Best Practices for Subsurface Injection of Fluids and Induced Seismicity*

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Abstract

Oklahoma experienced an average of 1.6 earthquakes of Magnitude 3 or greater (M3.0+) from the 1980s through 2008. Since that time, seismicity has increased to 907 M3.0+ earthquakes in 2015. More than 95% of these earthquakes occur over only ~17% of the area of Oklahoma. This pattern is generally attributed to increased injection of saline formation water co-produced along with oil and gas into the under pressured and relatively permeable Arbuckle Group, which lies directly on top of Precambrian crystalline basement (for example, Walsh and Zoback, 2015). Pressure communication from the Arbuckle to faults in the basement is interpreted to have reduced effective normal stress on the faults. This stress reduction allows faults aligned favorably with respect to the stress field in Oklahoma (SHMax = N 85° E) to move. The rise in seismicity began in about 2009, with 20 M3.0+ earthquakes, rose to 41 in 2010 and to 67 in 2011 (including the M5.7 Prague earthquake). The number dropped to 35 in 2012, then rose to 109 in 2013, to 579 in 2014, and to 907 in 2015. Oil price drops in 2014 and 2015 appear to have lead to a decrease in injection of co-produced formation water, beginning in late 2014. This in turn led to a decrease in earthquake frequency in 2016, with 508 M3.0+ earthquakes as of September 2016 (suggesting a year-end value at or below 650). In the meantime, actions by the Oklahoma Corporation Commission have called for cuts in injection equal to most of the reductions initially driven by economic forces. On the other hand, in 2016, two M5.0+ earthquakes (Galena Township M5.1; Pawnee M5.8 – the largest quake in Oklahoma history) have shaken the state. These two ensure that seismic energy released in Oklahoma will be larger in 2016 than in any other year on record. This paper will discuss the evolution of this seismicity, the regulatory actions taken to reduce seismicity by reducing deep injection, and the importance of declining oil price in reducing injected volumes in advance of full implementation of these regulatory directives. It will also discuss regional variations within the earthquake area, and some aspects of frequency-magnitude relationships in the earthquake catalog.

Selected References

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Yeck, W.L., A.F. Sheehan, H.M. Benz, M. Weingarten, and J. Nakai, 2015, Rapid Response, Monitoring, and Mitigation of Induced Seismicity near Greeley, Colorado: Seismological Research Letters, v. 87/4, p. 1-11.

Best Practices for Subsurface Injection of Fluids and Induced Seismicity

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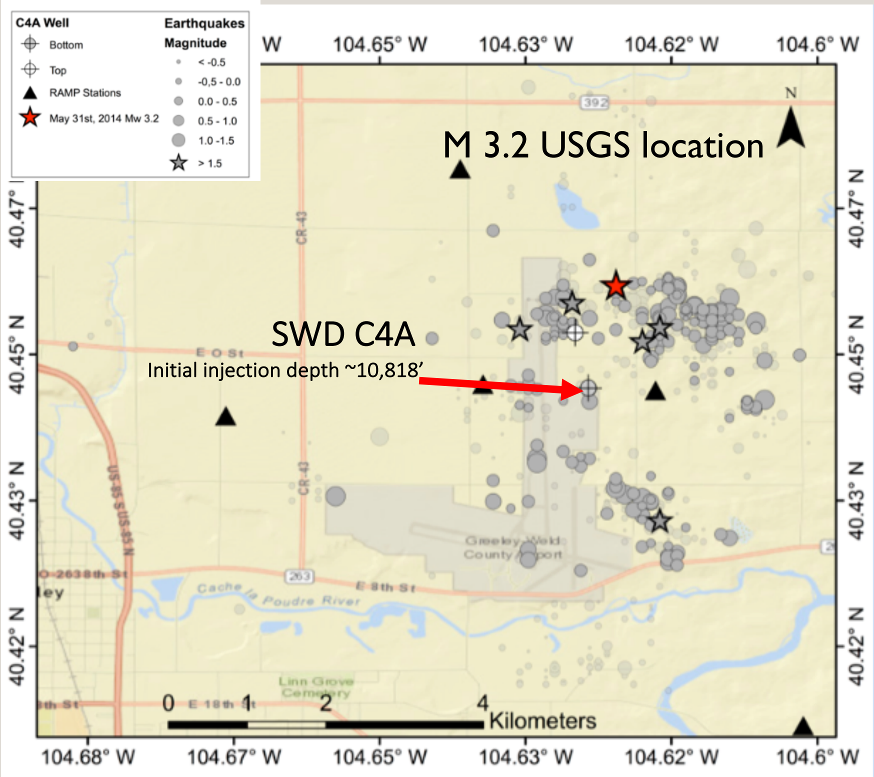
AAPG Centennial Convention and Exhibition

Houston TX

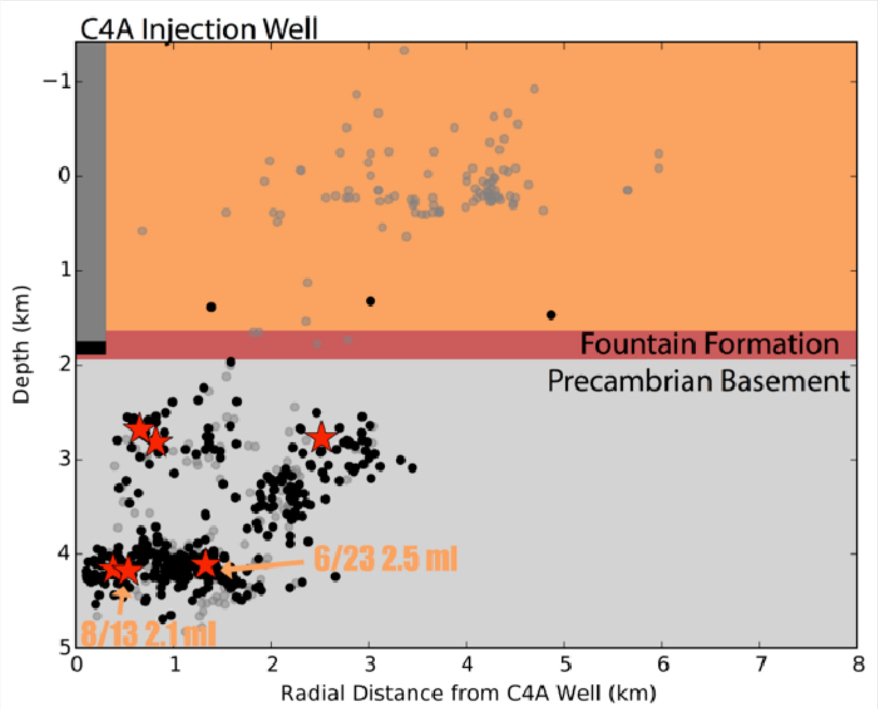
Outline

- Where Have We Been; Where are We Now?
  - Injection Induced Seismicity – Local and Regional
  - Seismicity Assciated with Hydraulic Fracturing
  - Alternatives to Disposal of Produced Water
- Where Do We Need to Go; What are the Best Practices?
  - Avoidance and Mitigation through Characterization
  - Remediation?

Injection Induced Earthquakes: Greeley, Colorado

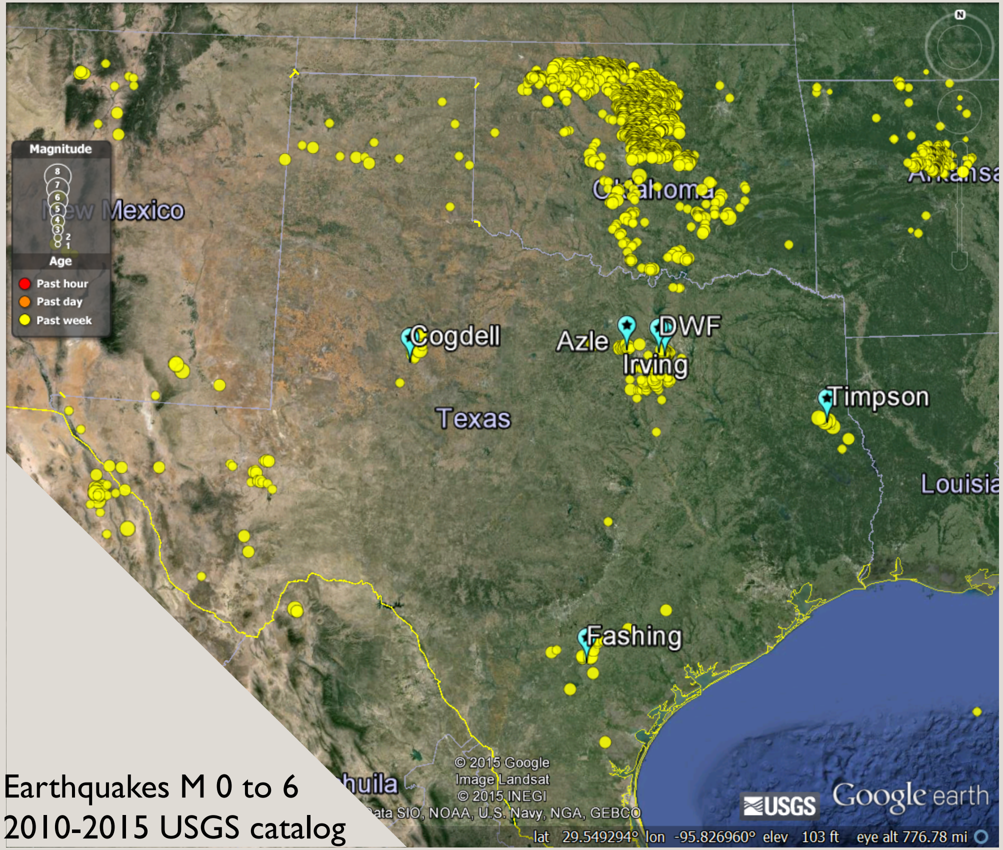


May 31, 2014 (MDT) Magnitude 3.2



Yeck, Sheehan, et al., 2015?, Courtesy Anne Sheehan, UC Boulder

Possible induced earthquakes in Texas

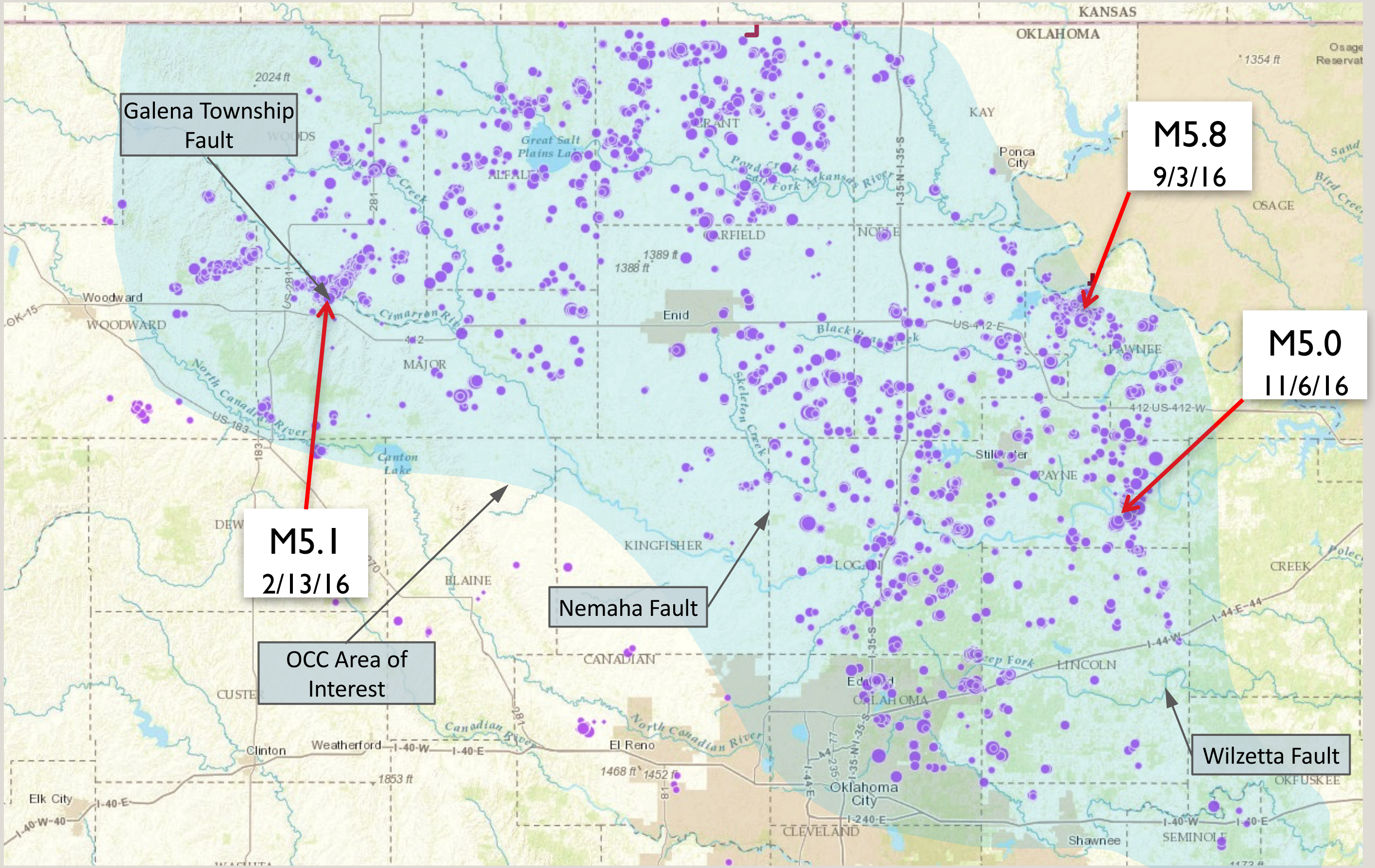


Earthquakes M 0 to 6
2010-2015 USGS catalog

- Dallas – Ft Worth (DFW)
- Fashing
- Cogdell
- Azle
- Timpson
- Irving

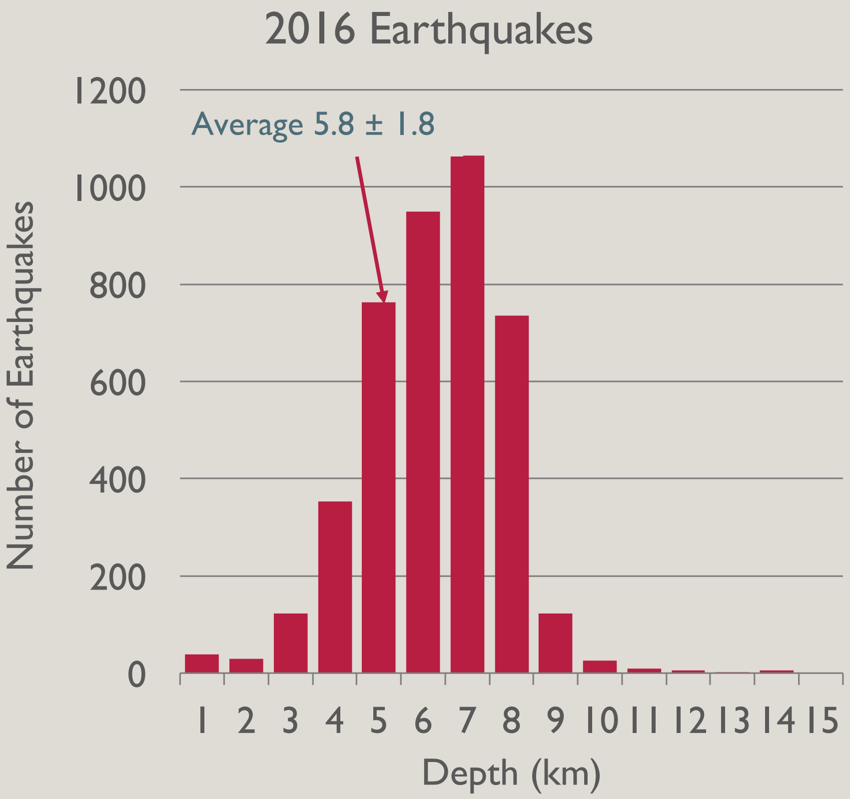
- Texas Railroad Commission hires first Texas State Seismologist
- RRC updates rules for disposal wells:
  - Operators must search USGS earth-quake database 100 miles around injection well.
  - Commission may require monitoring
  - Commission may set injection pressure and rate limits, temporarily shut down well, or revoke permit.

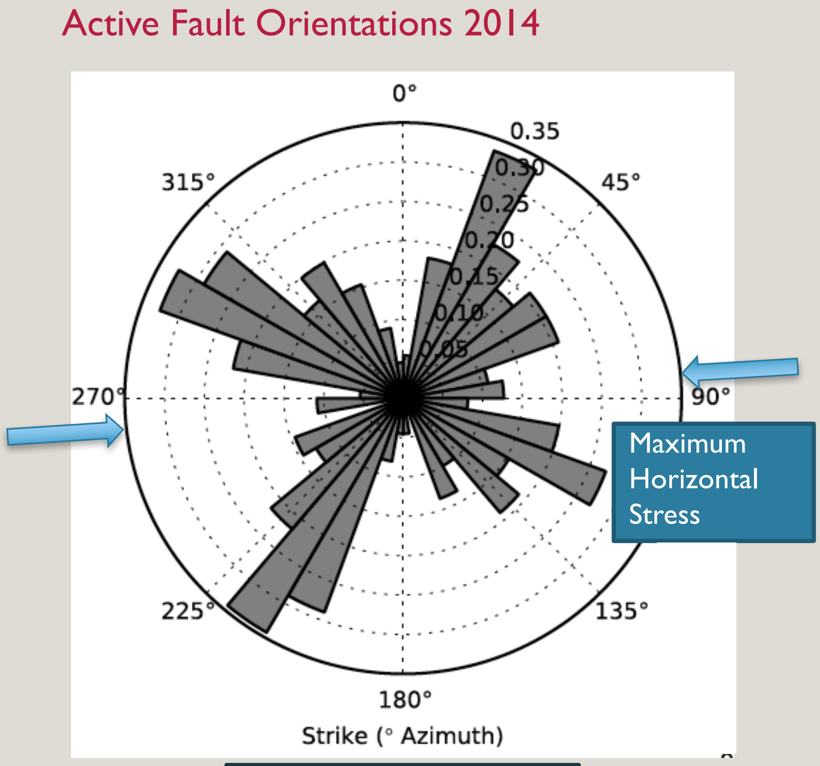
5. Oklahoma Earthquakes, 2016



Earthquake map available at OGS website: http://uok.maps.arcgis.com/apps/Minimalist/index.html?appid=3ebaf2b8de02406b94804cbdb5afbec8

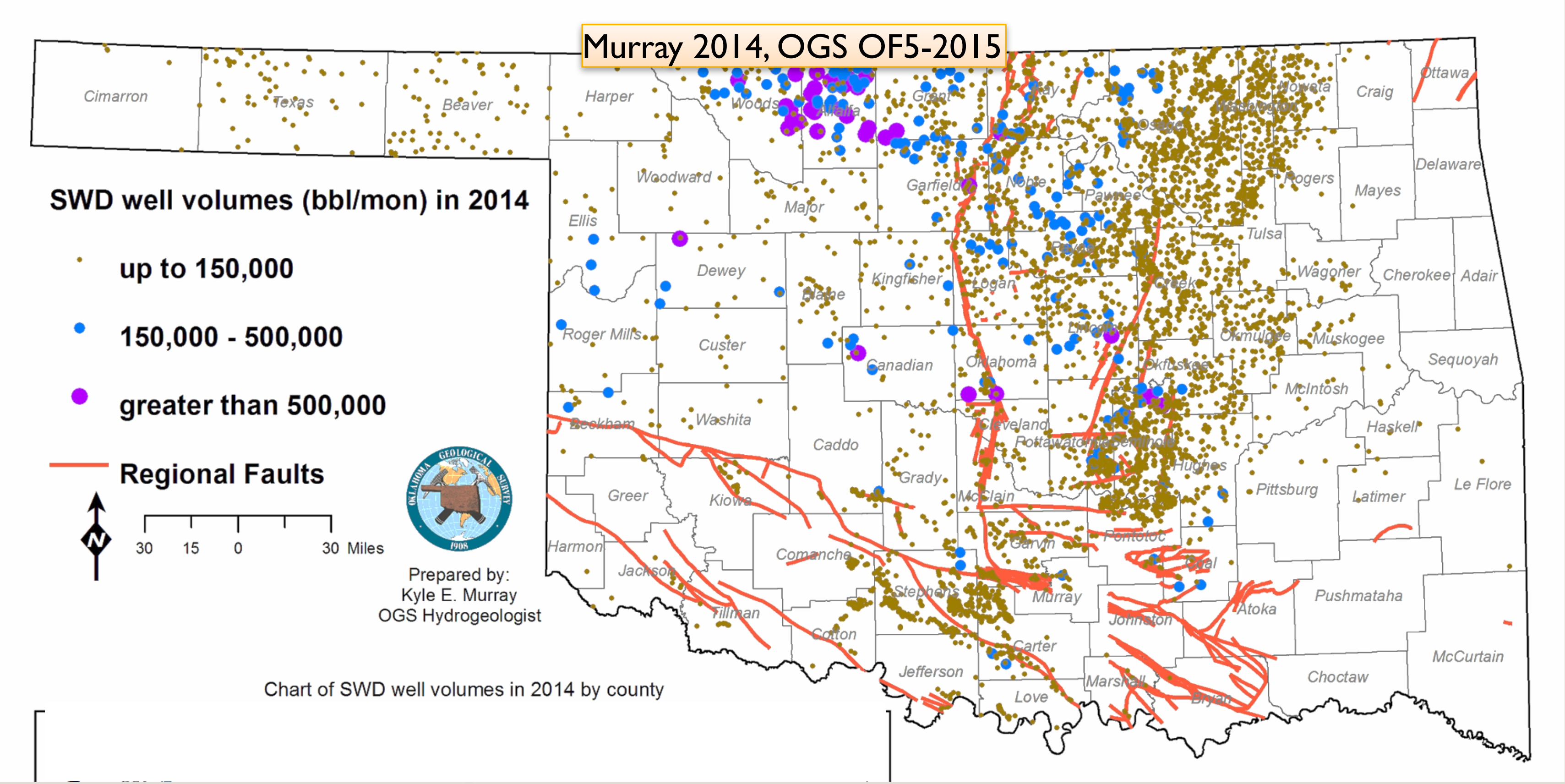
Earthquakes commonly occur in basement, favoring optimally aligned faults



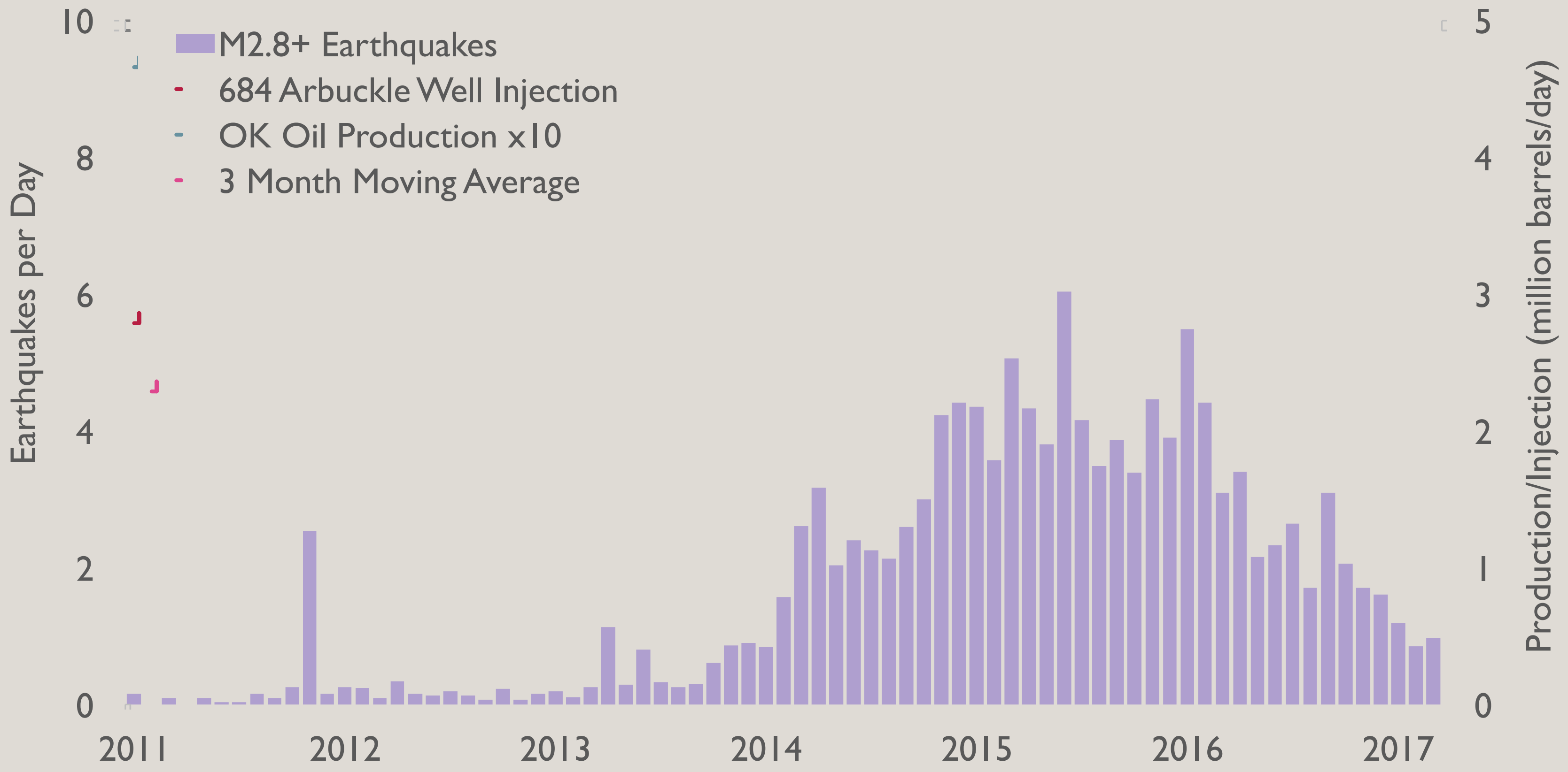


OGS OF1-2015

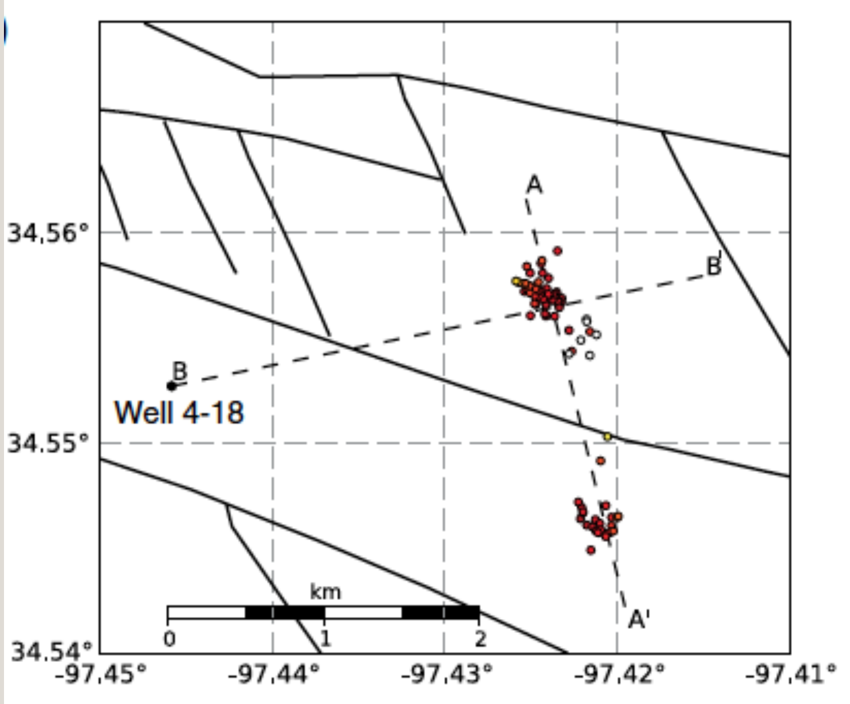
7 Earthquakes occur in vicinity of large volume Salt Water Disposal (SWD) wells

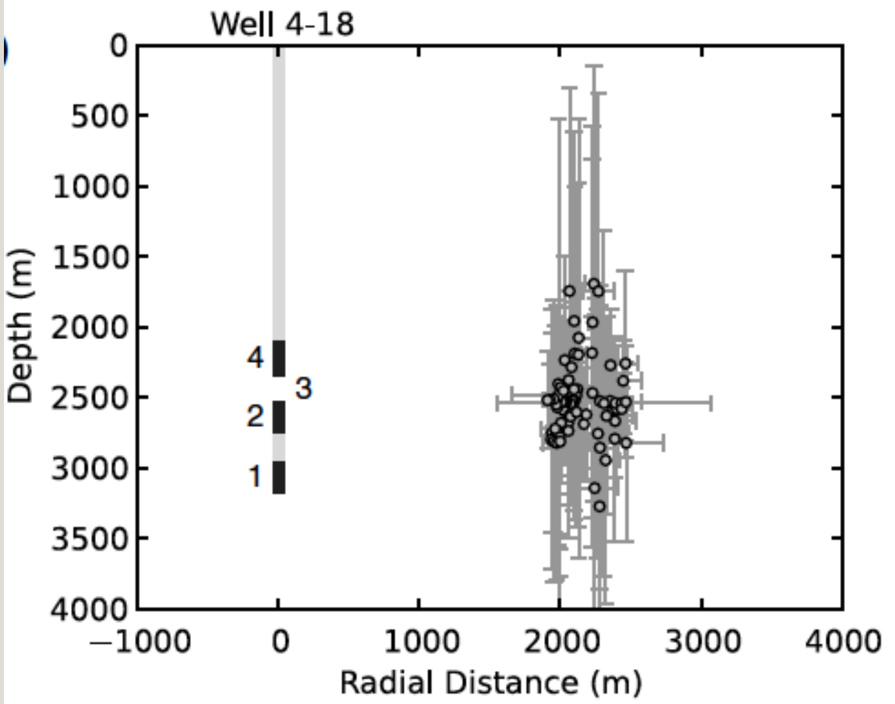


8 Earthquakes, Oil and Water



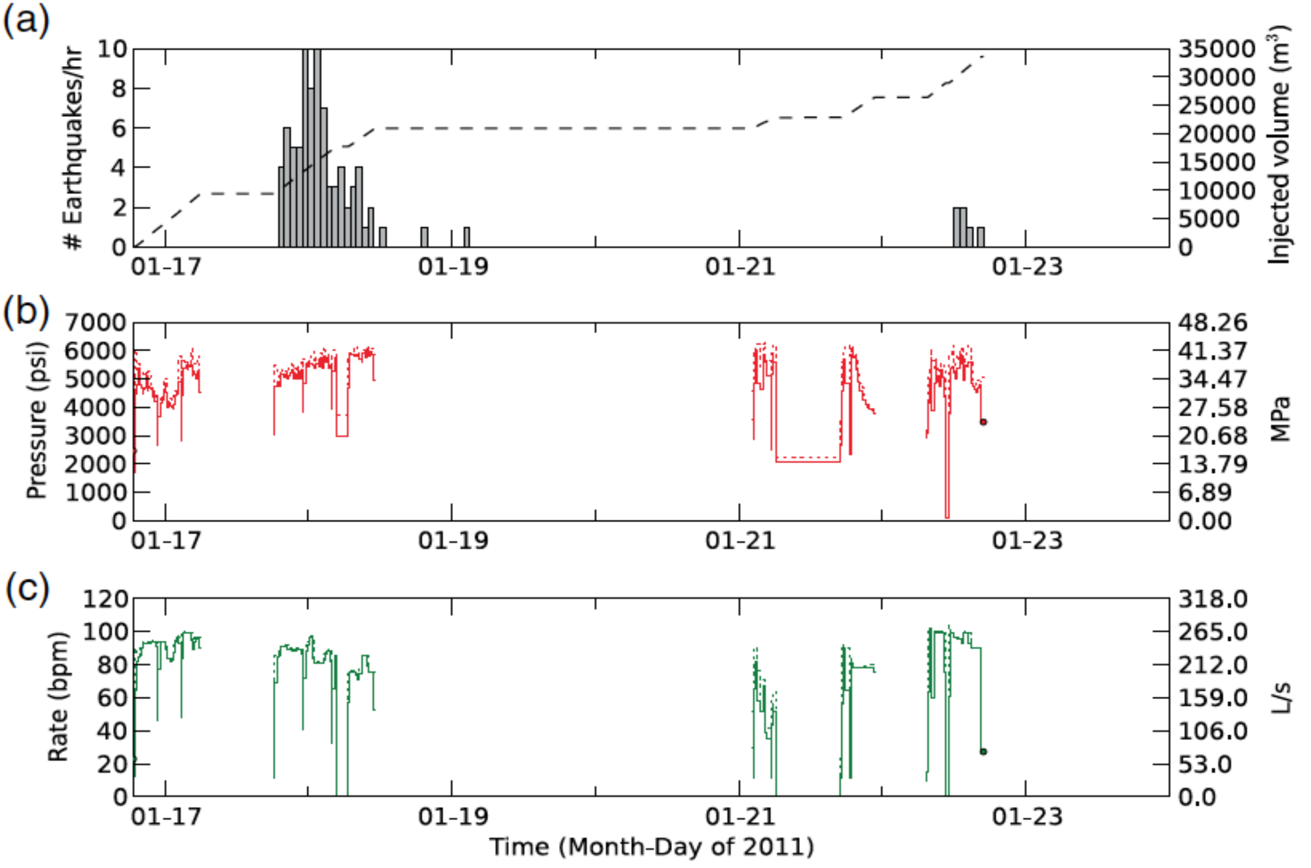
Earthquakes in proximity to hydraulic fracturing





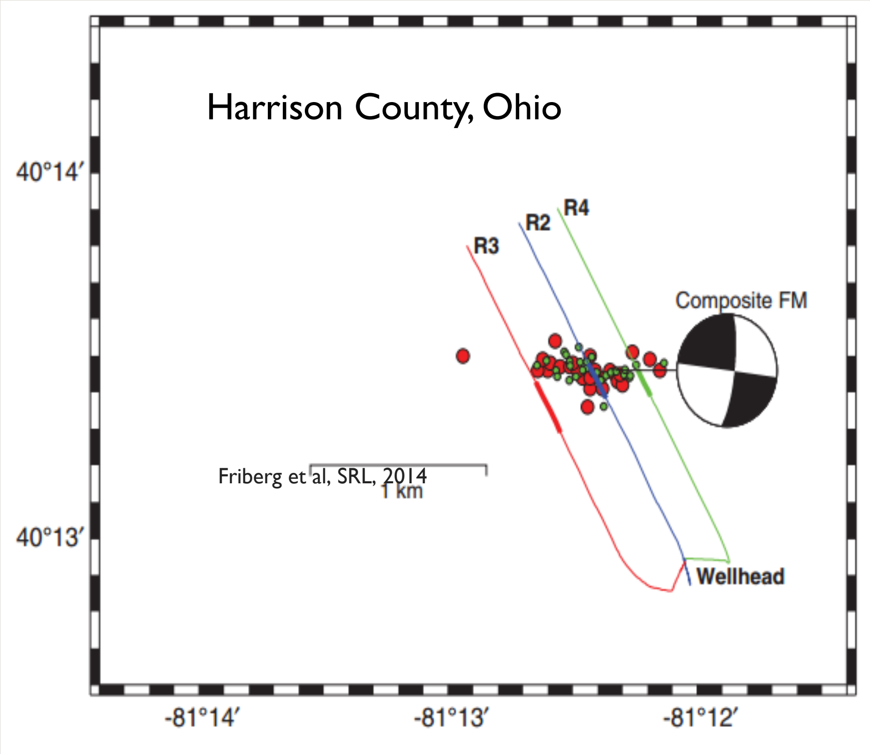
Holland, A.A., Bulletin of the Seismological Society of America, Vol. 103, No. 3, pp. 1784–1792, June 2013, doi: 10.1785/0120120109

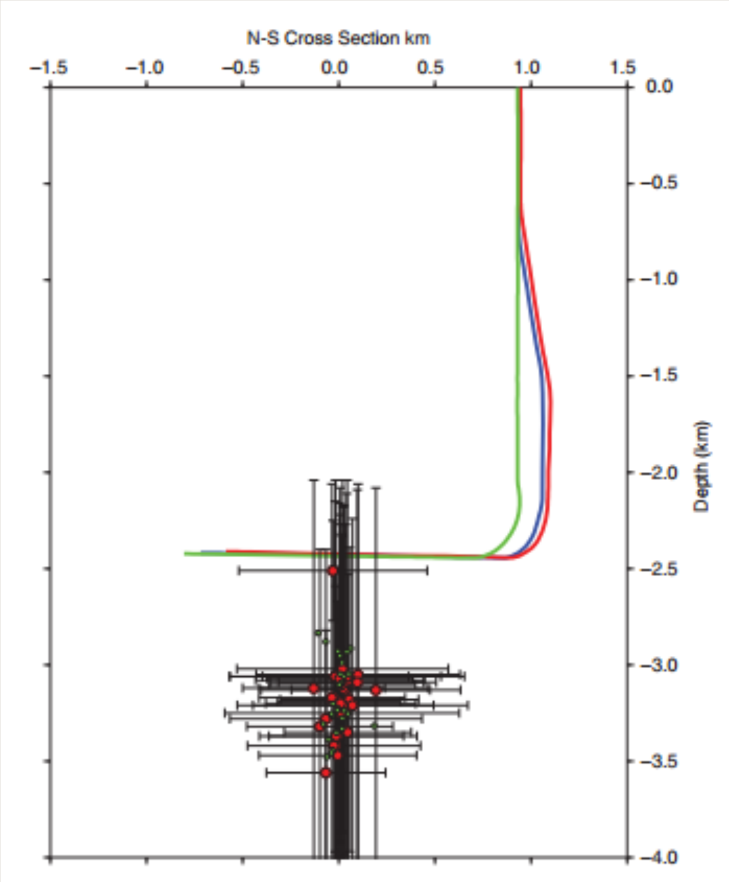
10 Earthquakes start & stop with fracturing stages



Holland, A. A. Bulletin of the Seismological Society of America, Vol. 103, No. 3, pp. 1784–1792, June 2013, doi: 10.1785/0120120109

Ohio earthquakes near **stimulation** operations (Utica Shale)





Earthquake activity occurred on pre-existing fault in basement below the fracturing interval.

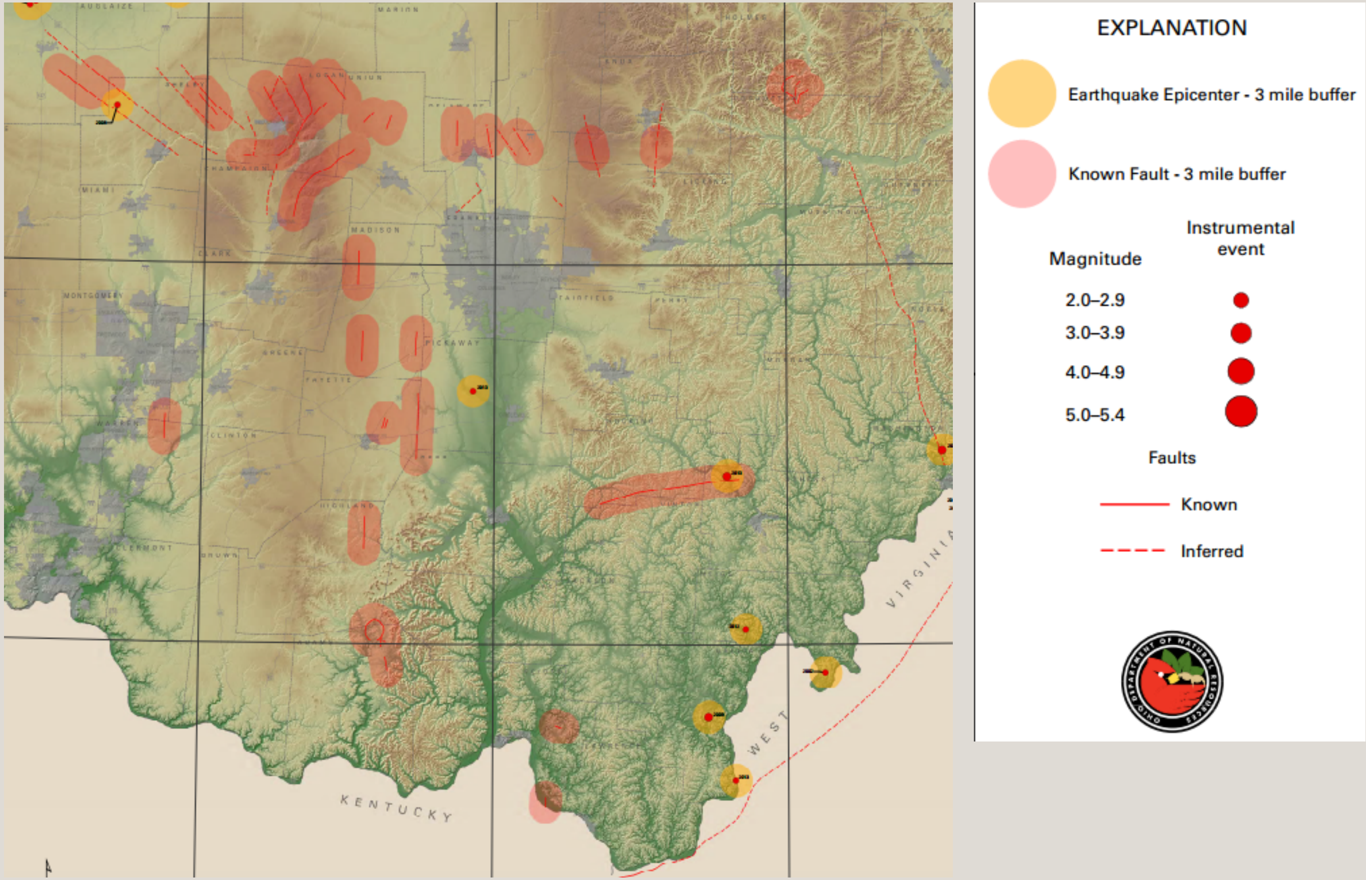
OK well completion seismicity guidance

- Action following anomalous seismic activity ≤2 km from completion operations
- Stoplight system, if Oklahoma Geological Survey magnitude ≥2.5; ≥3.0M; ≥3.5M
- Escalating review of operator's internal mitigation procedures by Oil & Gas Conservation Division of Oklahoma Corporation Commission
- Operations may resume if seismicity stops and mitigation approach considered adequate

Ohio permitting changes related to hydraulic fracturing

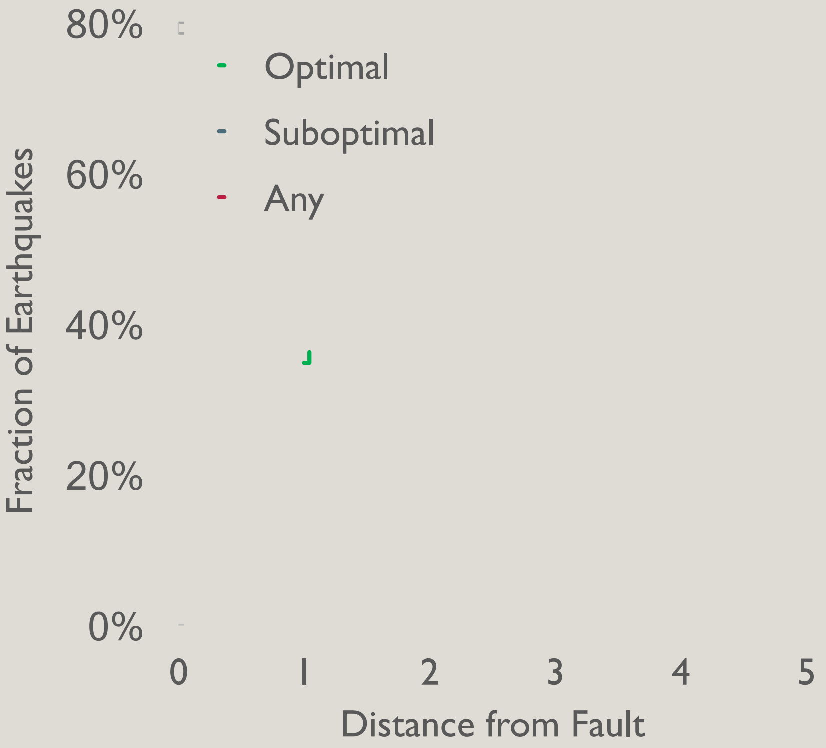
- Horizontal drilling <3 miles from known fault or area of seismic activity M2.0+ require companies to install seismic monitors.
  - If seismic event M1.0+, activities pause while cause is investigated.
  - If investigation reveals probable connection to hydraulic fracturing process, all well completion operations will be suspended.
- Ohio Oil and Gas Association (OOGA) established Induced Seismicity Workgroup to recommend possible alternative permit conditions based on ground motion similar to Ohio mining regulations.

ODNR map of buffer zones for hydraulic fracturing operations



http://oilandgas.ohiodnr.gov/portals/oilgas/pdf/seismicity/RECENT_EARTHQUAKE_EPICENTERS_IN_OHIO.pdf

Location of OK earthquakes and known faults



- 80% of earthquakes within 5 km of a known fault
- But only 34% of earthquakes within 2 km of any known fault
- 36% of earthquakes within 5 km of an optimally oriented fault
- 12% of earthquakes are within 2 km of an optimally oriented fault

Oklahoma Governor's Produced Water Task Force

Oklahoma Water for 2060
Produced Water Reuse and Recycling

ISSUED FOR COMMENT

Prepared for

WATER FOR 2060

State of Oklahoma OWRB Water Resources Board the water agency

March 2, 2017

ch2m

401 S. Boston Avenue Suite 330
Tulsa, OK 74103-4425

- Matched large producing counties to nearby use options
- Compared costs of typical disposal operations to:
  - Oil & Gas industry re-use (w/ possible intercounty transport)
  - Evaporation (w/ low- or high-salinity produced water)
  - Desalination for surface discharge, power plant, orindustrial uses
- Average costs per barrel of water ranged from \$0.47-\$4.58 with wide uncertainty in estimates
  - Industry re-use - \$0.47-\$0.69
  - Desalination - \$1.76-\$4.58
  - Evaporation - \$1.66-\$1.79

Recommendations of Produced Water Task Force

1. Reduce challenges to water re-use through targeted regulations and legislation:
   - Remove legal ambiguity about ownership of produced water
   - Establish bonding requirements for water impoundments without being an impediment
   - Make right-of-way for pipelines for recycled/re-used water easier to obtain
   - Request delegation from the U.S. EPA to Oklahoma for discharge permits
2. Facilitate re-use of produced water in oil and gas operations
3. Study feasibility of transferring Mississippi Lime produced water to STACK play.
4. Continue evaluation of evaporation as an alternative to injection.
5. Consider all environmental and stakeholder impacts, and data gaps before implementing long-term projects.

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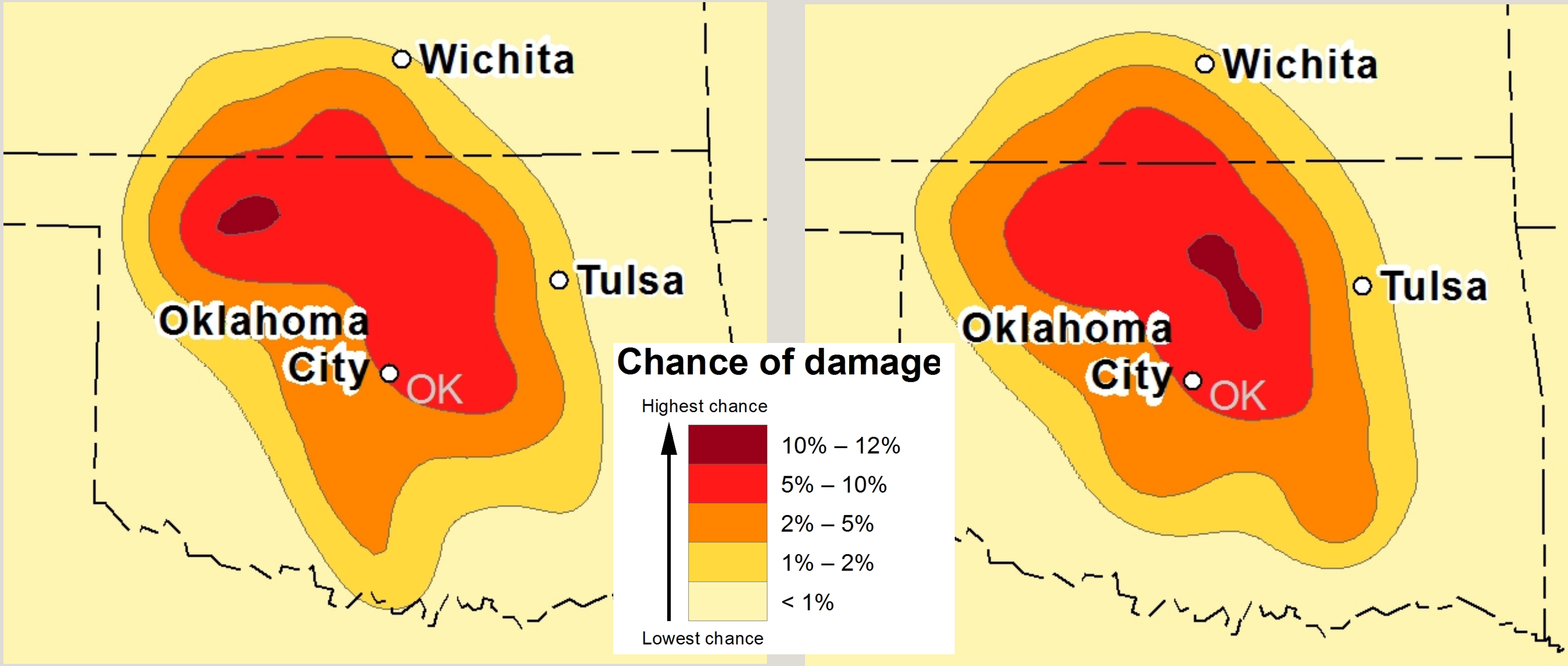
Where Do We Need to Go?

- Improved seismic monitoring – regional and local; greater completeness
- Sophisticated data management for injection and seismicity
- Research into patterns and mechanisms of induced seismicity
- Better characterization of basement geologic structure
- Improved geomechanical/hydrologic modeling incorporating fracture networks
- Enhanced treatment and utilization of produced water

Backup Slides

USGS One-Year Hazard Forecast

2016 | 2017



Human Activity Can Induce Earthquakes

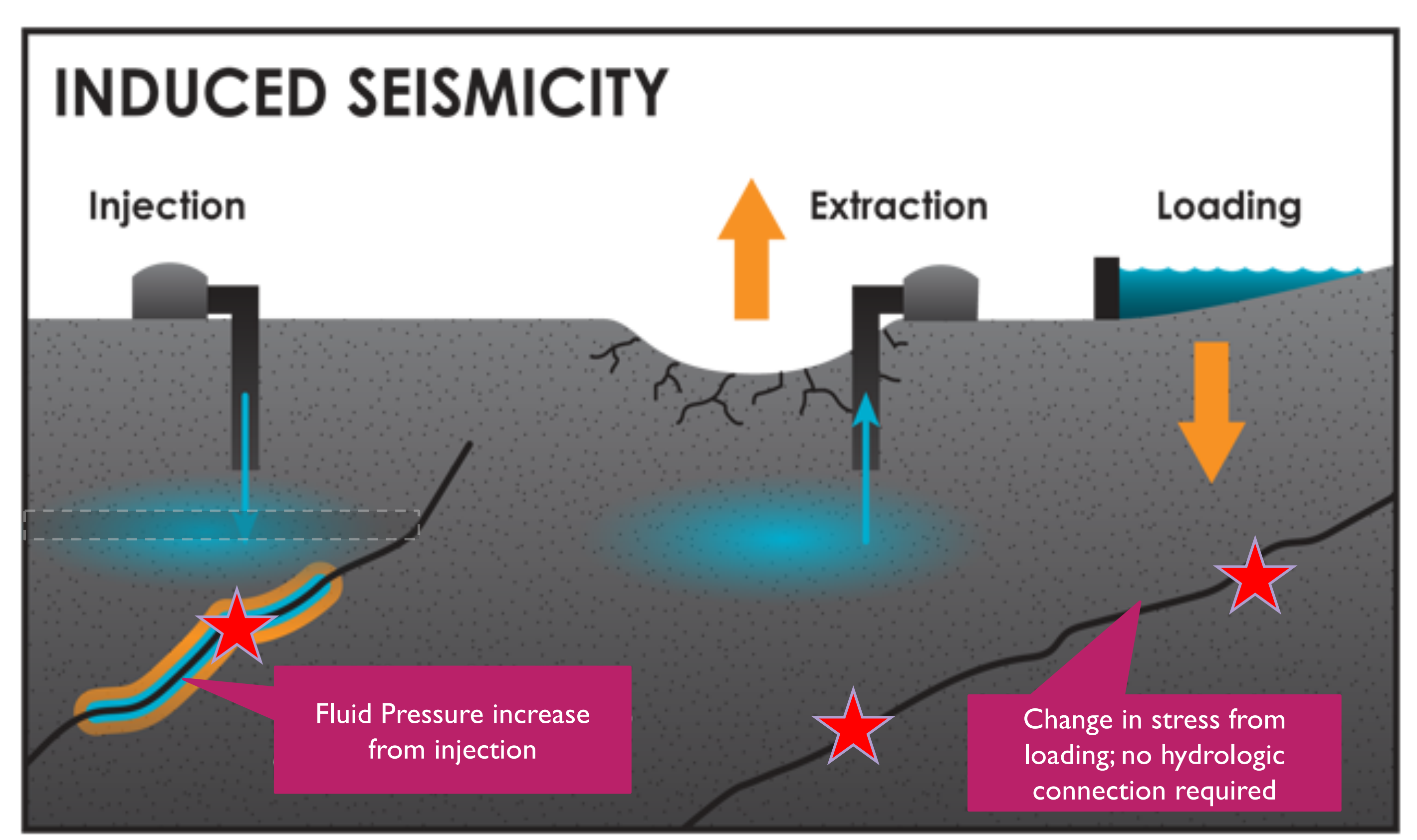
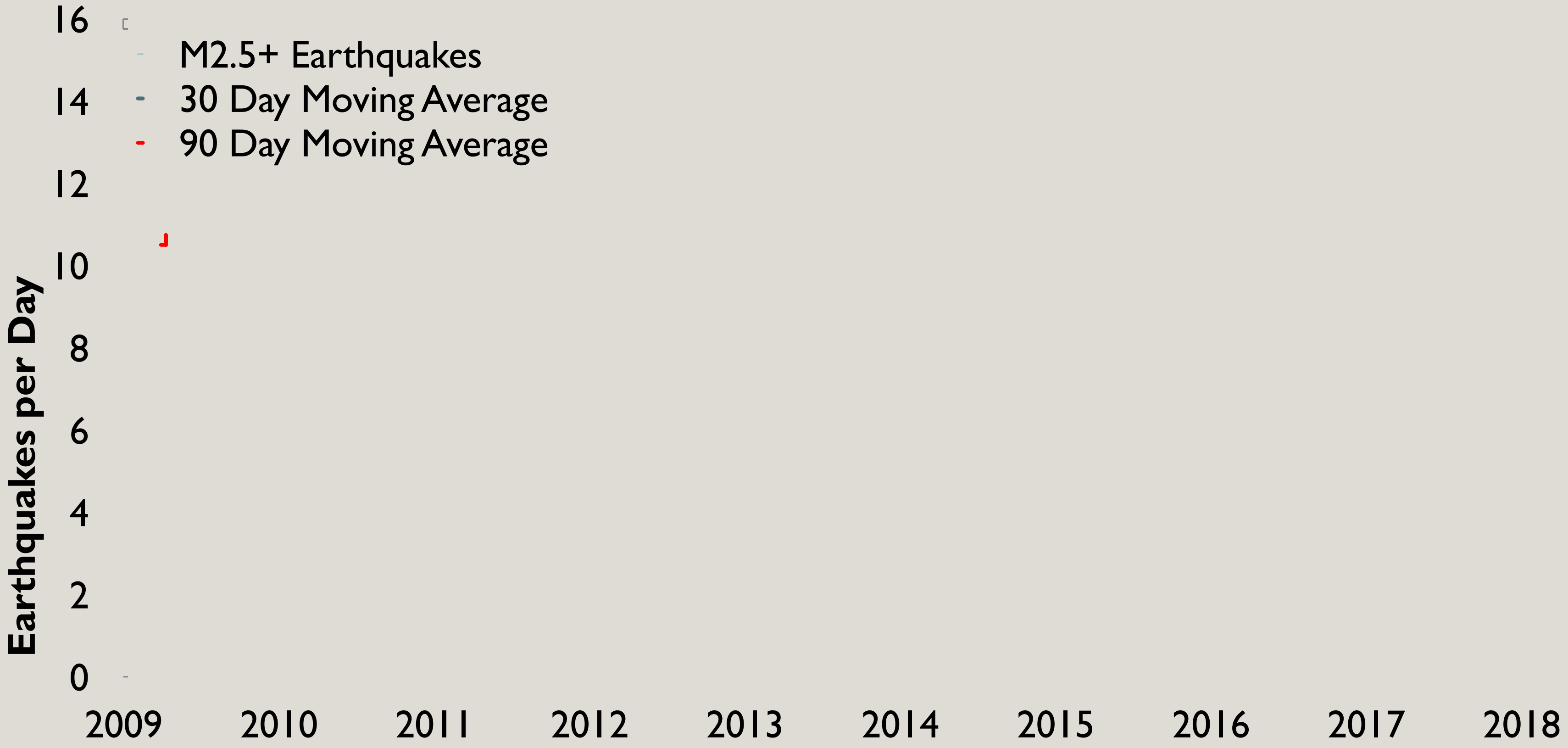
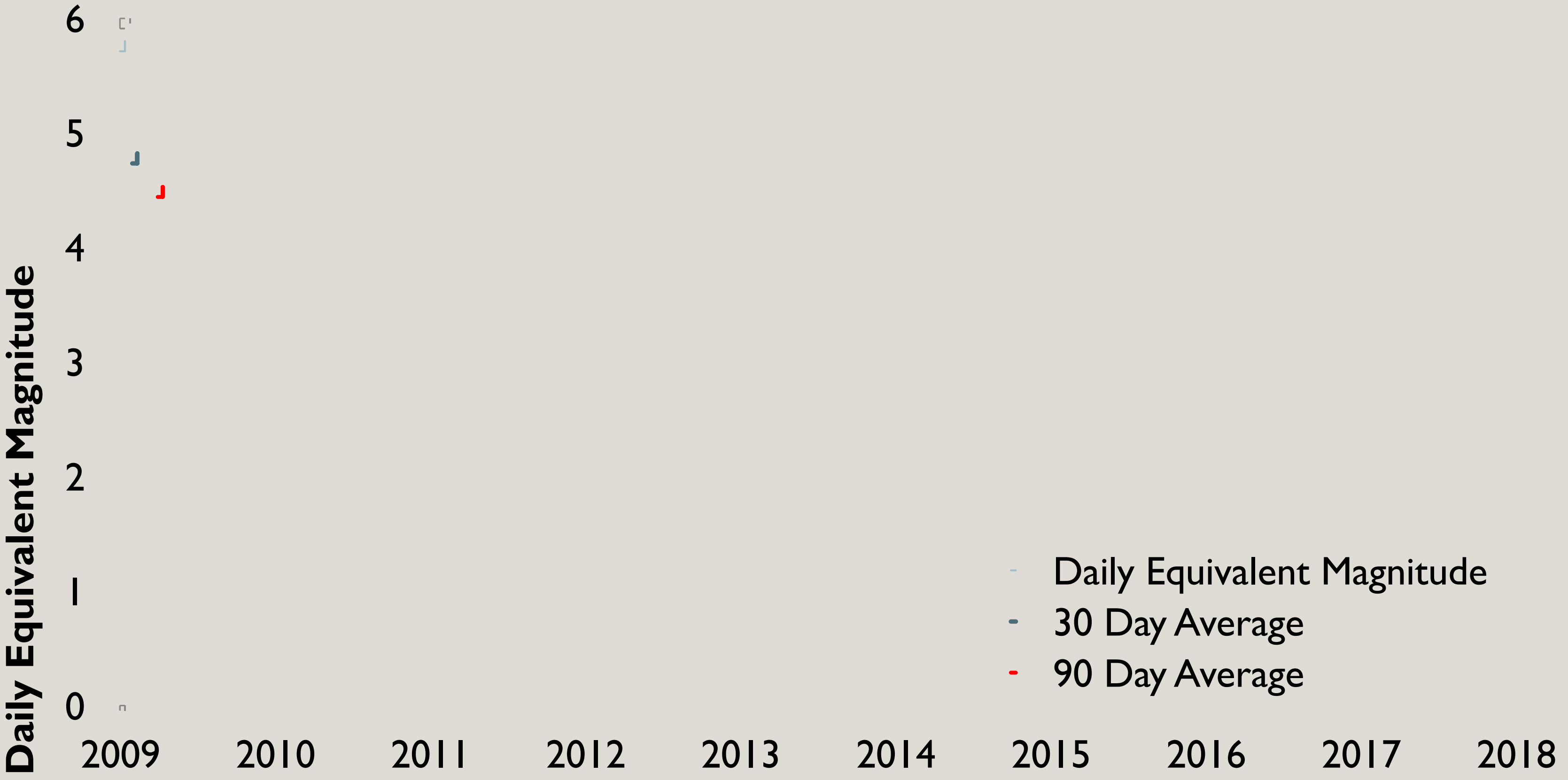


Figure modified from: http://www.earthmagazine.org/article/ground-shaking-research-how-humans-trigger-earthquakes

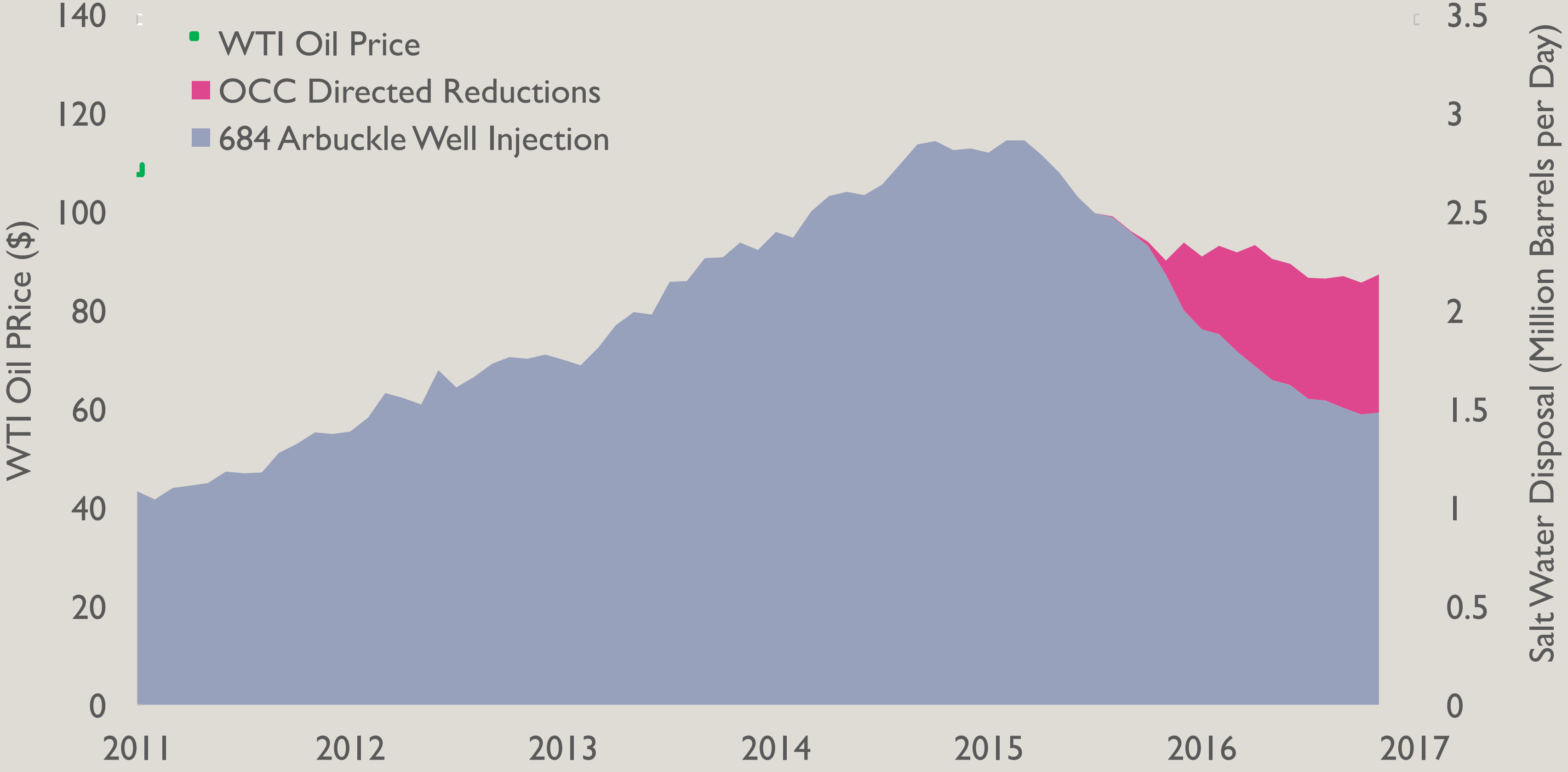
Oklahoma M2.5+ Earthquakes



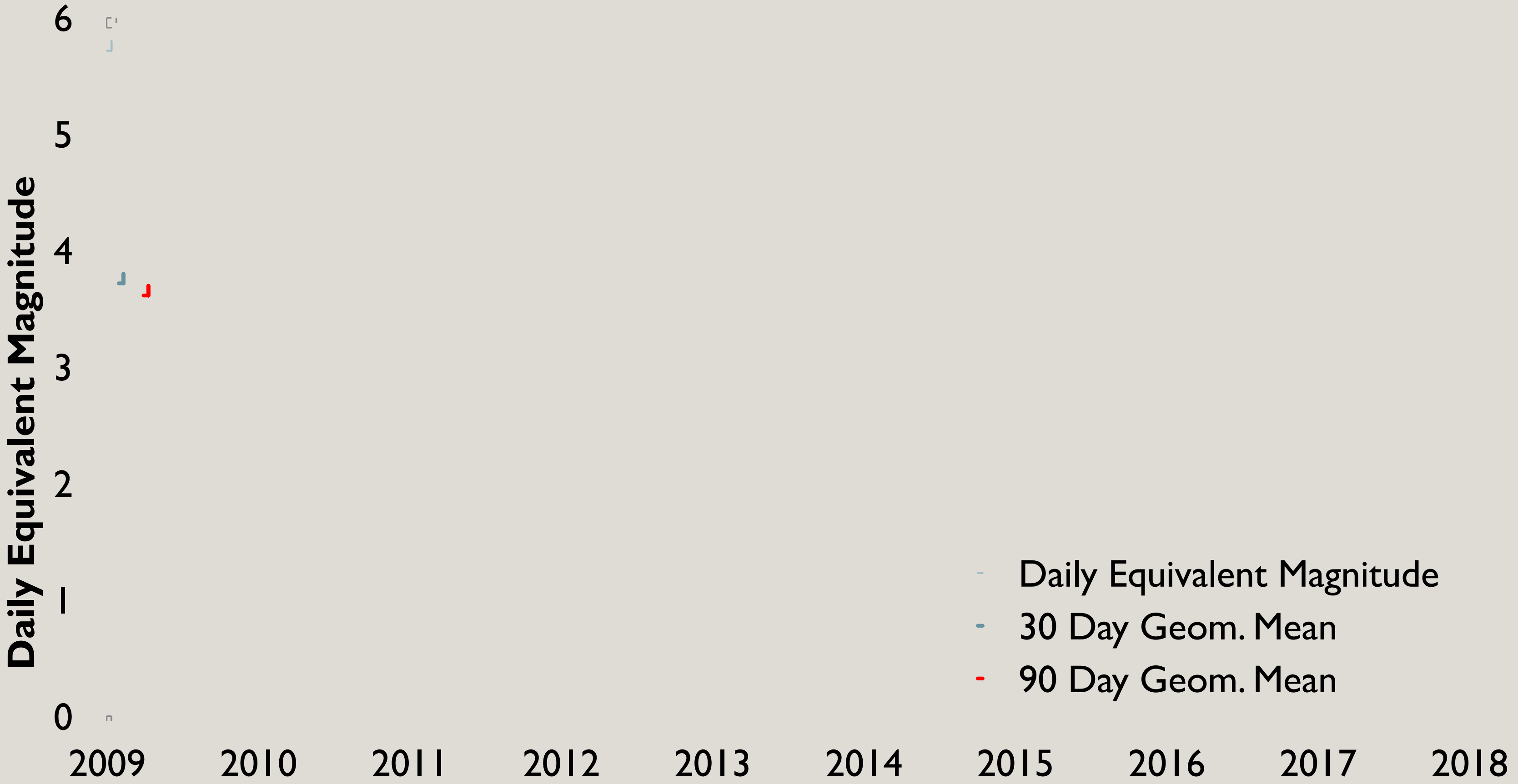
23 Daily Equivalent Magnitude in Oklahoma



Oil Price, Injection Rate and OCC Directed Reductions



Daily Equivalent Magnitude in Oklahoma



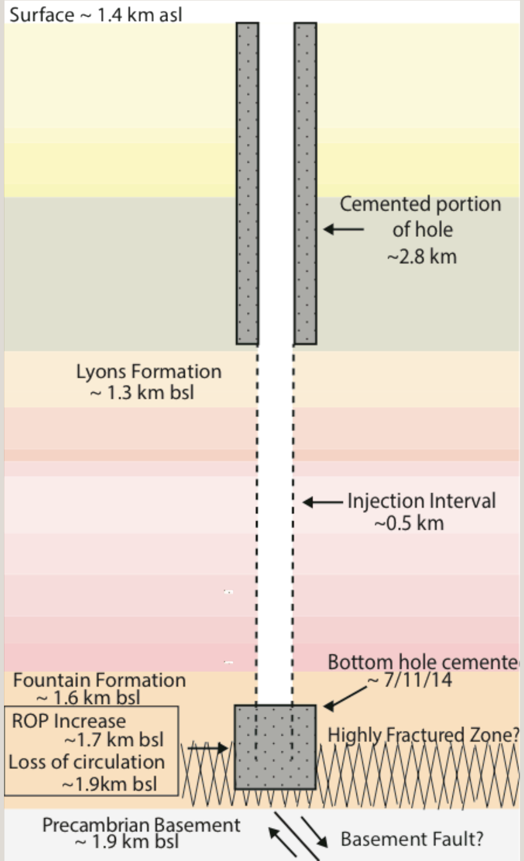
Re-use of Flowback and Produced water in OK

- Continental Resources operates water recycling facilities in SCOOP & STACK play operations.
- Newfield Exploration installed >160 miles of buried water pipeline infrastructure in SCOOP & STACK.
  - Investment in water pipelines has potential to reduce truck traffic by 100,000 round trips per year.
  - Constructed OCC-regulated produced water storage pits with total capacity of 8.4 MMB, 4.4 MM for produced water.
- Devon Energy initiated water re-use system in Cana-Woodford Shale.
  - Developed a 500,000-barrel storage/re-use facility for water from natural gas wells in W. Oklahoma.
  - Includes network of pipelines to carry water from production sites to re-use facility, back to completion sites.
- Cimarex Energy used large portable storage tanks to re-use flowback fluids for hydraulic fracturing of new wells in Cana field in Oklahoma.

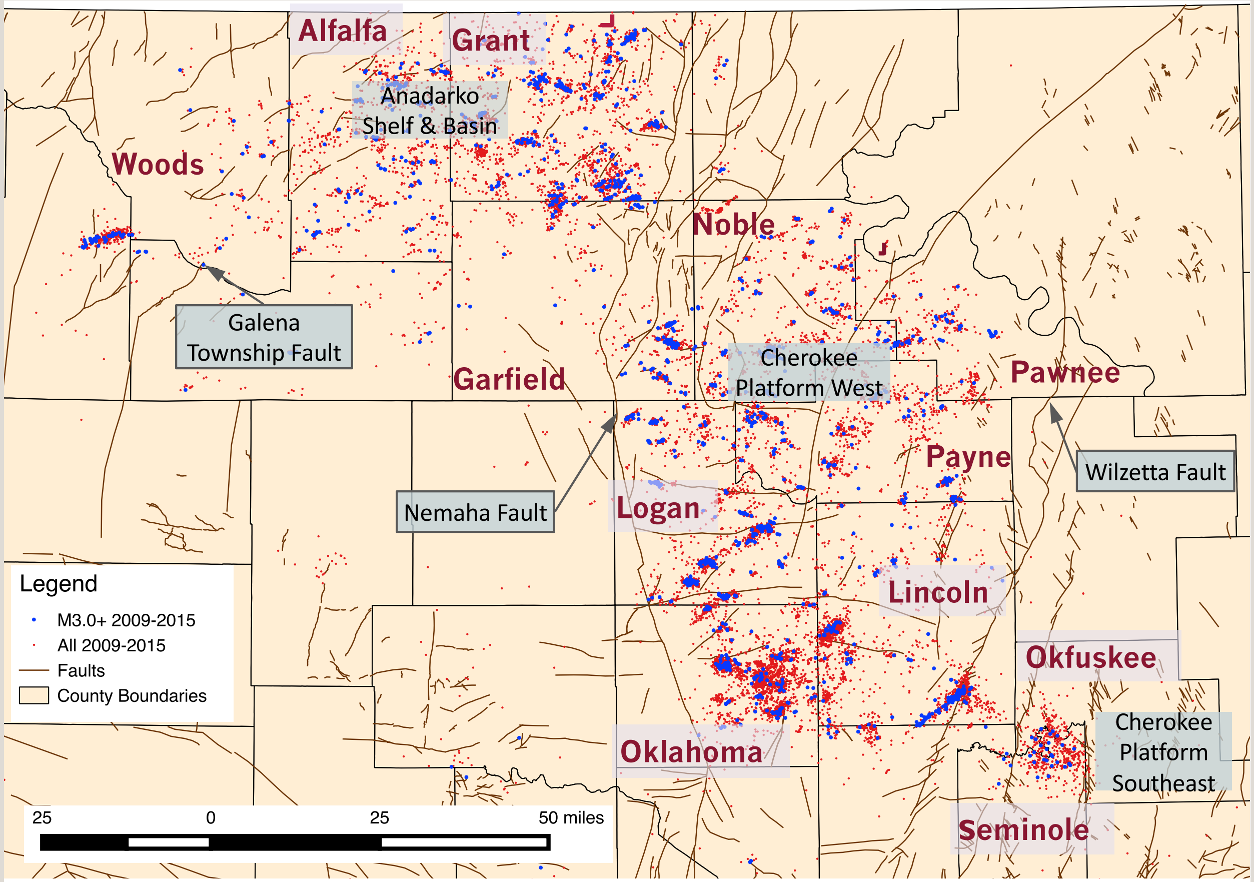
27 Greeley, Colorado History

- Seismic monitoring initiated by CU Boulder (Sheehan & others).
- Located near SWD C4A well injection into Lyon and Fountain formation, 500 ft above basement rock.
- C4A Injection started 4/2013, increased 8/2013.
- SWD shut in June 23, 2014; cemented back 458 feet. Injection restarted July 2014.
- No events M>1 since April 2015.
- COGCC Seismic monitoring protocol:
  - No M2.5+ within 2.5 miles of well.
  - Monitoring required for SWD well >10,000 BBL/day
- CU adding 6 new stations, Colorado Geological Survey will add 1 new station east of Greeley.

C4A well post-quake modifications



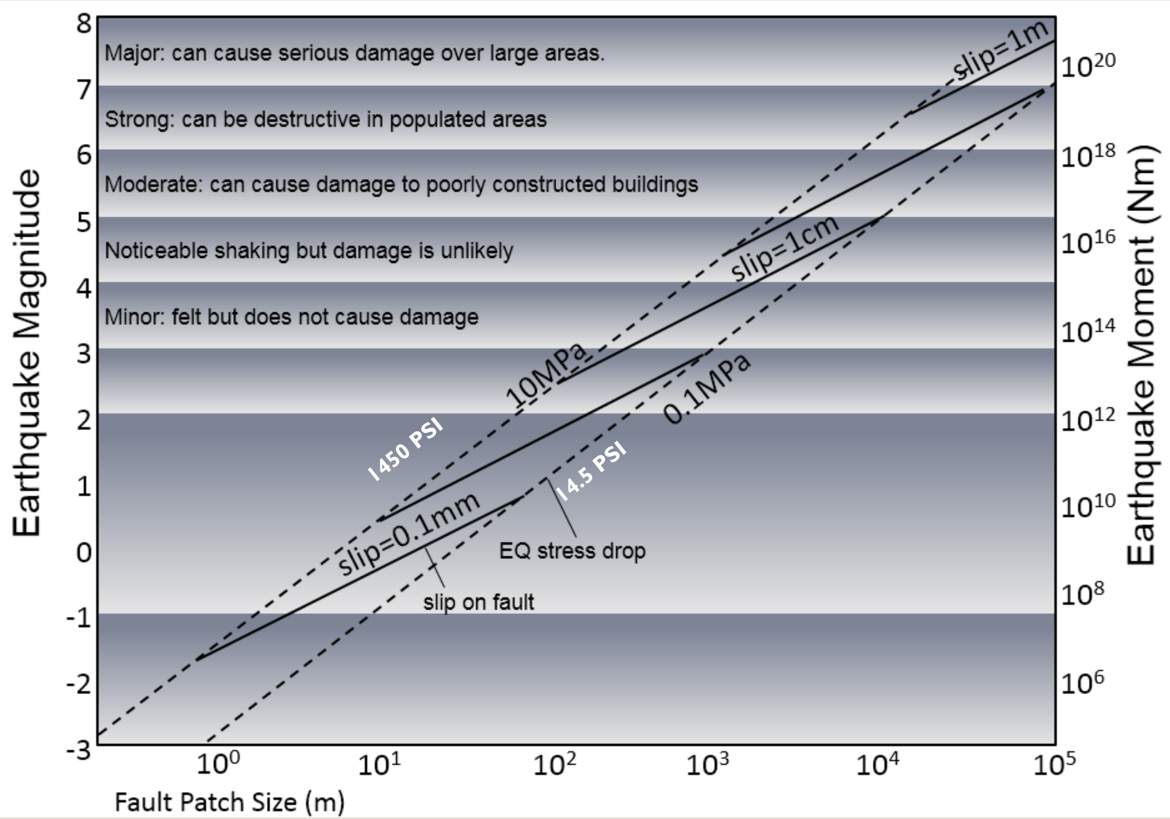
Oklahoma Earthquakes 2009-2015



Earthquake size related to fault size and slip

Felt earthquakes

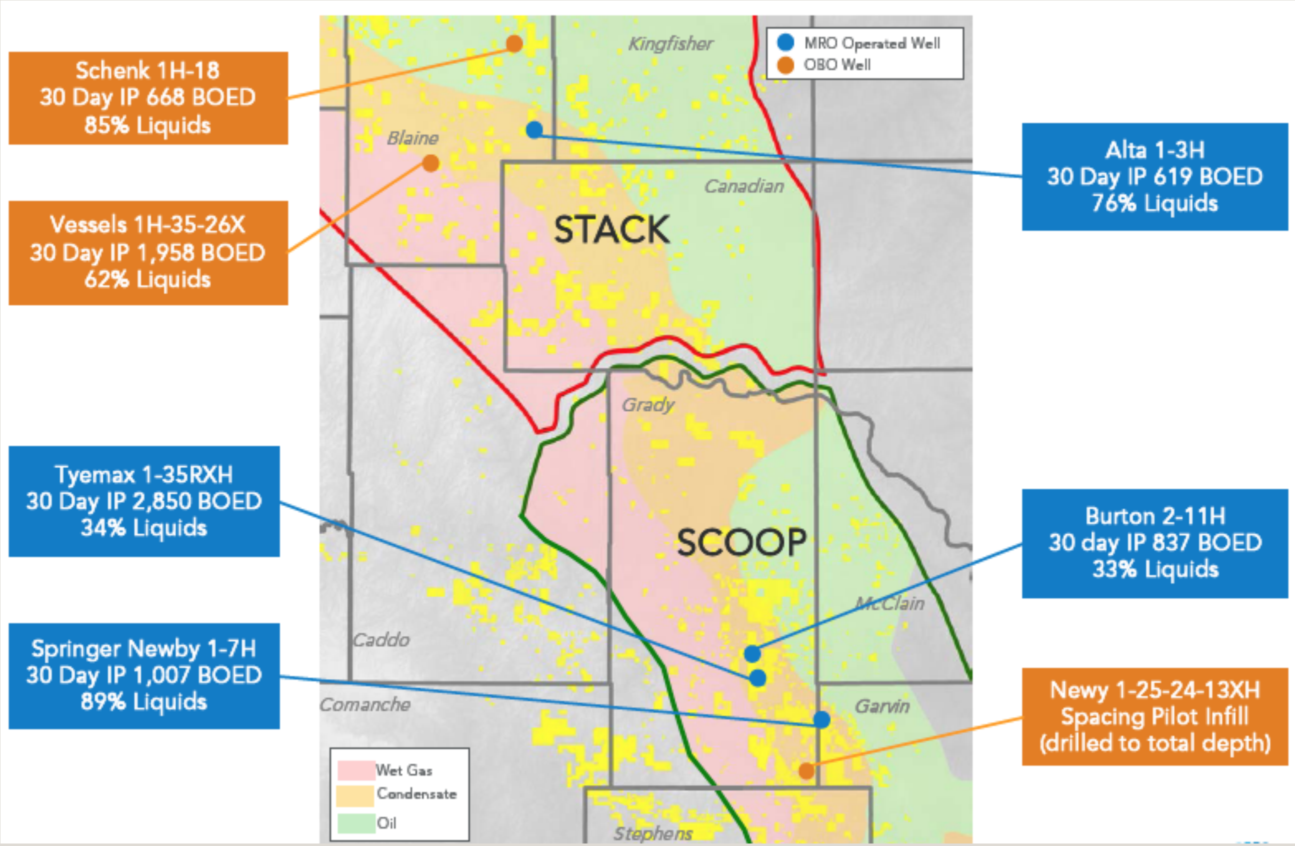
Typical frac monitoring event



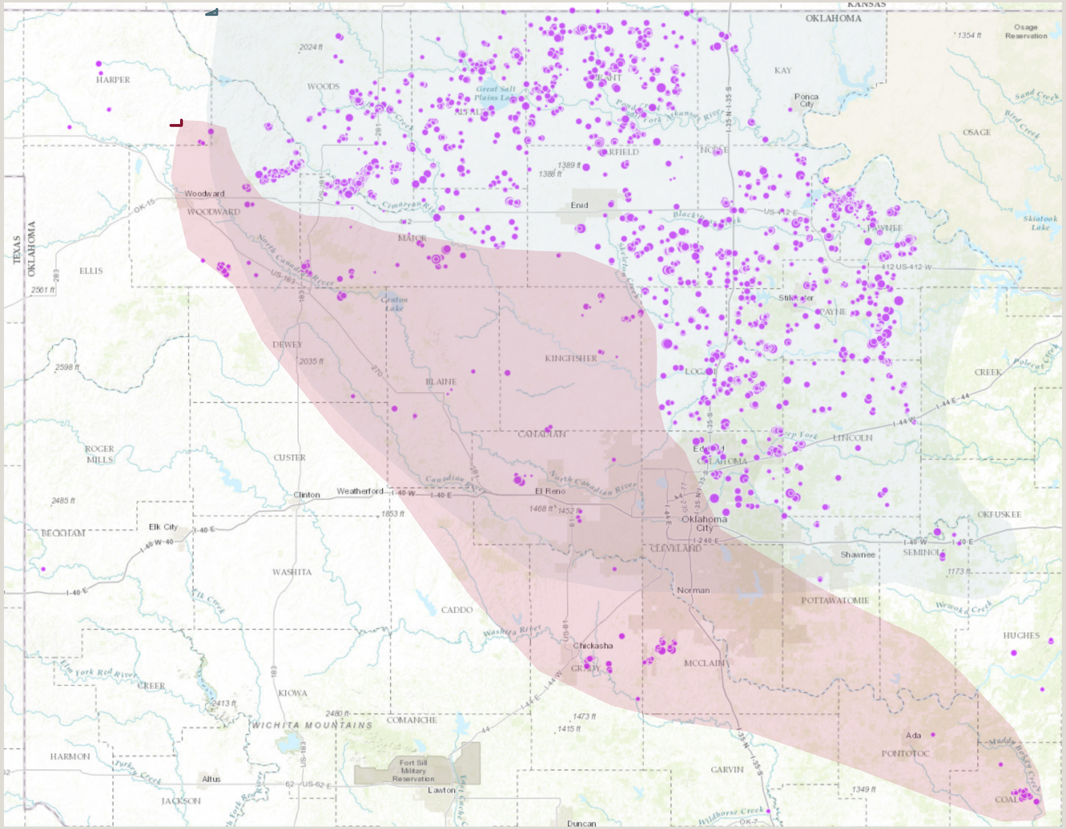
PRAGUE, OK

Courtesy of M. Zoback, based on Stein and Wysession, 2003

30 STACK & SCOOP Play Areas



2016 Oklahoma Earthquakes



Earthquake AOI

Area of Potential Completion-Related Earthquakes

Acknowledgments

- **OGS Staff Engaged on the Seismicity Issue**
  - **Seismology**: Jacob Walter, Jefferson Chang, Fernando Ferrer, Noorulann Ghouse, Junjun Hu, Andrew Thiel, Isaac Woelfel
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  - Secretary of Energy and Environment (through Recovery Act)
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