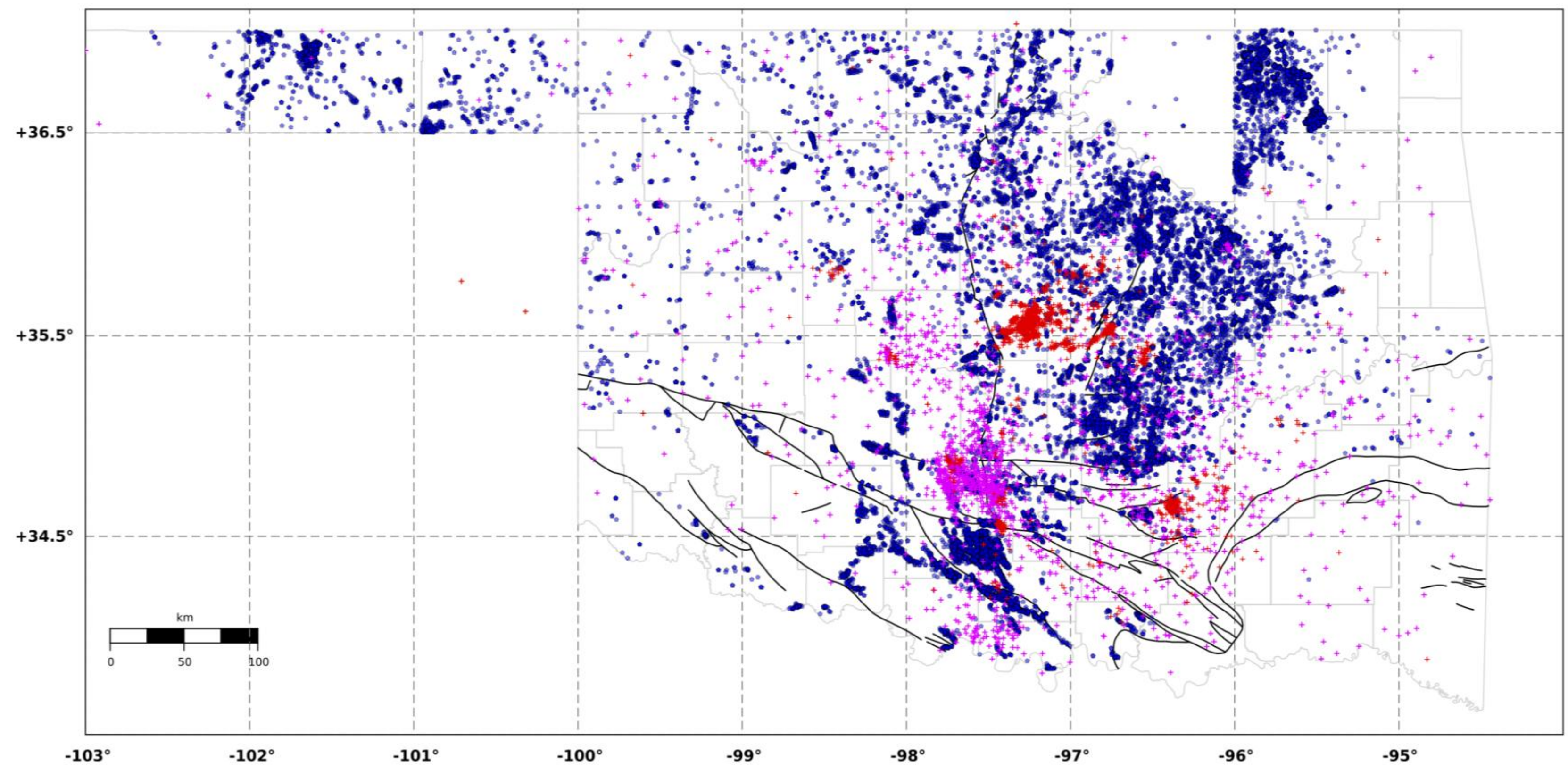
Induced Seismicity from Water Disposal

- Possible Cases from Oklahoma
  - M5.6 Prague Earthquake, 3 disposal wells within ~1 mile
  - Jones Earthquake Swarm, ~1800 earthquakes, M_{max}=4.0, large volume wells within 8-12 miles
  - Examining other possible cases
- Other recent possible cases
  - Guy/Greenbrier, Arkansas, hundreds of earthquakes, M_{max}=4.7
  - Youngstown, Ohio, ~12 earthquakes, M_{max}=4.0
  - DFW Airport, Texas, ~11 earthquakes, M_{max}=3.3
  - Barnett Shale, Texas, 67-150 earthquakes, M_{max}=3.0

Outcome of recent cases

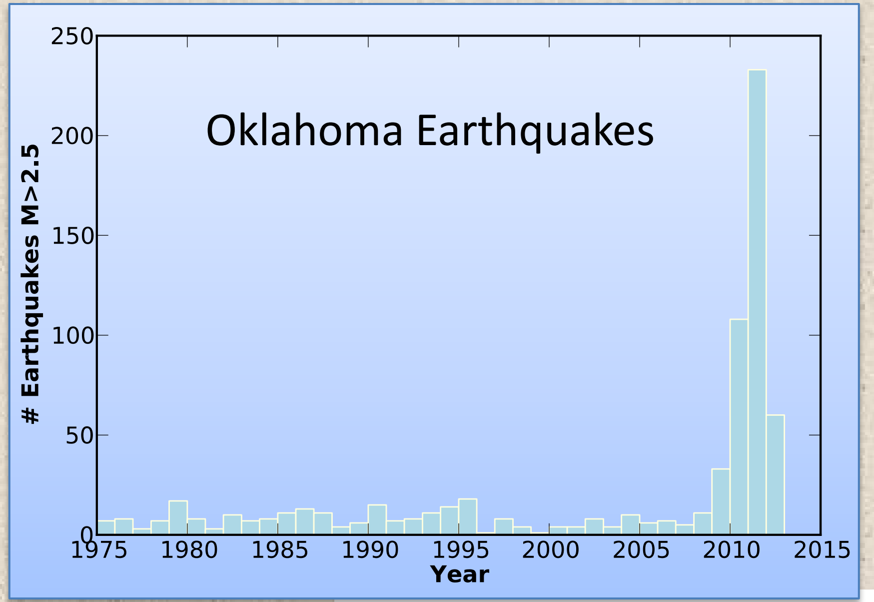
- Voluntary or mandatory shut-in of UIC Class II disposal wells (Texas, Arkansas and Ohio)
- Moratorium Zones for UIC Wells (Arkansas)
- New permitting and monitoring requirements (Arkansas and Ohio)

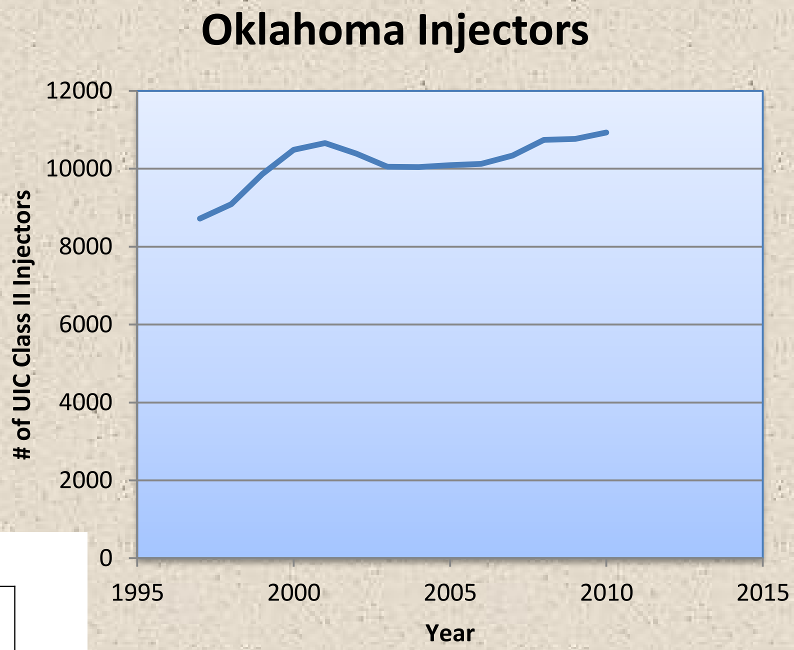
UIC Wells and Earthquakes

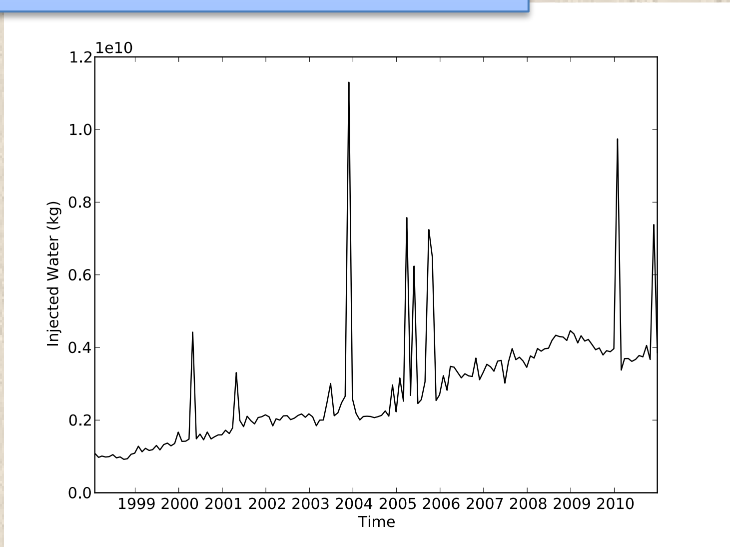


- More than 7,500 active UIC Class II Wells in Oklahoma
- Often spatially clustered

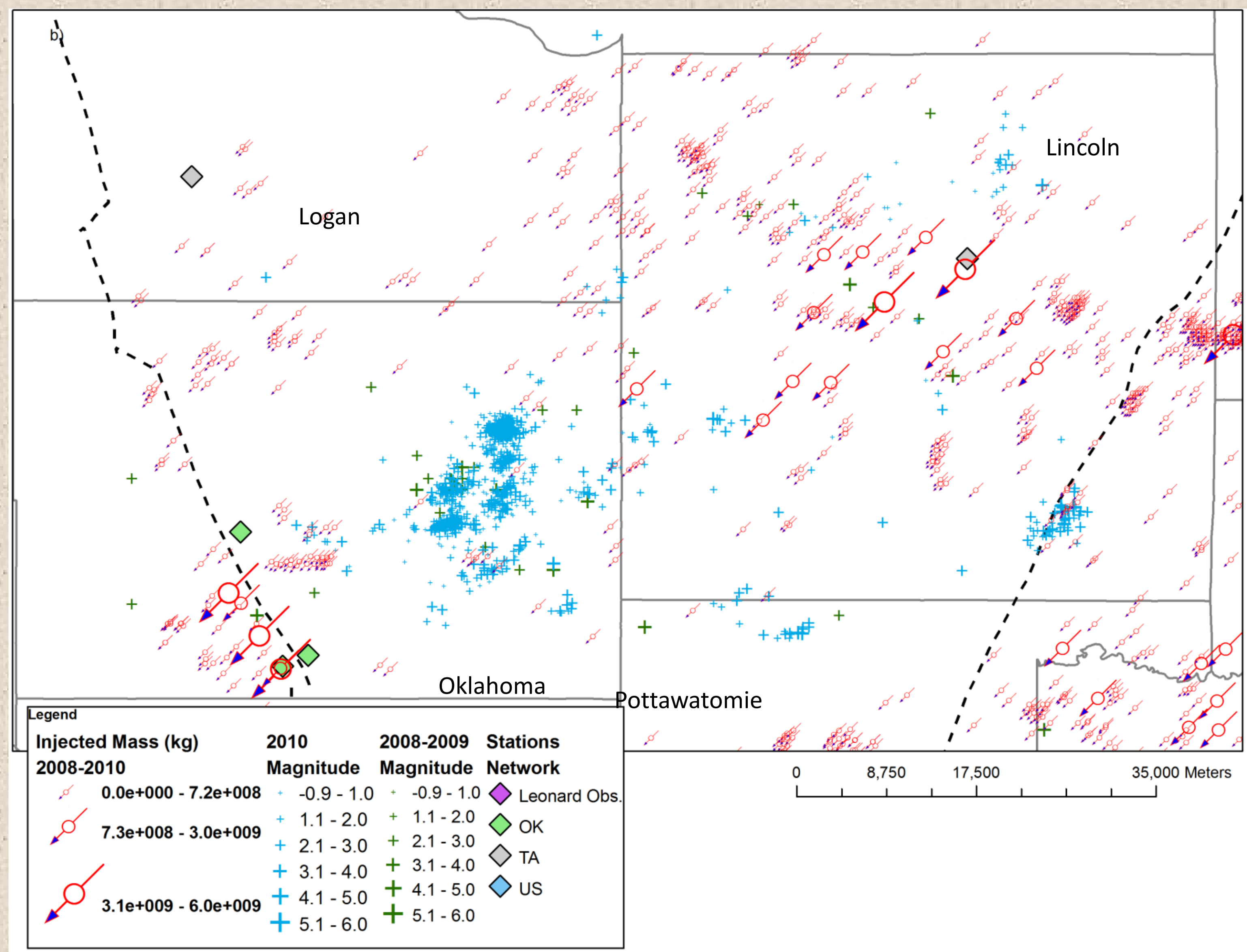
Increase in Earthquakes is Not Matched by an Increase in Fluid Injection







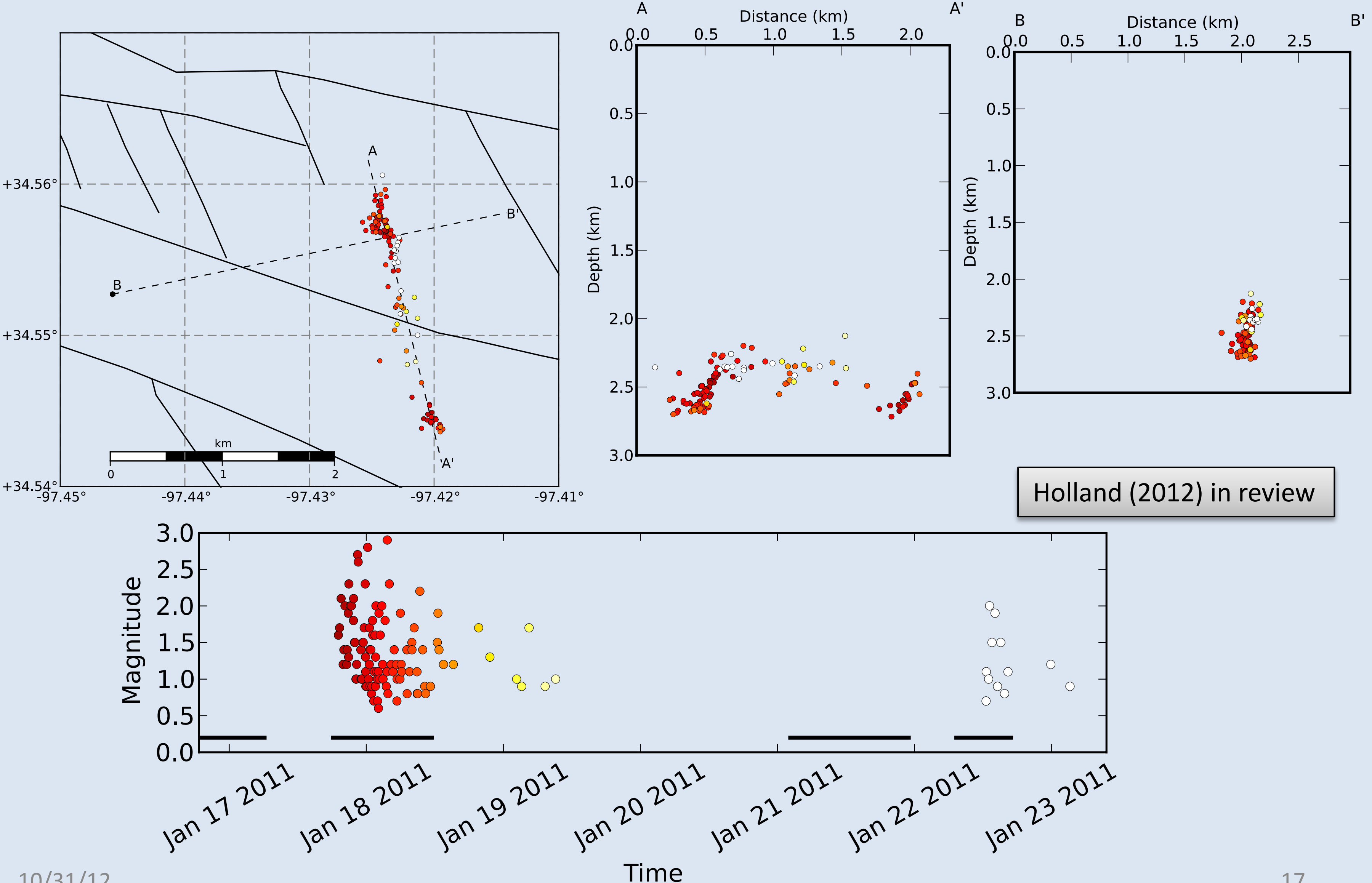
Fluid Injection in Central, OK



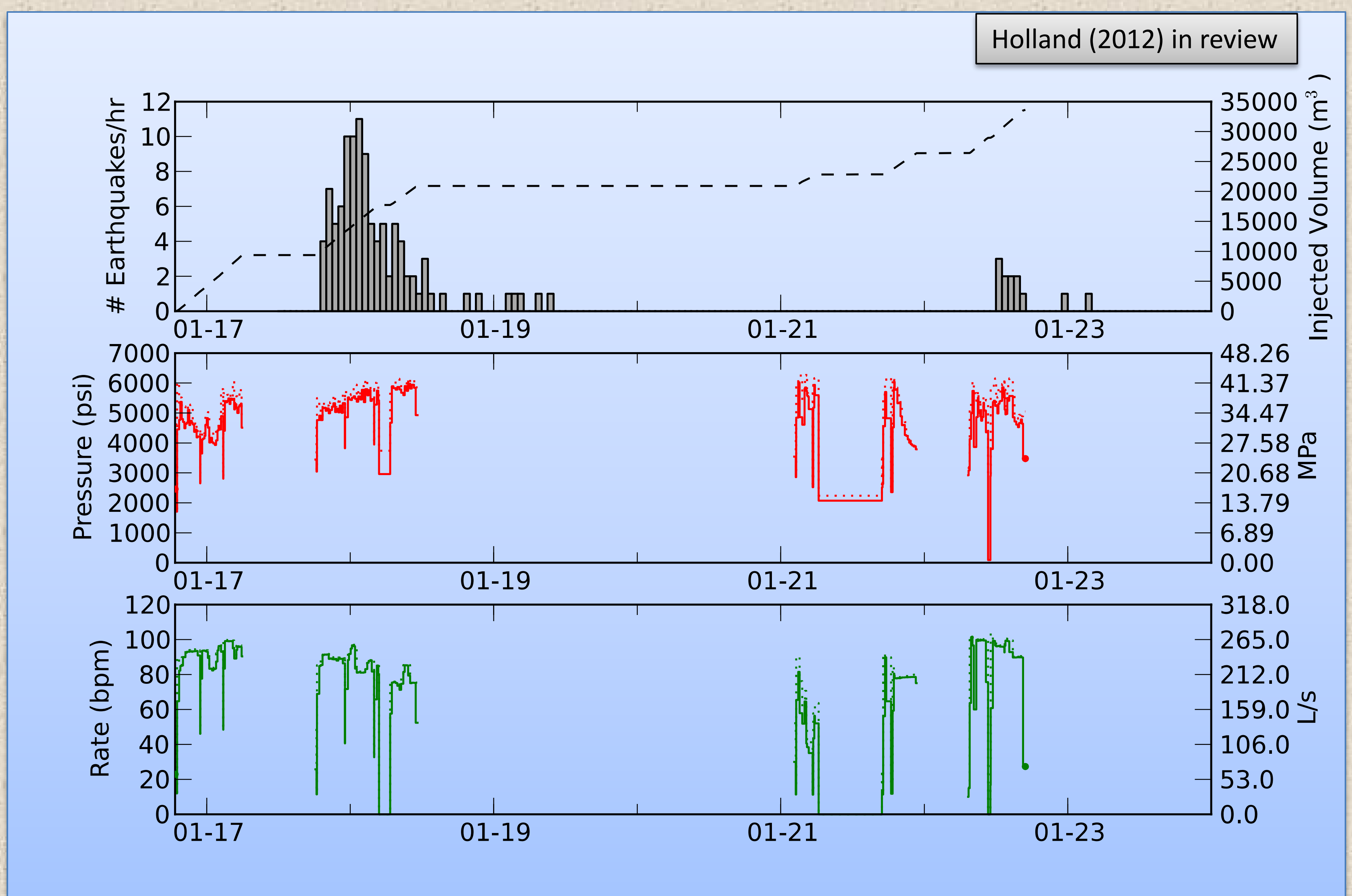
Induced Seismicity from Hydraulic Fracturing

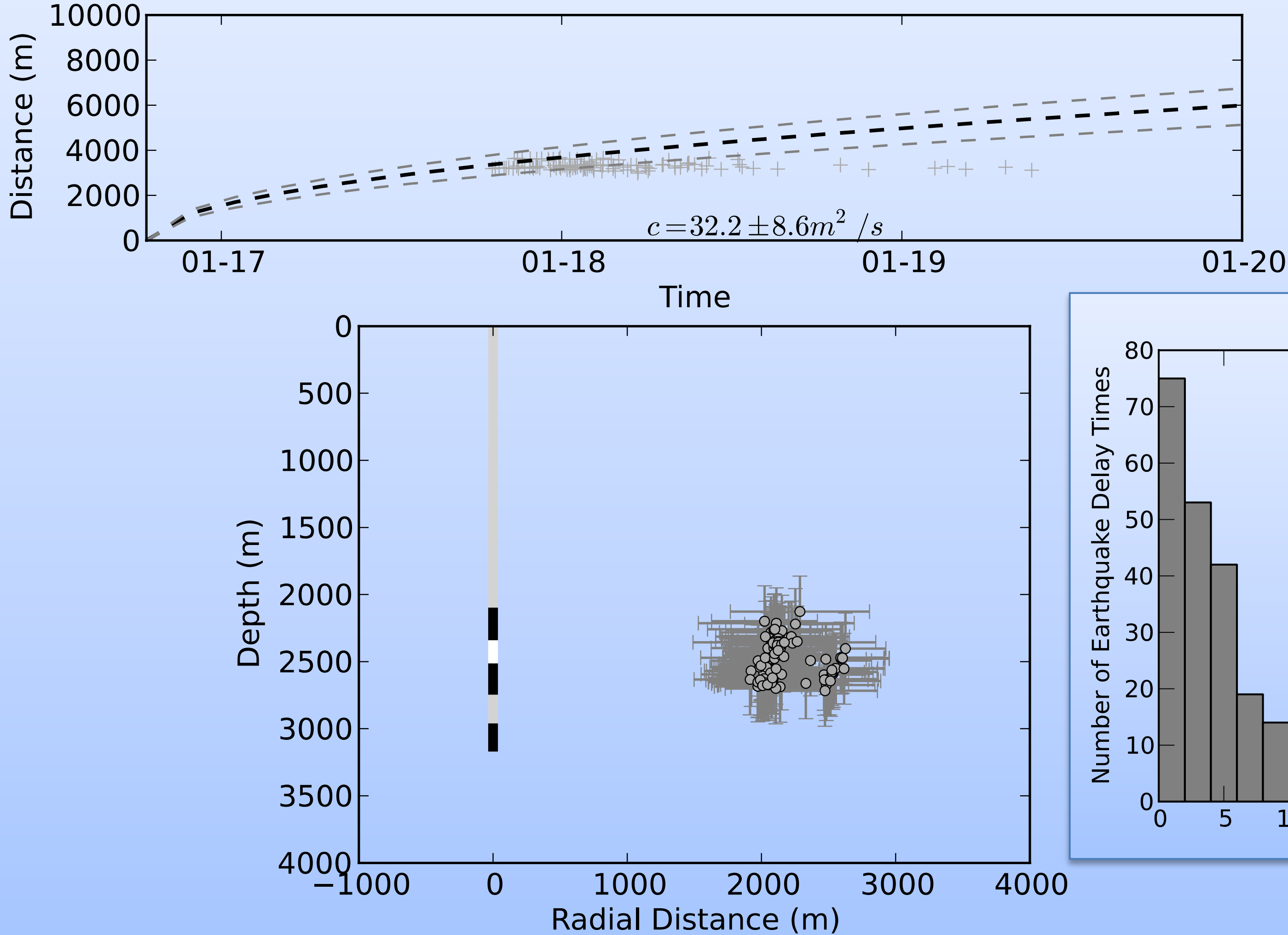
- Recent Cases from Oklahoma
  - Eola Field, Garvin County, ~100 earthquakes, M_{max}=2.9
  - Possible, Union City Field, Canadian County, ~10 earthquakes, M_{max}=3.4
  - Examining other possible cases
- Other recent cases
  - Blackpool, United Kingdom, >50 earthquakes, M_{max}=2.3
  - Horn River Basin, British Columbia, >40 earthquakes, M_{max}=3.5

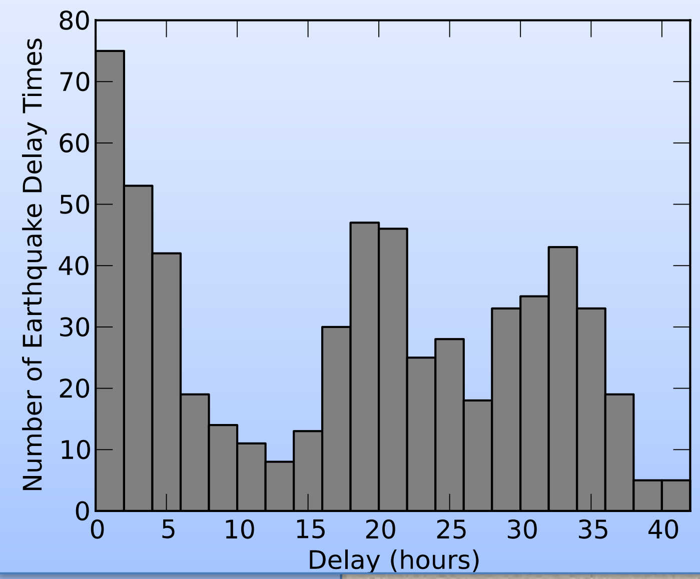
Eola Field, Garvin County



Holland (2012) in review


Holland (2012) in review
Earthquakes/hr
Injected Volume (m³)
Pressure (psi)
MPa
Rate (bpm)
L/s
01-17
01-19
01-21
01-23

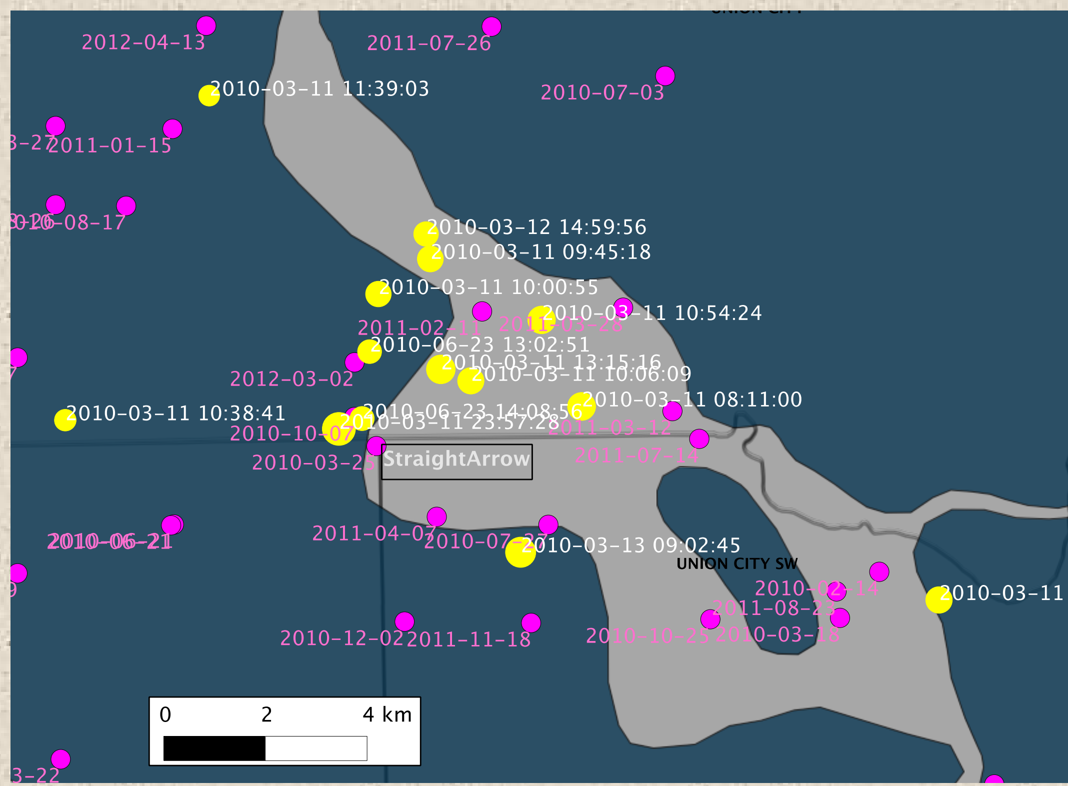




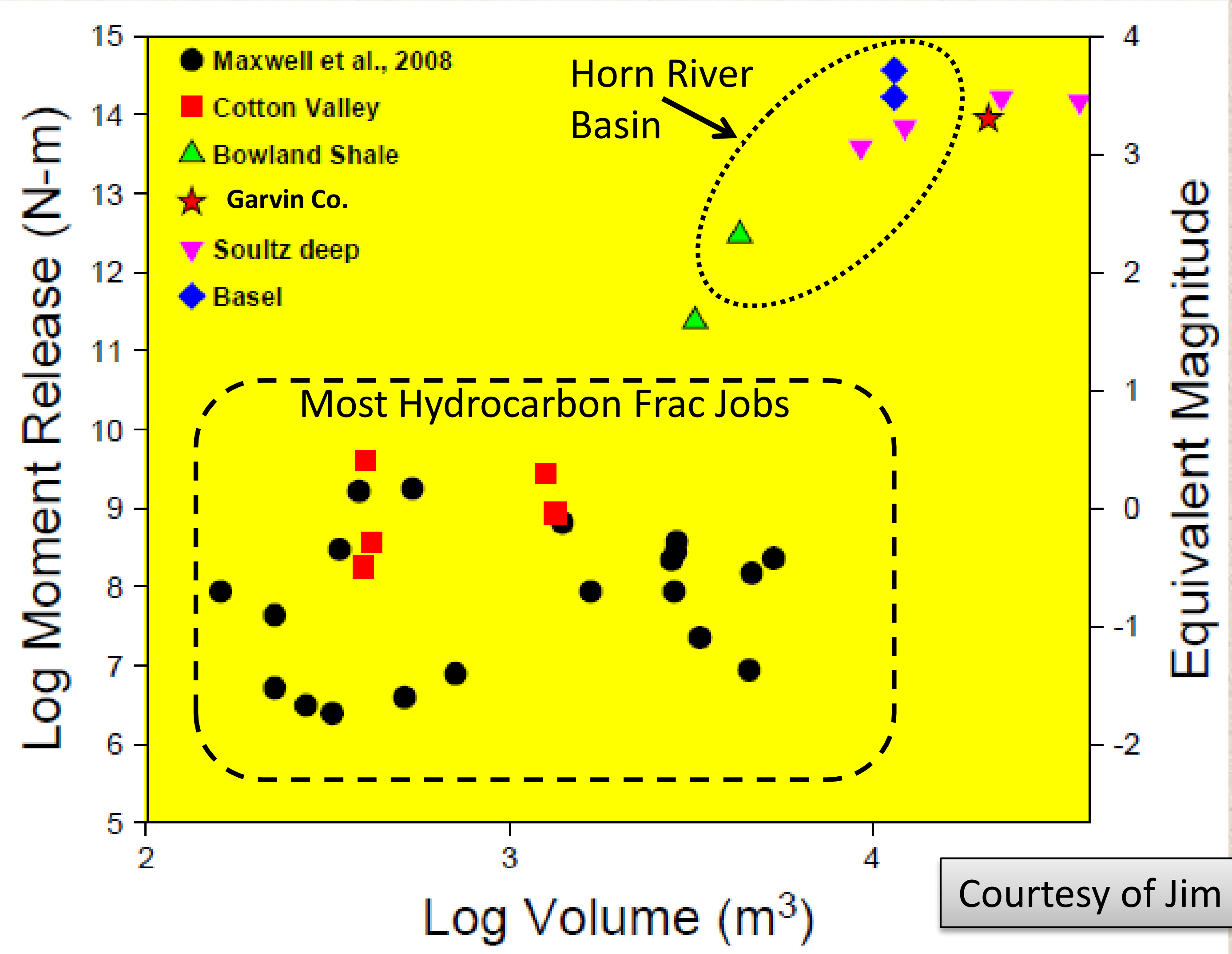
Holland (2012) in review

Union City Field, Canadian County

- Straight Arrow Well
- 16 stage frac
  - Completed 3/12 1:00 UTC
  - First earthquake 3/11 07:41
  - M3.4 at 23:57
  - Total 10 earthquakes M2.1-3.4 on 3/11
- Visually identify similar examples



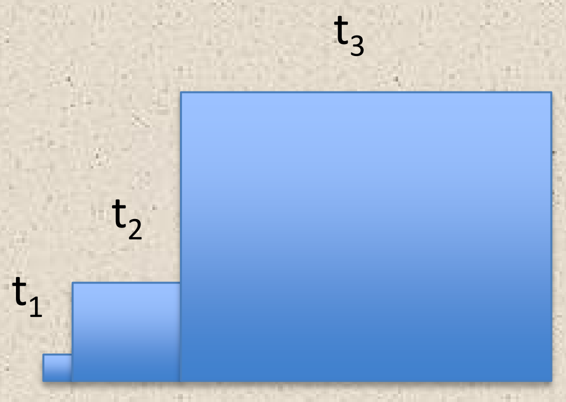
Induced Seismicity from Hydraulic Fracturing



Courtesy of Jim Rutledge

Maximum Magnitude

- Earthquake magnitude is related to rupture area and the average slip over that area
- Earthquake rupture dynamics
  - Big earthquakes start small
- M_{max} controlled by
  - fault size and properties
  - stress on the fault
  - initial rupture energy



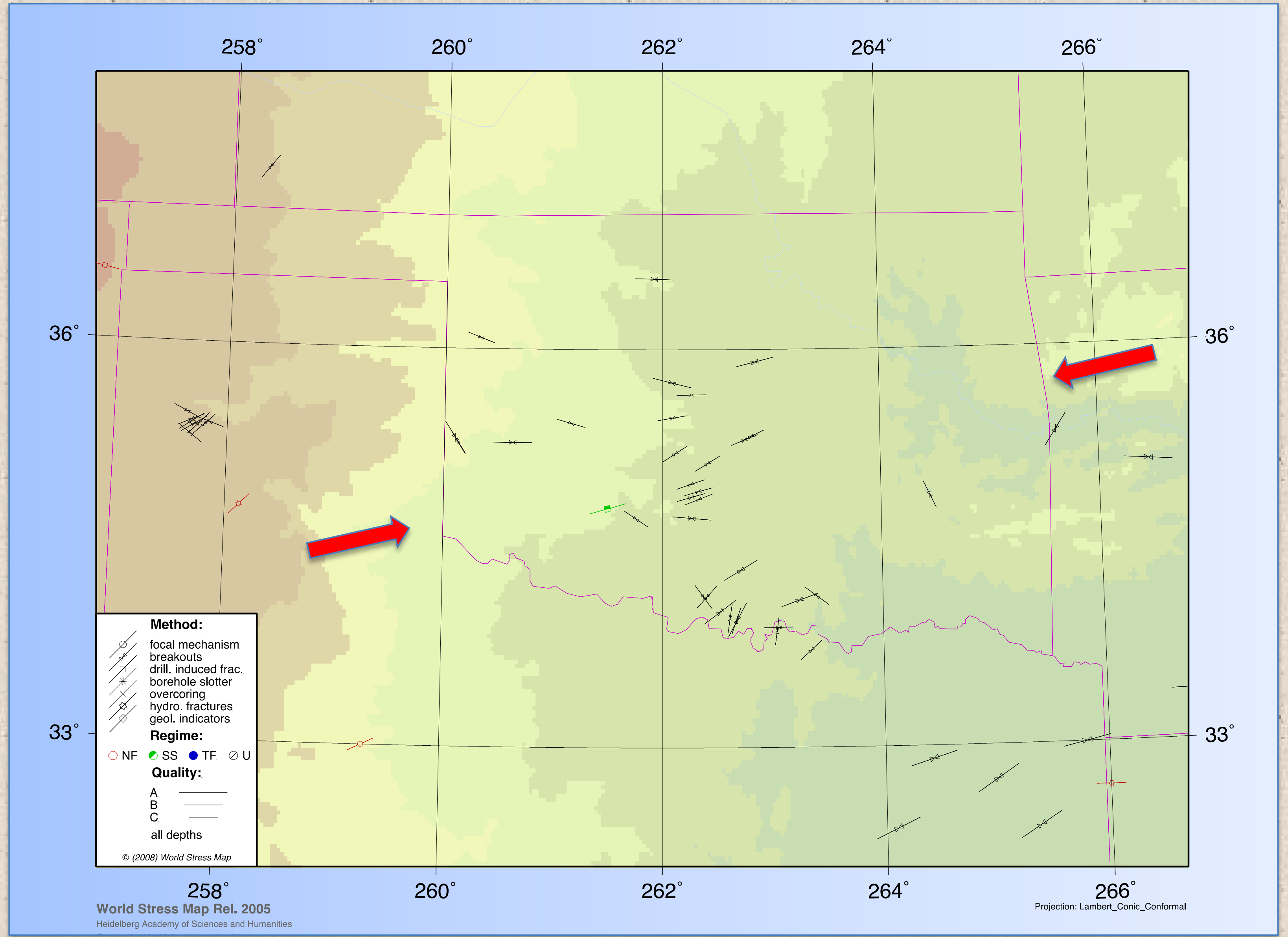
Large faults represent large potential hazards

- knowing whether or not they are favorably oriented in the regional stressfield for slip is important
- but to be cautious maybe greater set-backs are warranted

Concerns of Induced Seismicity in the Mississippian Play

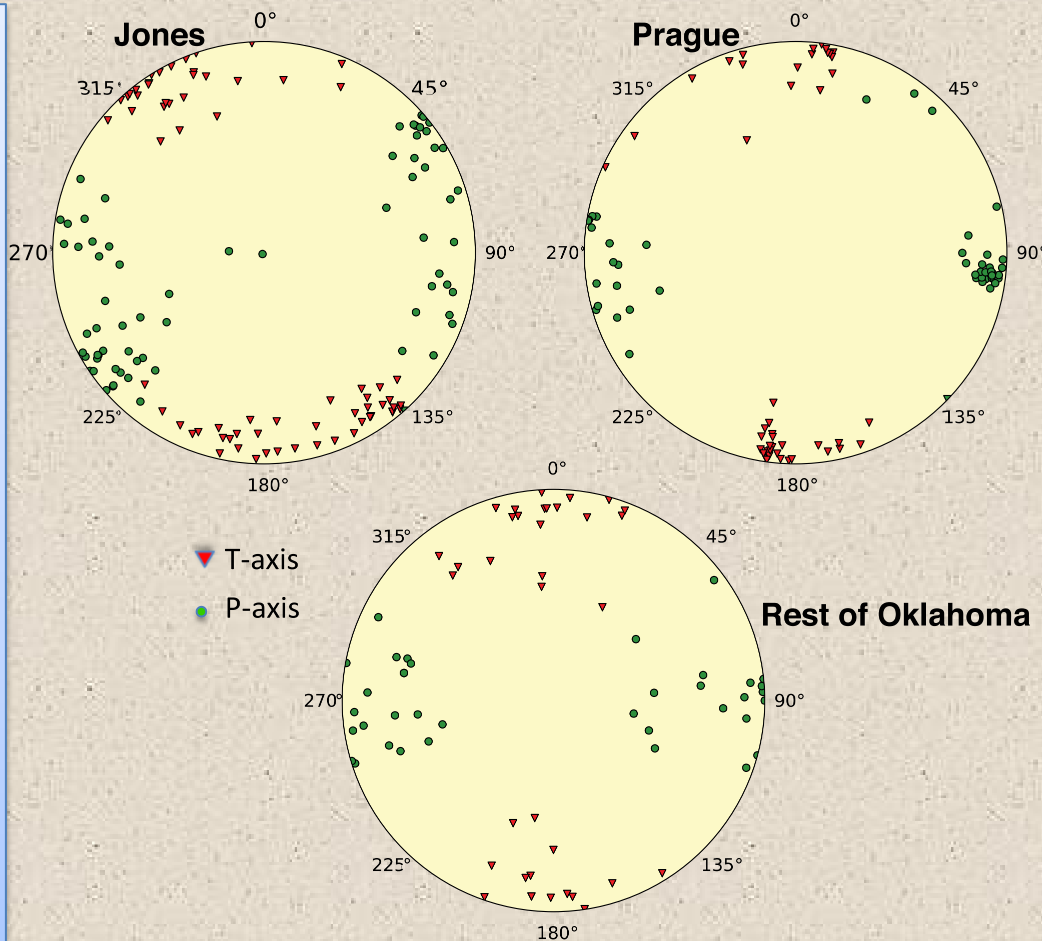
- Significant amount of hydraulic fracturing
- Large amounts of produced water to dispose of within the Arbuckle
- Arbuckle is near the basement where faults may be stressed to near failure
  - Fractures and faults in basement may be poorly if identified at all

The Regional Stress Field in Oklahoma



Avoiding Potentially Active Faults

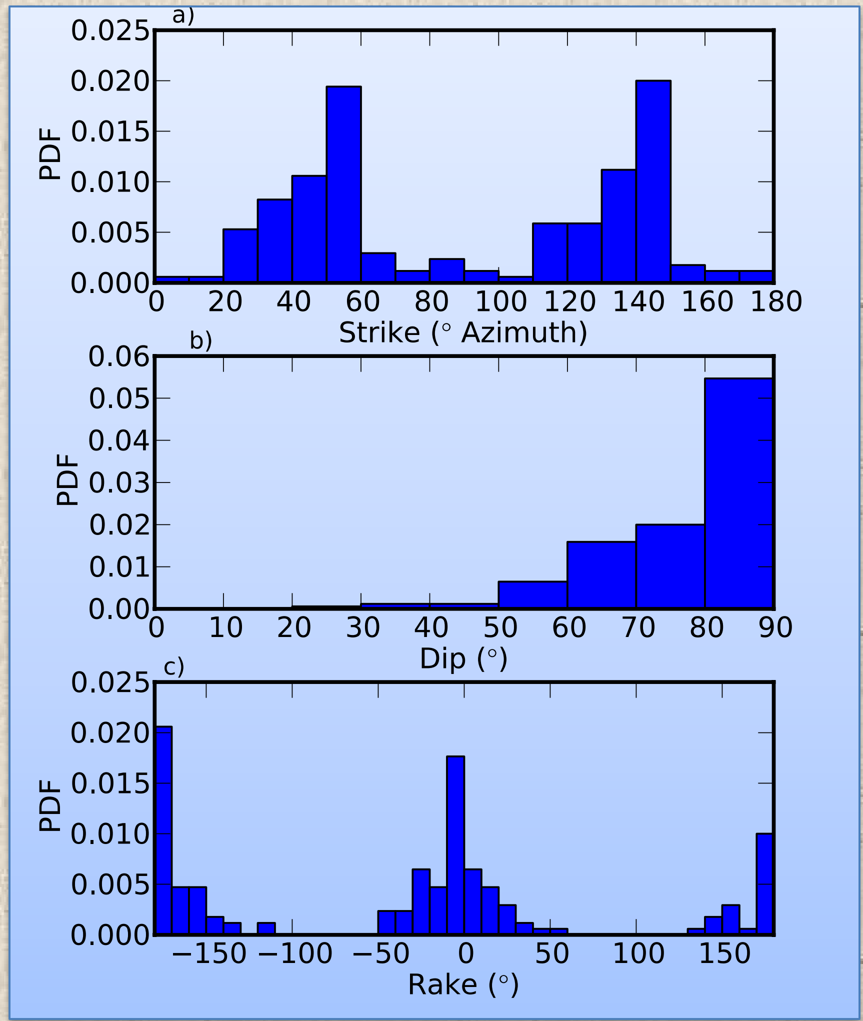
- 154 earthquake focal mechanisms
- Define the distribution of orientations for active faults in Oklahoma
- This information can be used to modify operations to avoid faults
  - oriented in a way that is more likely to have triggered earthquakes
  - or are large, which may not be completely favorable to slip, but pose a greater hazard



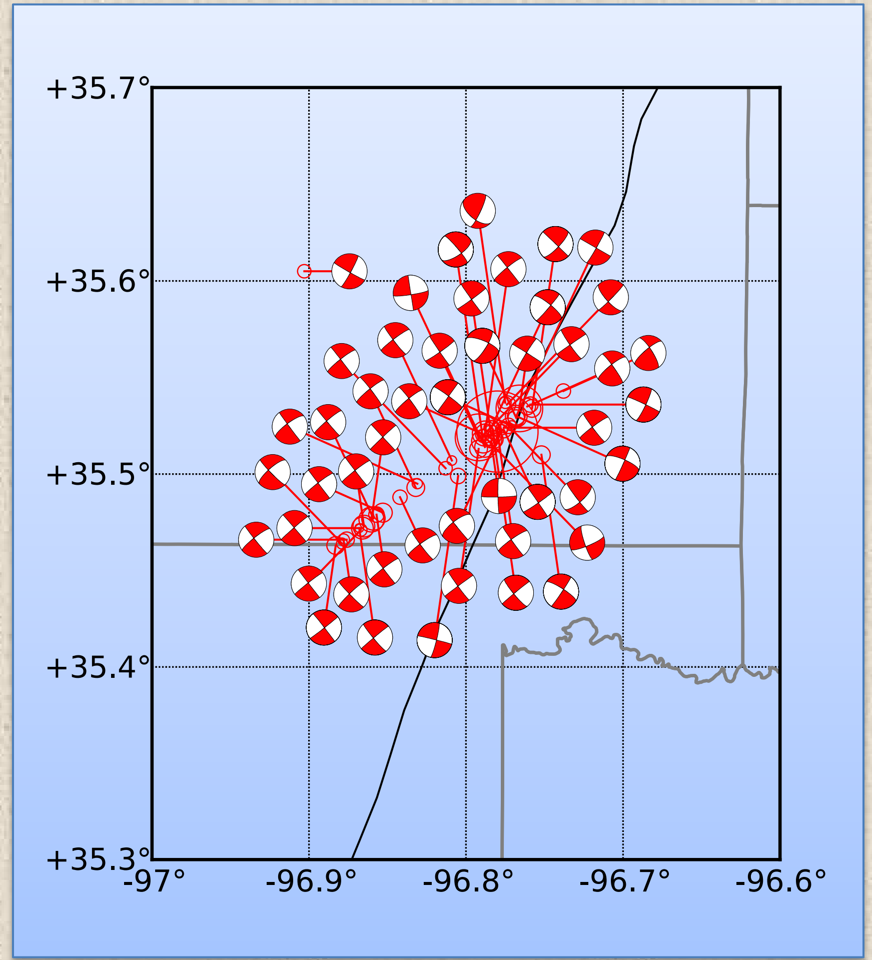
Optimal Fault Orientations in Oklahoma
(in review Seismol. Res. Lett.)

Calculate a Probability Density Function (PDF) from fault orientations

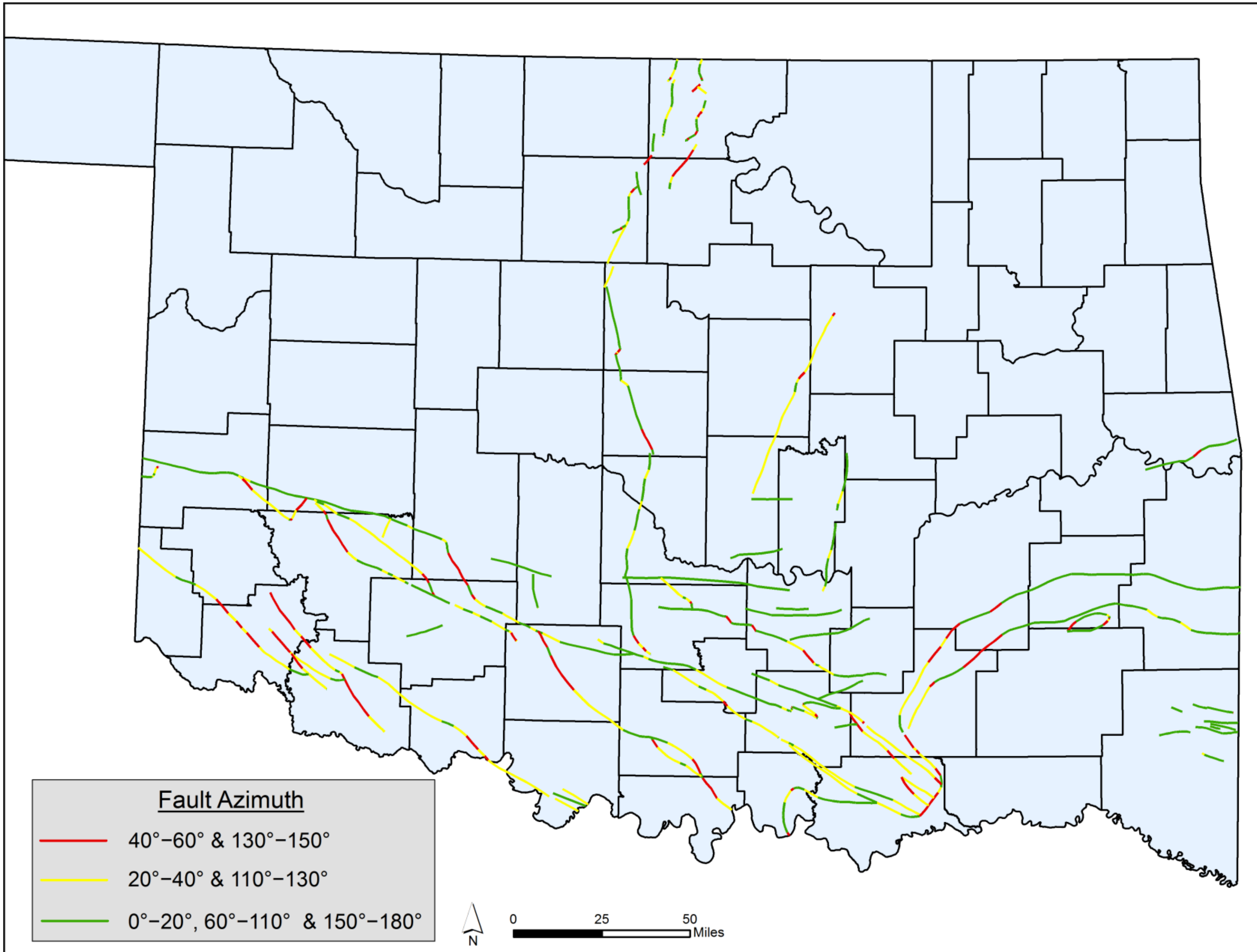
PDF for all earthquakes
Outside Jones Swarm

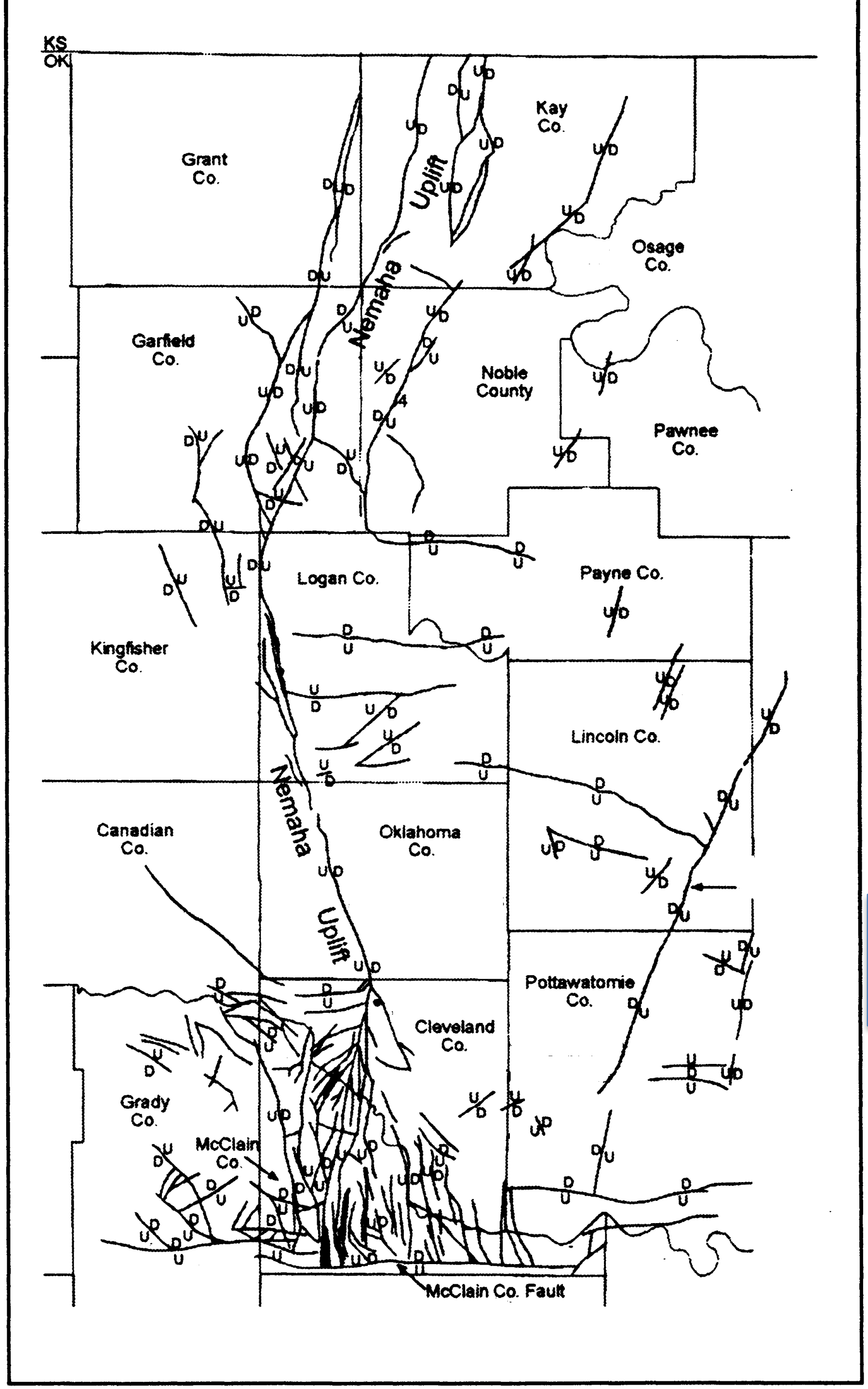


Example focal mechanisms
Prague M5.7 EQ Sequence

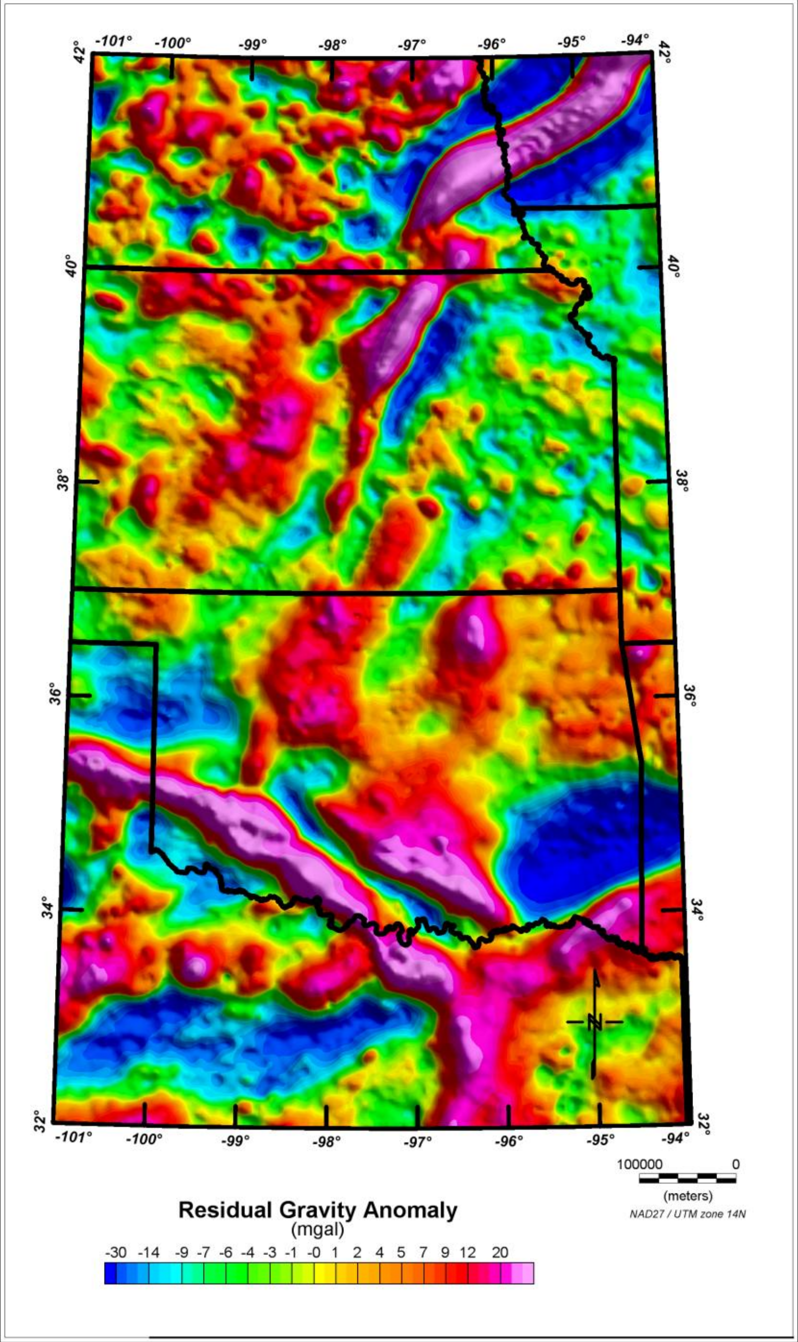


Characterizing Fault Rupture Likelihood





Parker Gay (Shale Shaker, 2003), modified from Lloyd Gatewood map



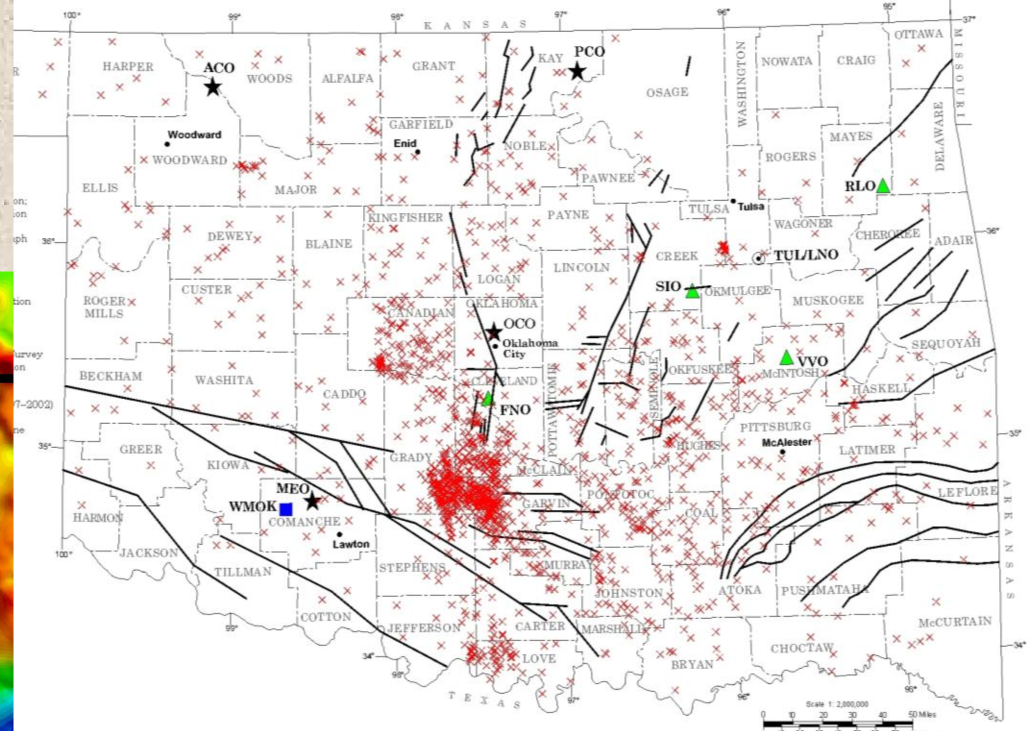
Residual Gravity Map

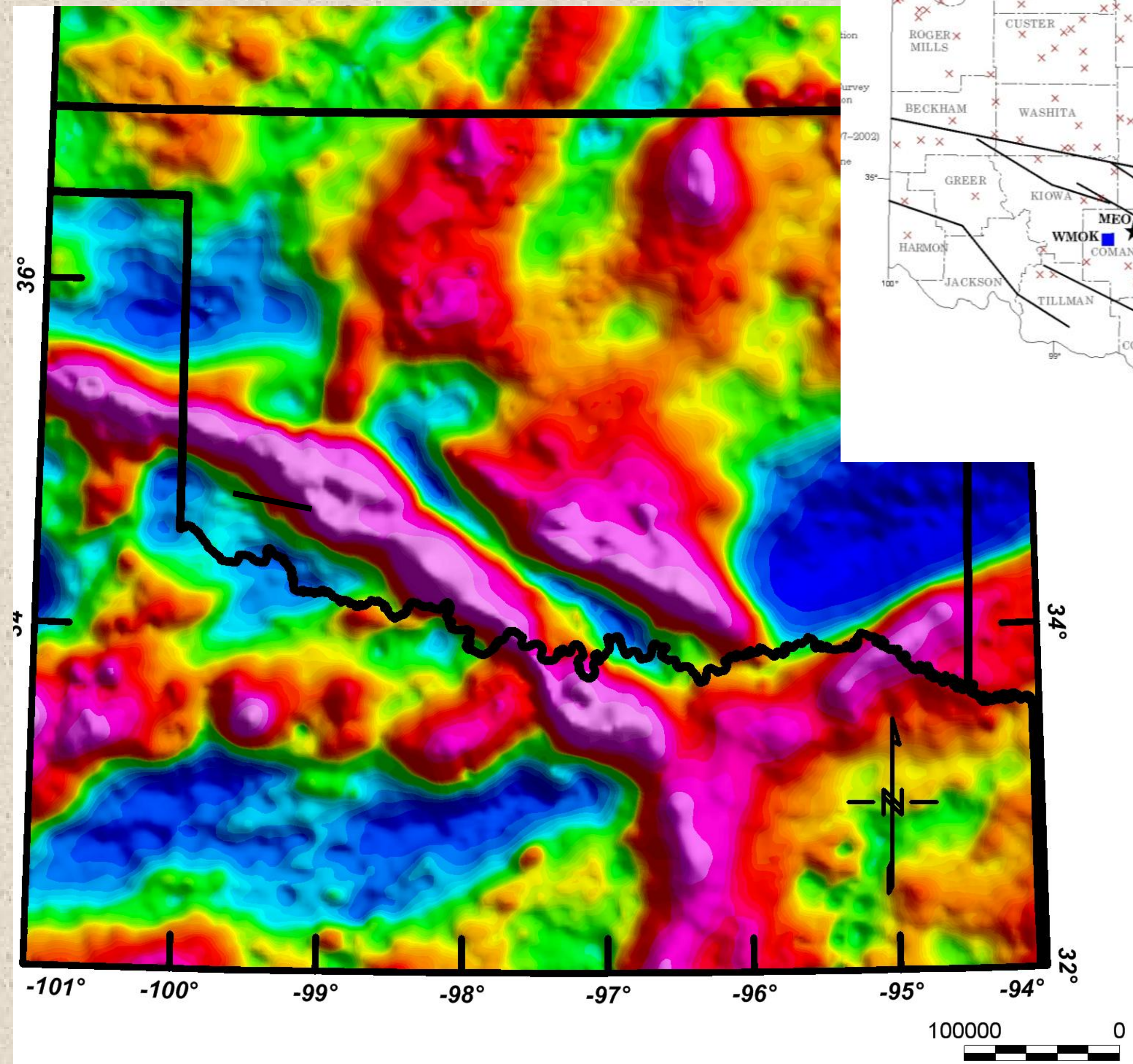
This map enhances shorter-wavelength features and clearly suggests that the Mid-Continent rift system extends across southern Kansas and northern Oklahoma.

Studies motivated by recent earthquake activity in central Oklahoma reveal N-S trending structures (Nemaha tectonic zone) that correlate with seismicity.

This map clearly suggests that the Mid-Continent rift system extends across southern Kansas and northern Oklahoma.

Some of these structures are favorably oriented to reactivated





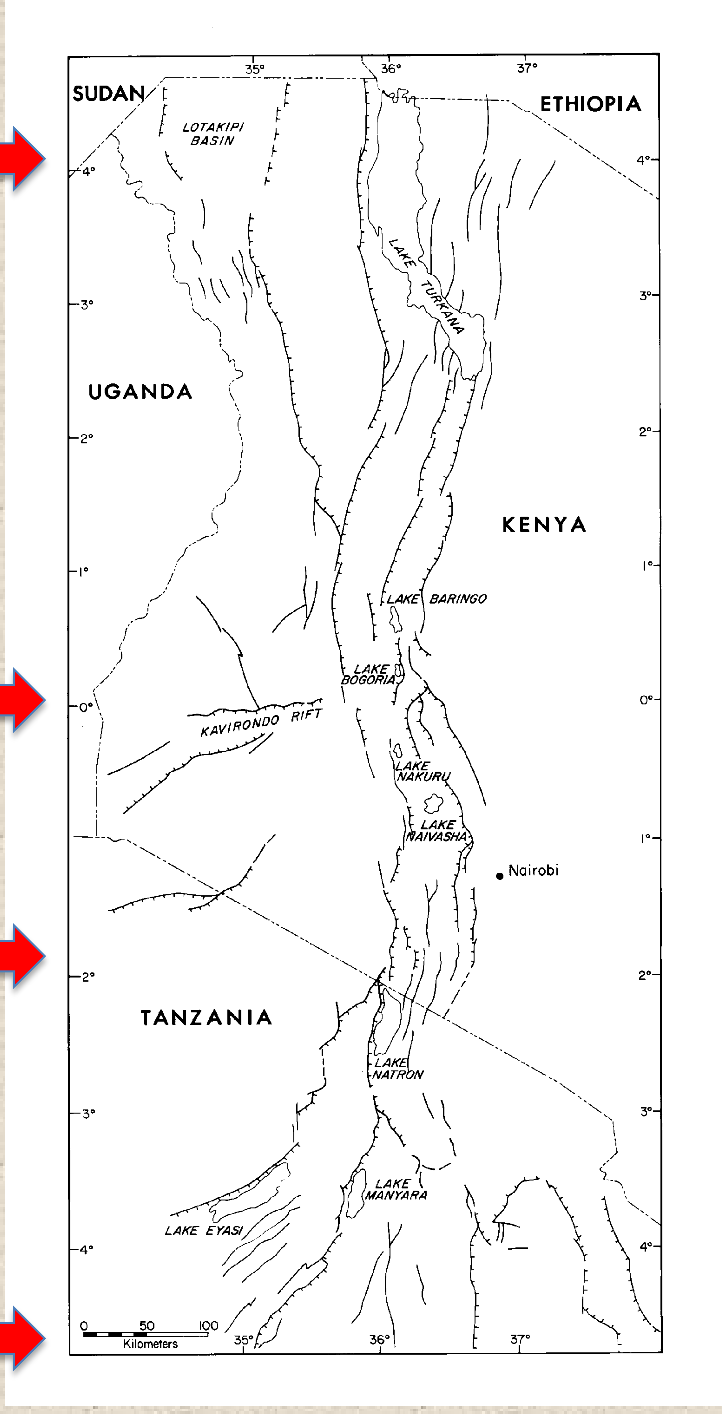
Residual Gravity Anomaly
(mgal)

Nebraska

Wichita, KS

Oklahoma City

The Texas border



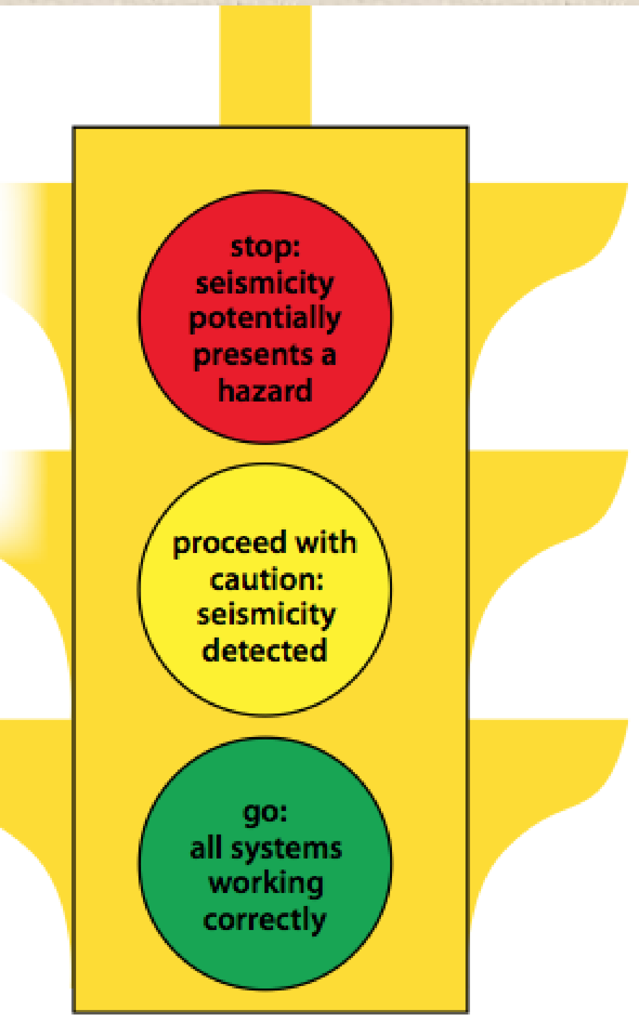
Southern Kansas and Central Oklahoma may have looked like this 1100 million years ago.

(The scale is approximately the same)

There could be many old faults lurking in the basement

Risk Mitigation Strategies

1. Avoid injection into active or potentially active faults
2. Minimize and monitor pore pressure changes at depth
3. Install local seismic monitoring arrays
4. Establish modification protocols in advance
5. Be prepared to alter plans or abandon wells



Zoback (2012) Earth AGI

OGS Seismic Station Sponsorship

- Provides a way to transparently address the possibility of induced seismicity
- Removes duplication between operators
- Can be tailored to meet individual operators requirements
- Rapid reporting for operational feedback for participants
- Cost effective
- Improves products like
  - optimal fault orientations
  - Earthquake locations
- Equipment donations are tax deductible