Oklahoma Earthquakes:
Evolving Patterns, Likely Causes, State Actions, Industry Engagement

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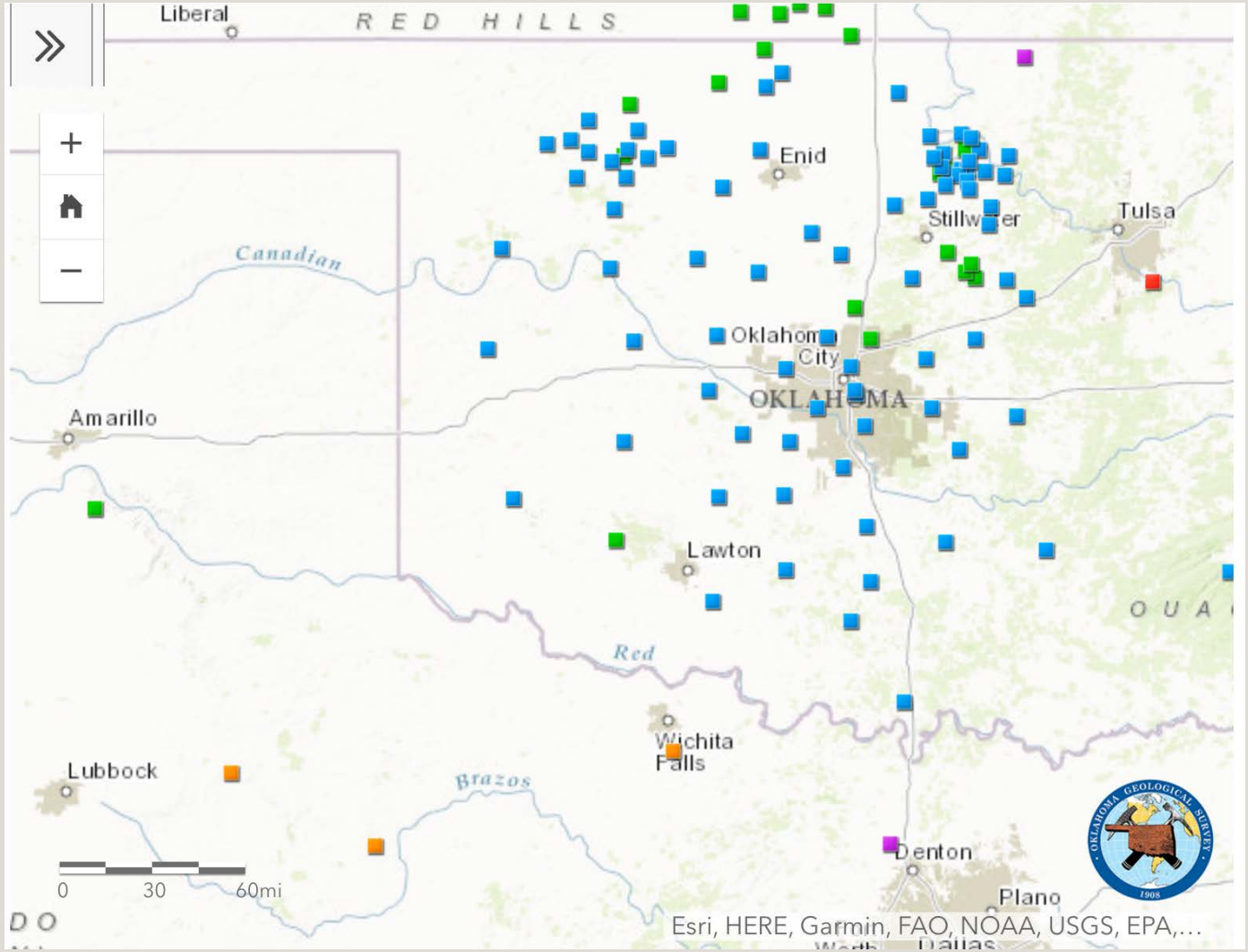
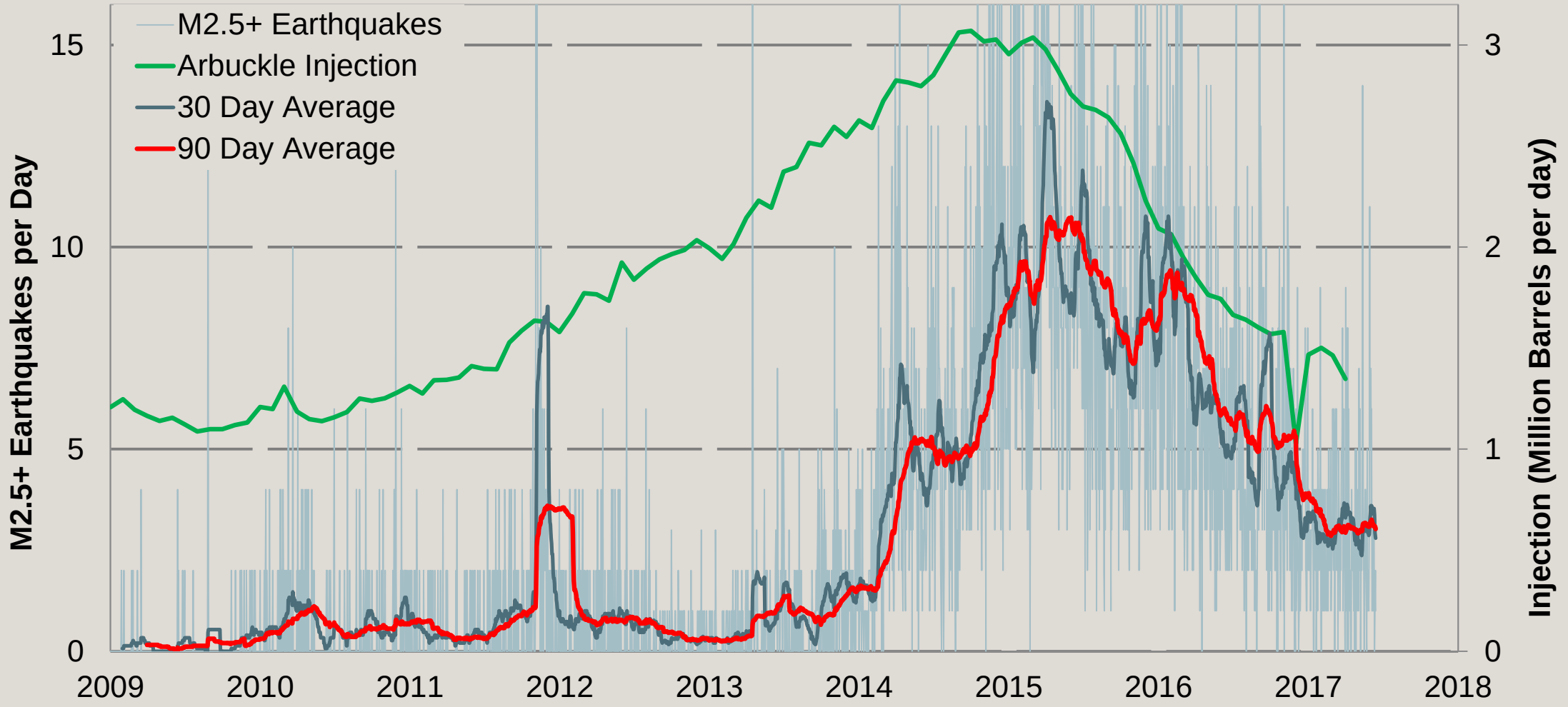
The Oklahoma Geological Survey is a state agency for research and public service located on the Norman Campus of the University of Oklahoma and affiliated with the OU College of Earth and Energy. The Survey is chartered in the Oklahoma Constitution and is charged with investigating the state's land, water, mineral, and energy resources and disseminating the results of those investigations to promote the wise use of Oklahoma's natural resources consistent with sound environmental practices.

We are not a regulatory authority

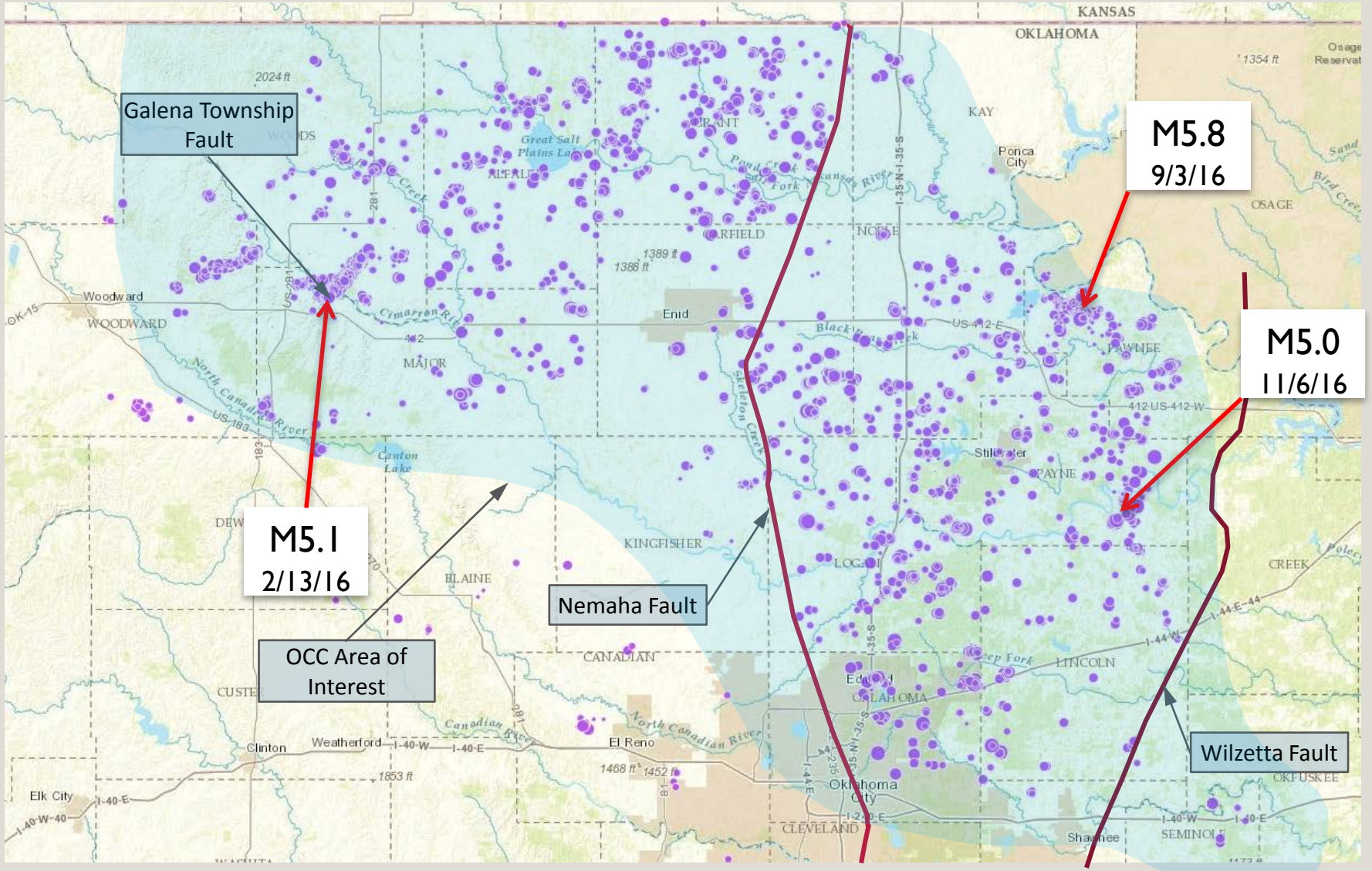
3 OGS Monitors ~140 Seismometer Stations



4 Oklahoma M2.5+ earthquakes



5 Oklahoma earthquakes, 2016

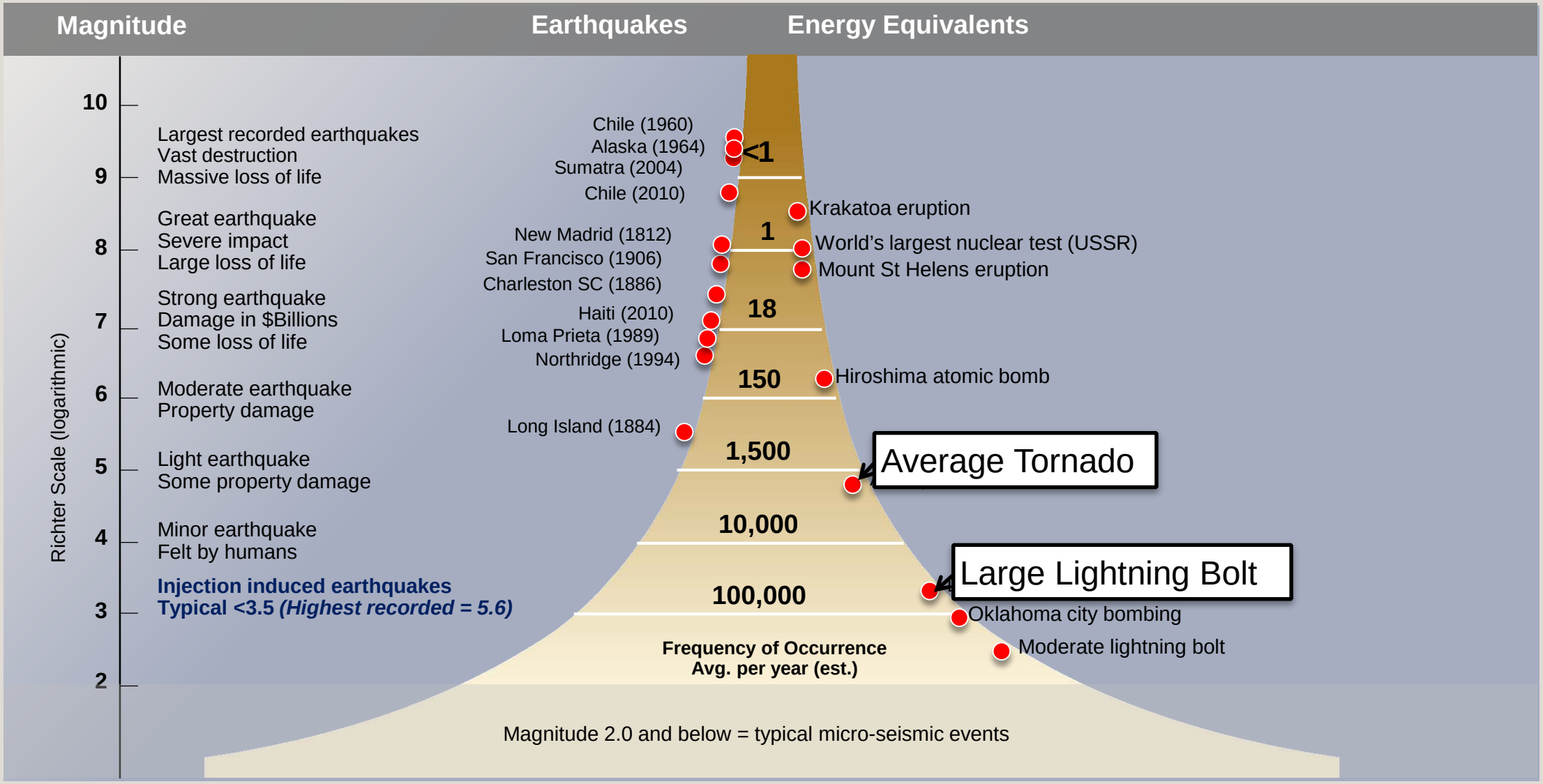


Earthquake map available at OGS website: http://uok.maps.arcgis.com/apps/Minimalist/index.html?appid=3ebaf2b8de02406b94804cbdb5afbec8

6 Measuring an earthquake

- Magnitude
  - Scaled estimate of energy released as seismic waves
  - Proportional to rupture area
- Magnitude measured multiple ways (M_L, m_b, M_w, M_o, M_s)
  - Estimates are uncertain, and rarely the same between different methods
  - Scales logarithmic (+1 unit of magnitude = ~10 times shaking & ~32 times the energy release)
- Earthquake Intensity
  - Varies with distance from the earthquake
  - Qualitative estimate (using Modified Mercalli scale ranging from I-XII)

7 Earthquake magnitude & frequency



8 Human activity can induce earthquakes

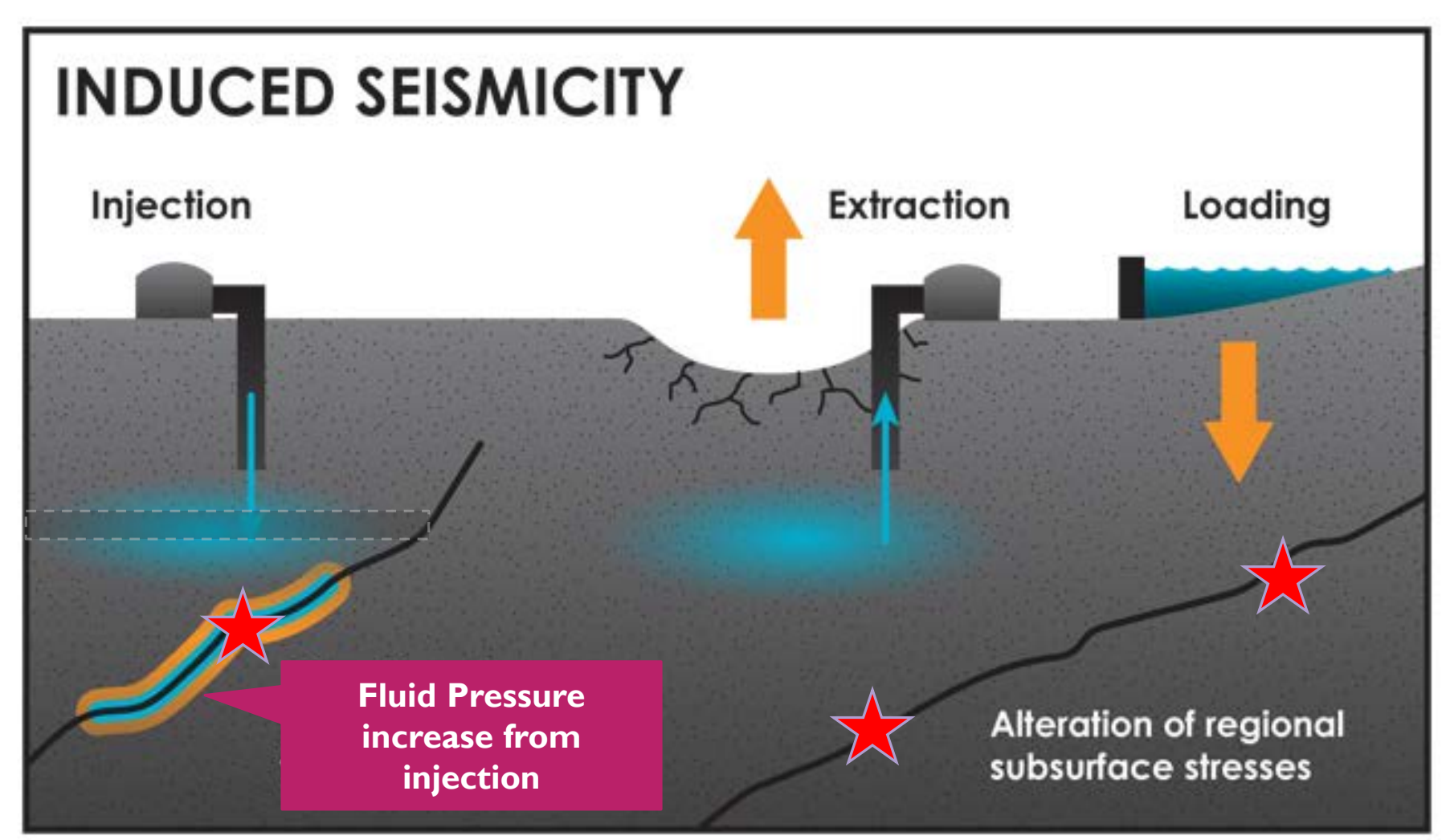
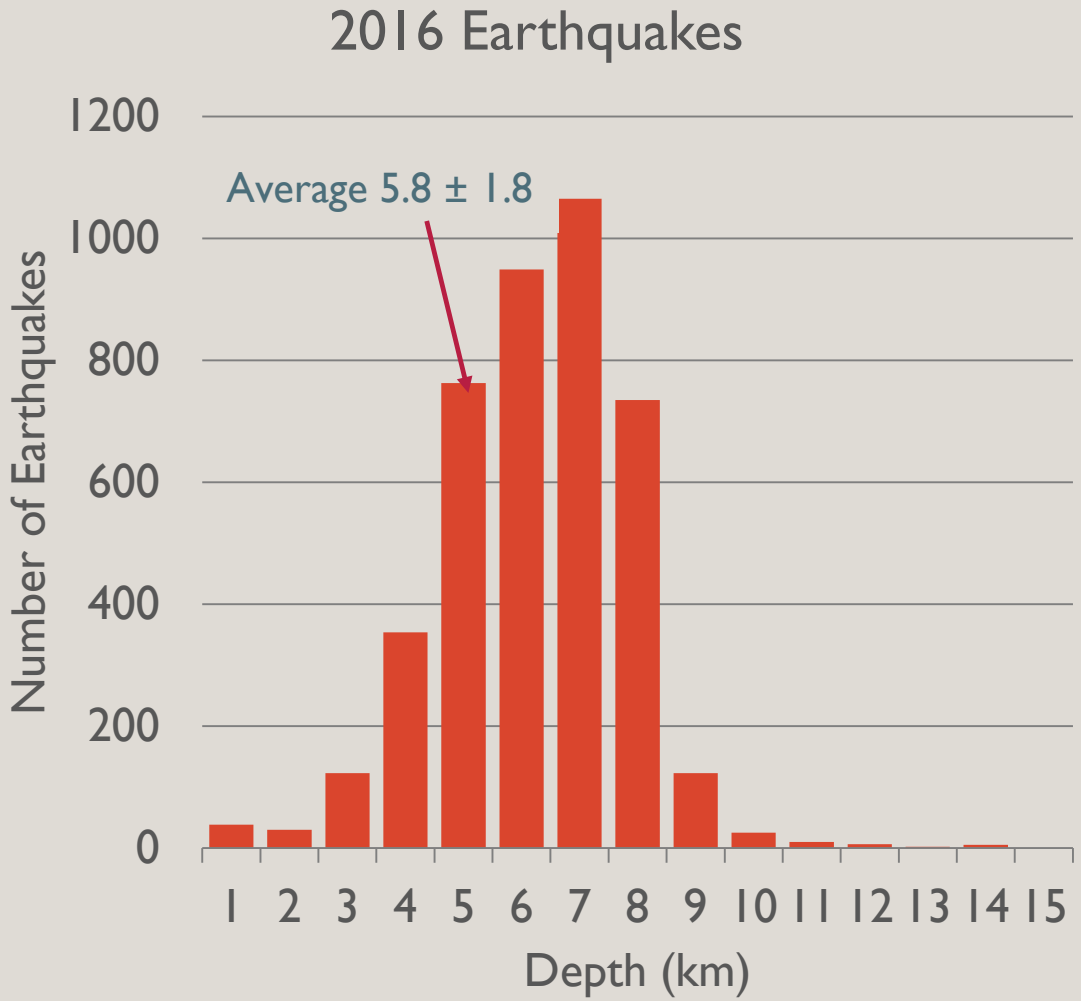
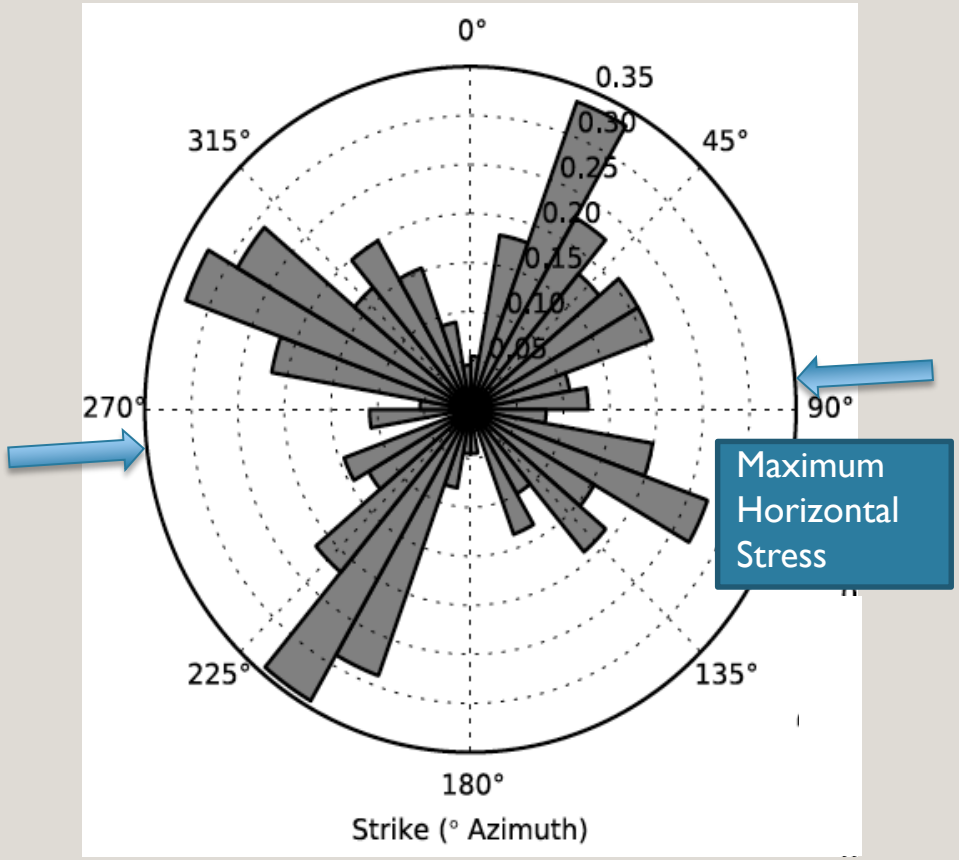


Figure modified from: http://www.earthmagazine.org/article/ground-shaking-research-how-humans-trigger-earthquakes

9 Earthquakes occur in basement, on optimally aligned faults



Active Fault Orientations 2014



OGS OF1-2015

10 Earthquakes occur in areas of large volume disposal wells

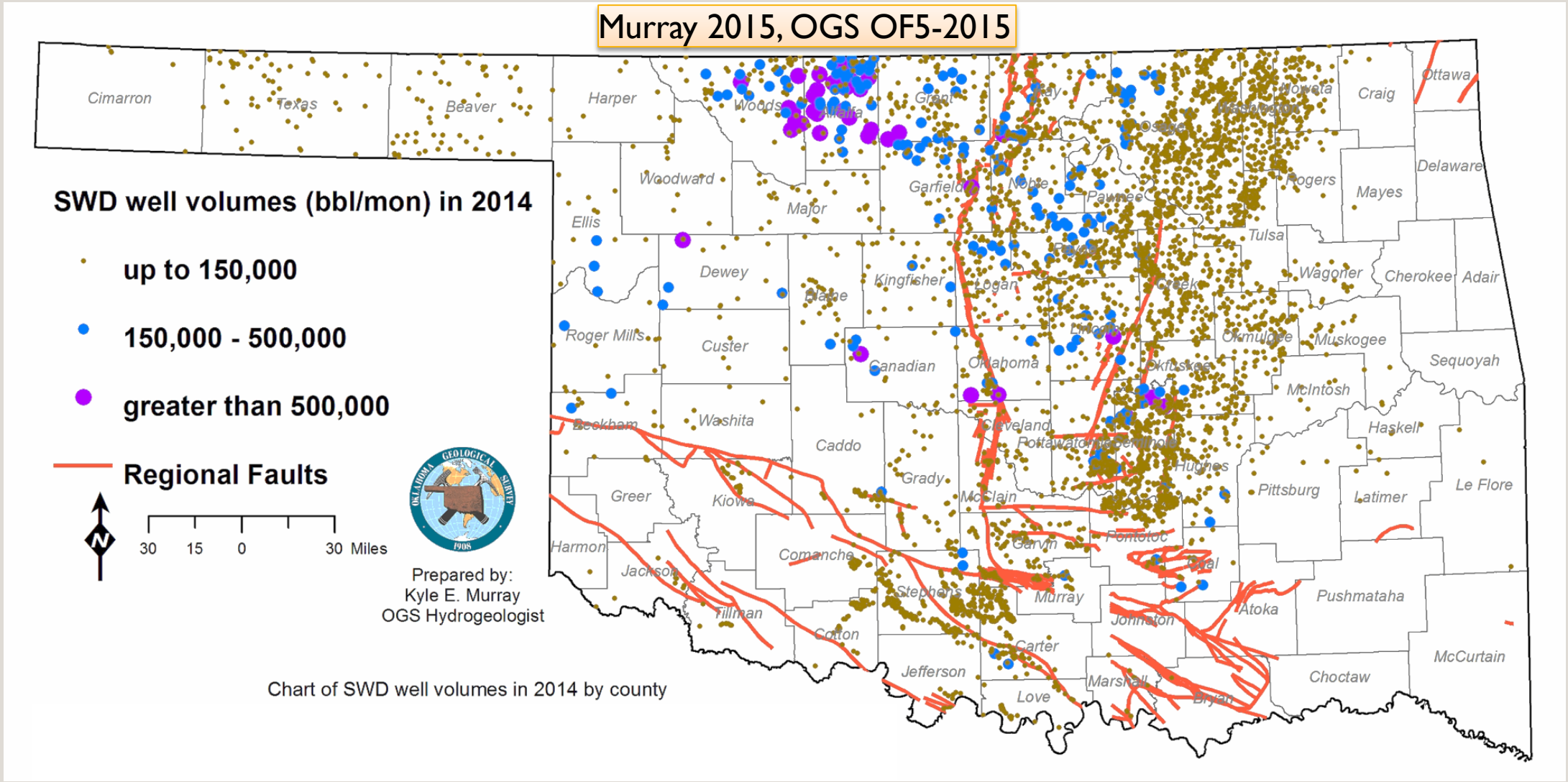
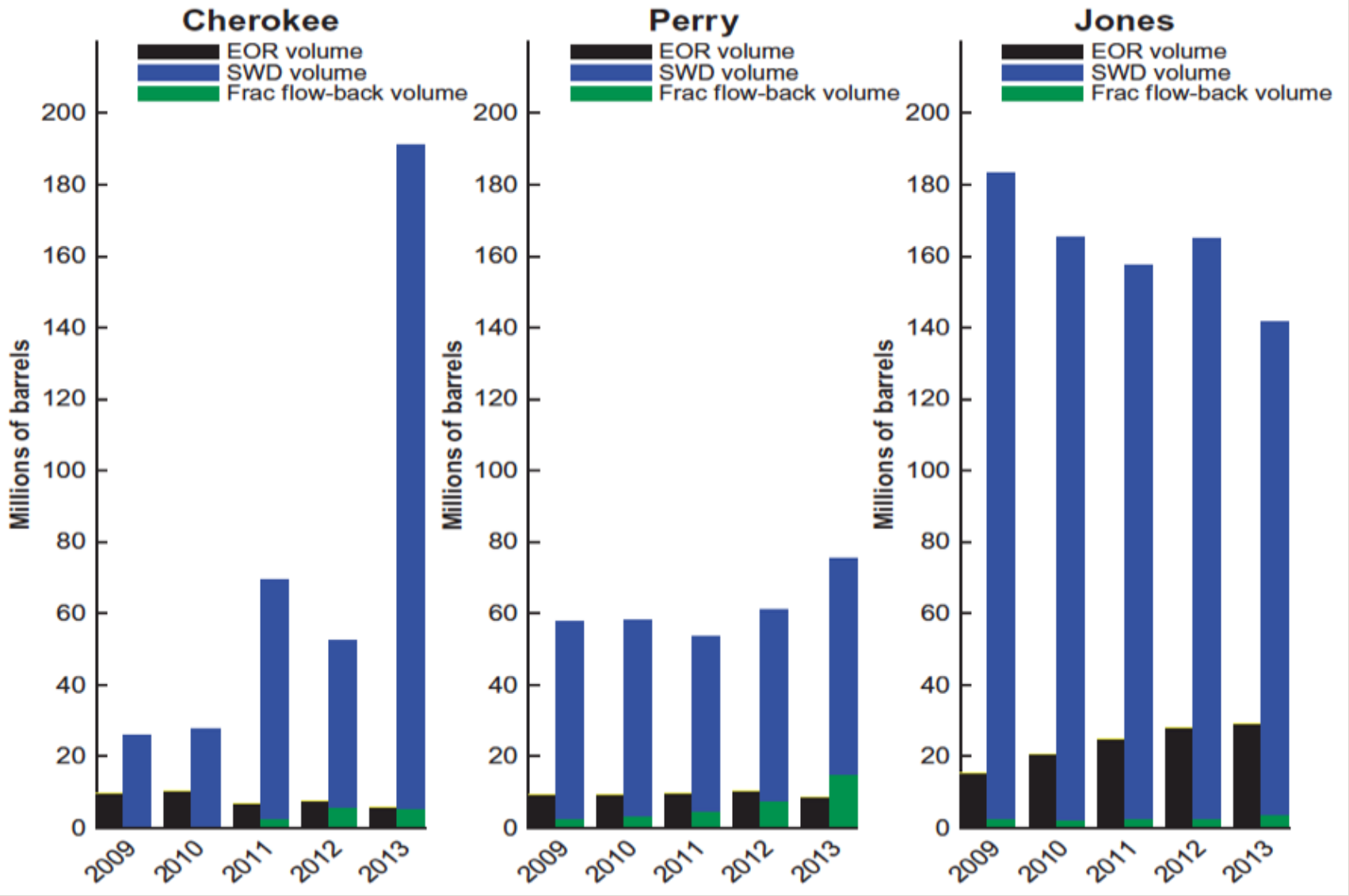


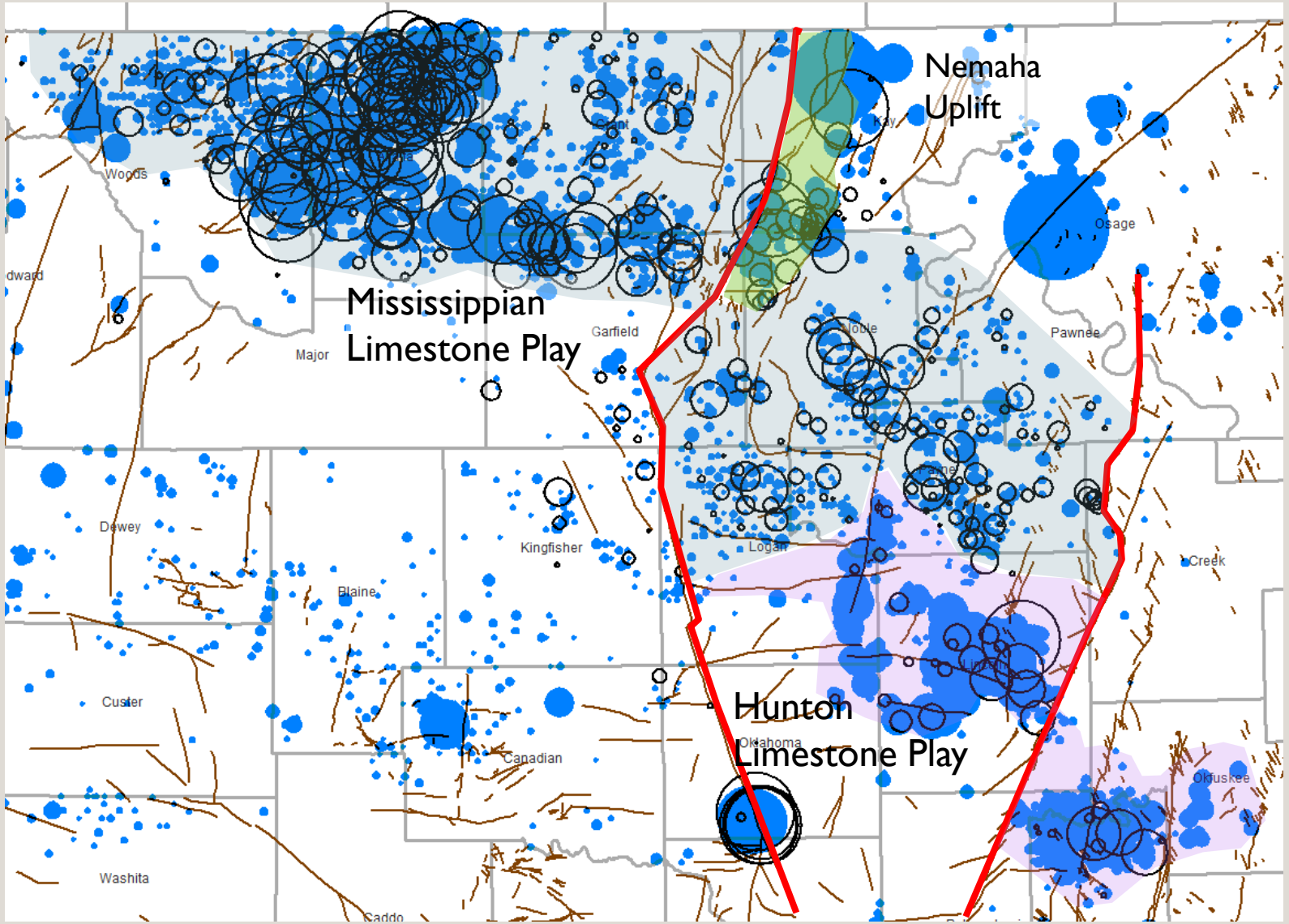
Chart of SWD well volumes in 2014 by county

Disposal contains <5% flowback water from hydraulic fracturing



Source: Walsh, F. R., and Zoback, M. D. (2015) Oklahoma's recent earth-quakes and saltwater disposal. Sci. Adv. 2015; 1:e1500195, 18 June 2015

12 Different plays; different water cuts; different seismic history



Initial Water Production

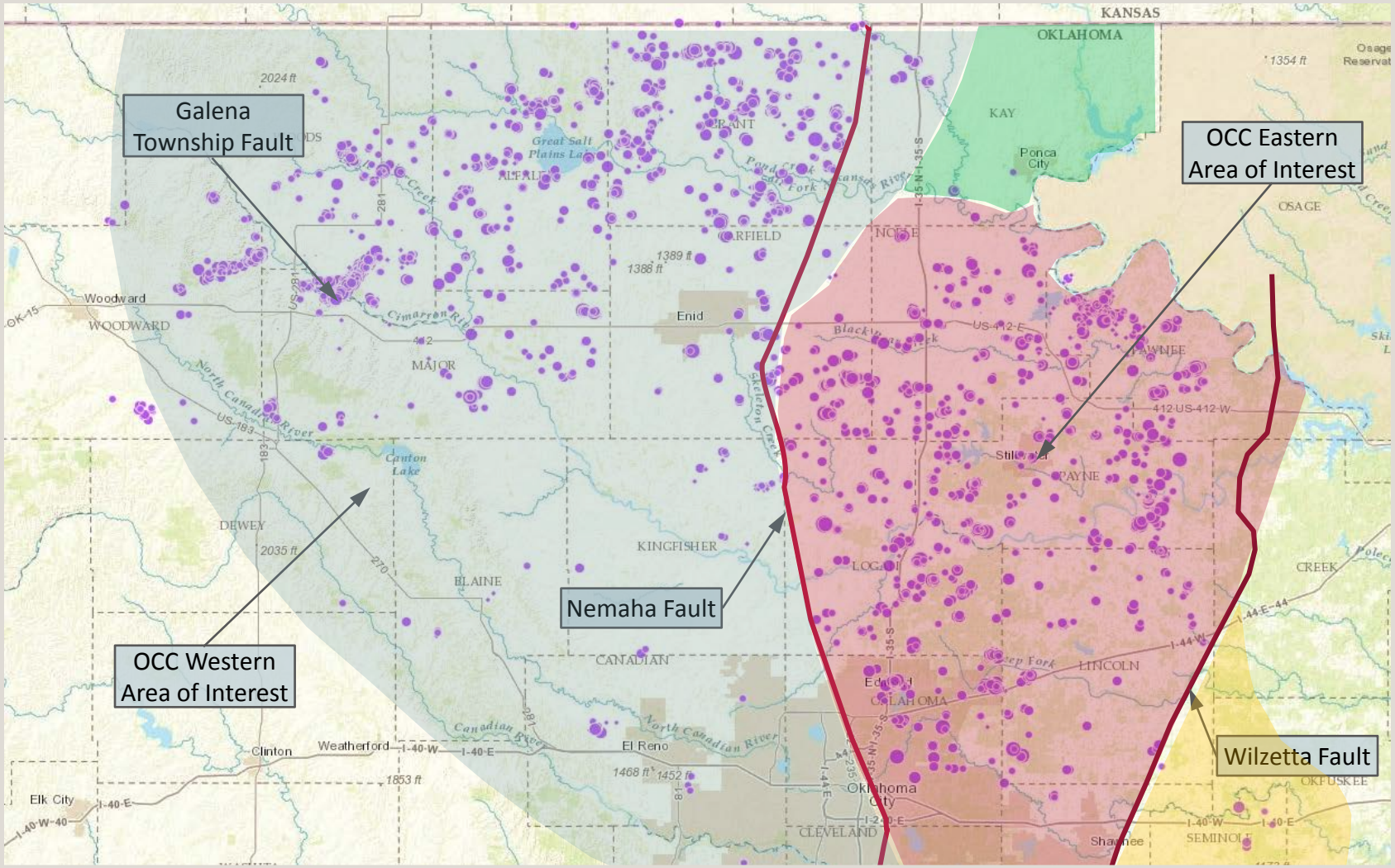
Cumulative Injection

Figure Courtesy of
Anna Stafford, IPA LLC

State actions on induced seismicity

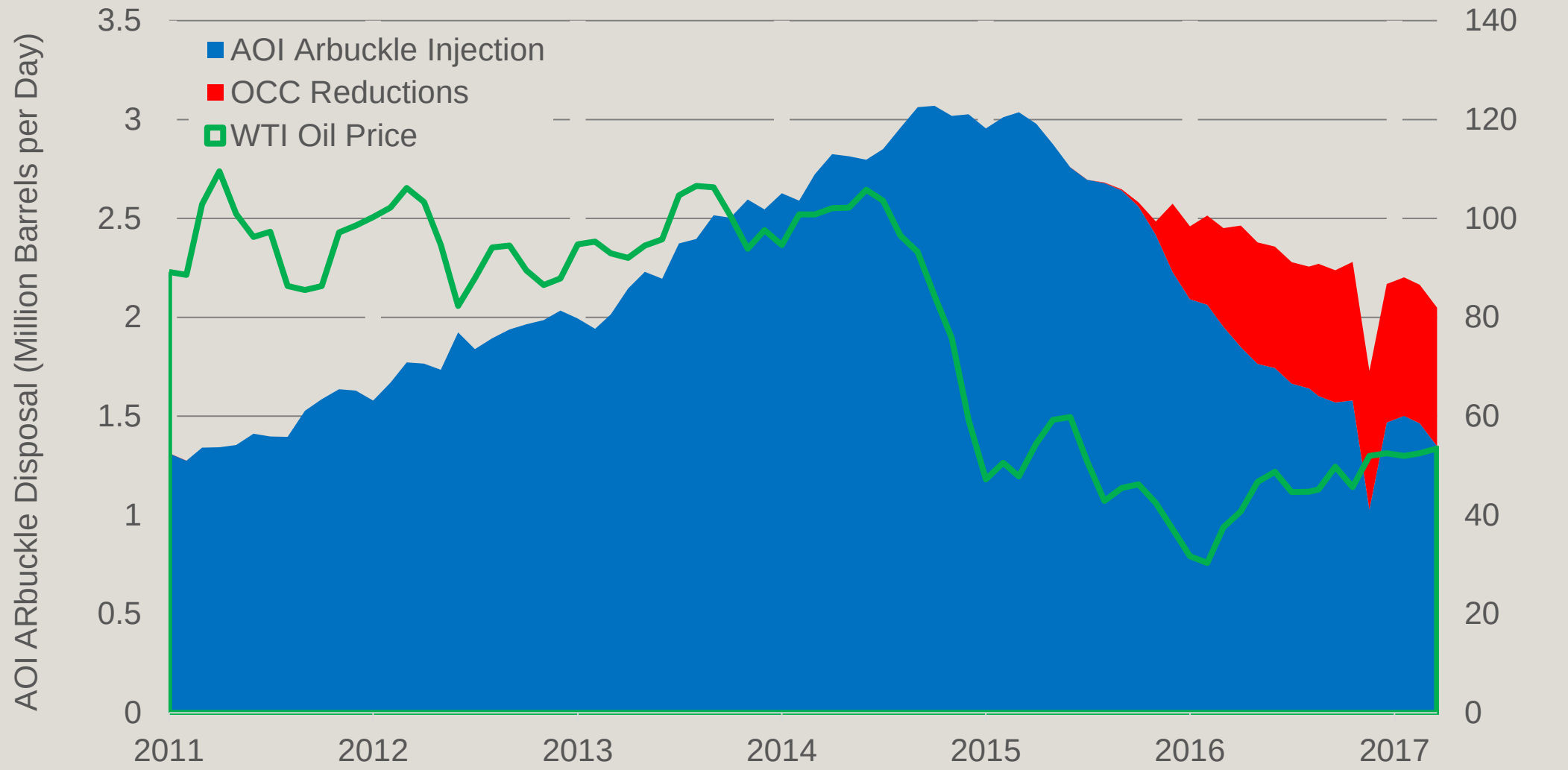
- Governor creates Coordinating Council on Seismicity (2014)
- OCC directives reduce injection (2015)
- Oklahoma Geological Survey (OGS) position paper (2015)
- Secretary of Energy funds $200,000 seismicity projects (2015)
- Governor's Water for 2060 Produced Water Working Group (2015)
- RPSEA funded stations added to OGS network (2016)
- Governor's Emergency Fund $1,387,000 to OCC, OGS (2016)
- New tracking system for earthquakes and injection for OCC (2016)

14 Oklahoma Corporation Commission (OCC) Actions



- Arbuckle Group injection wells in Area of Interest (AOI) submit weekly report of daily injection rate
- Wells in Precambrian basement plugged back or cut injection 50%
- Reductions and shut-in wells reduced overall injection by >900,000 BWPD since mid-2015
- Caps on injection rate in Western and Eastern AOI reduce potential for price-driven increases

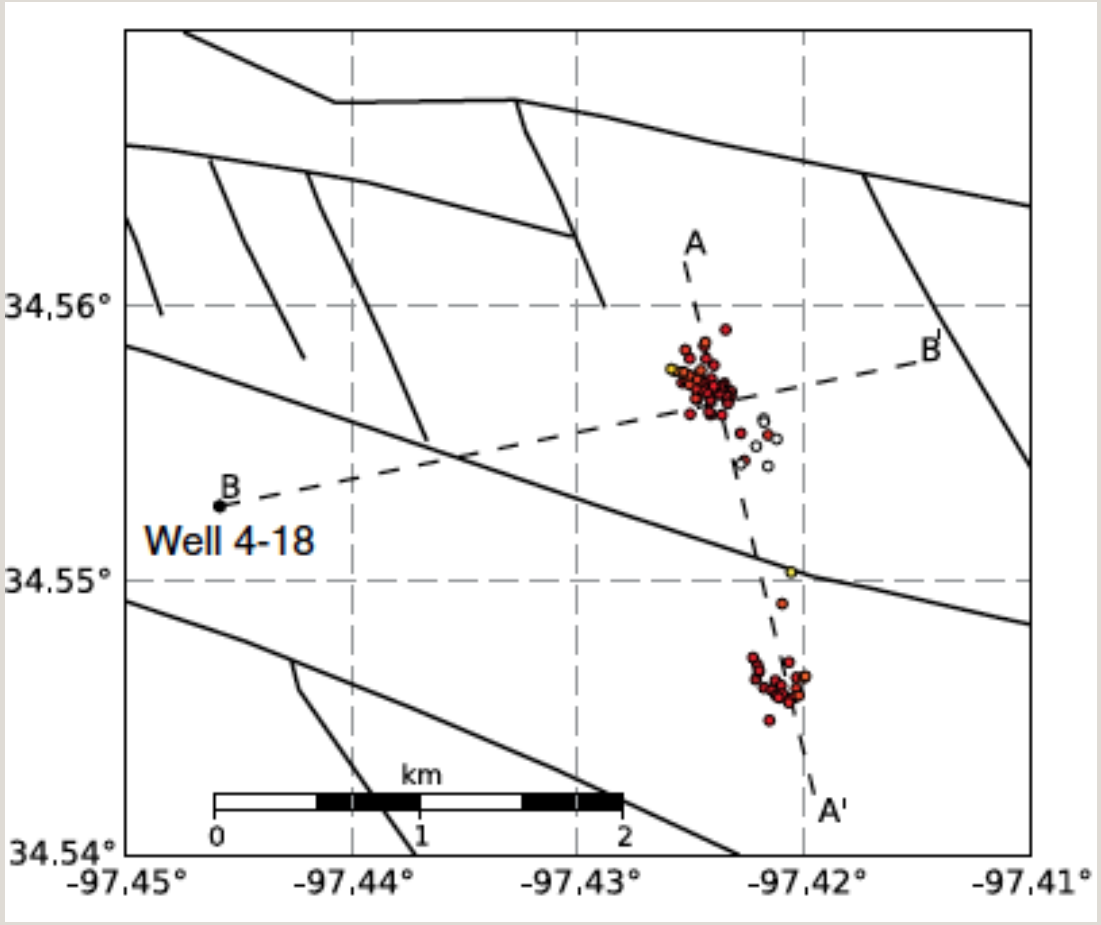
15 Oil Price, Injection Rate and OCC Directed Reductions

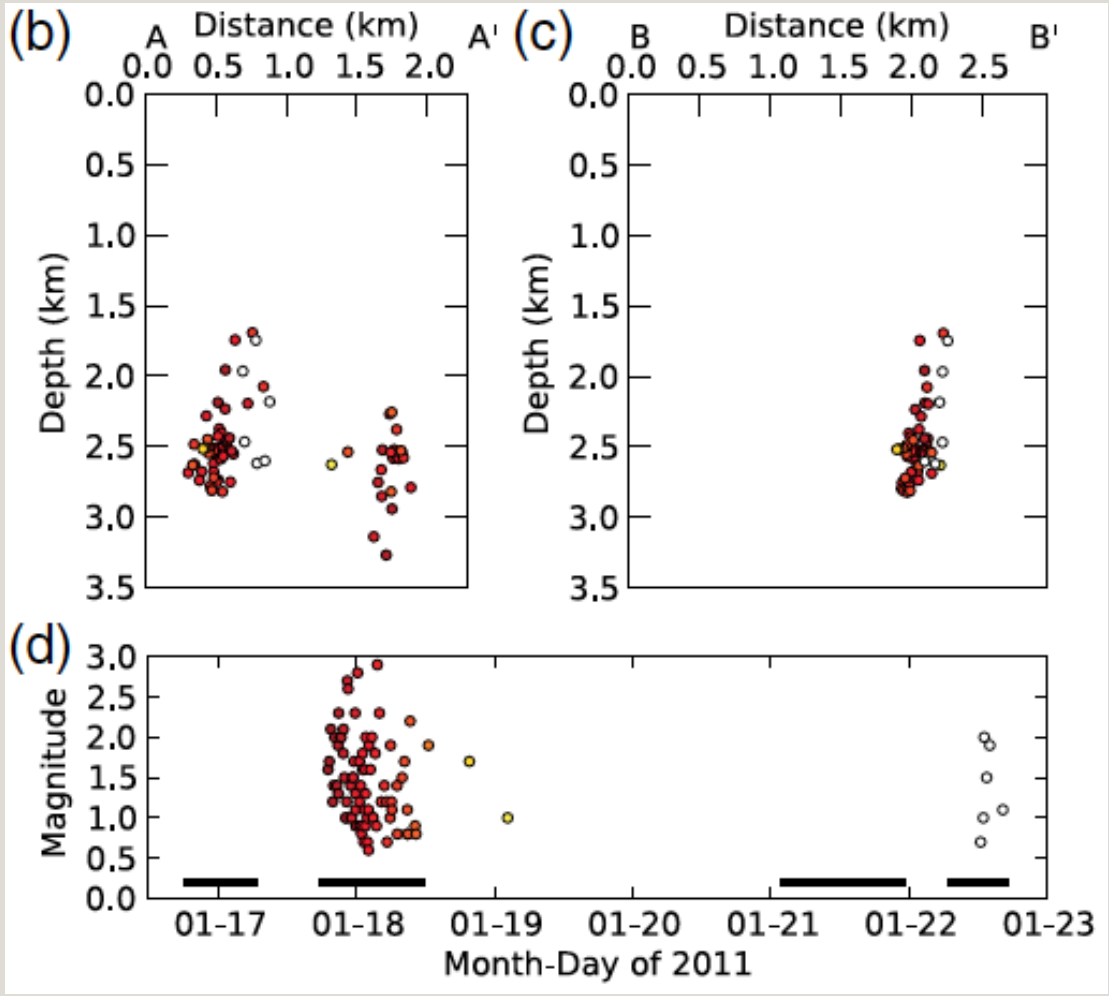


16 Recommendations of Produced Water Task Force (2017)

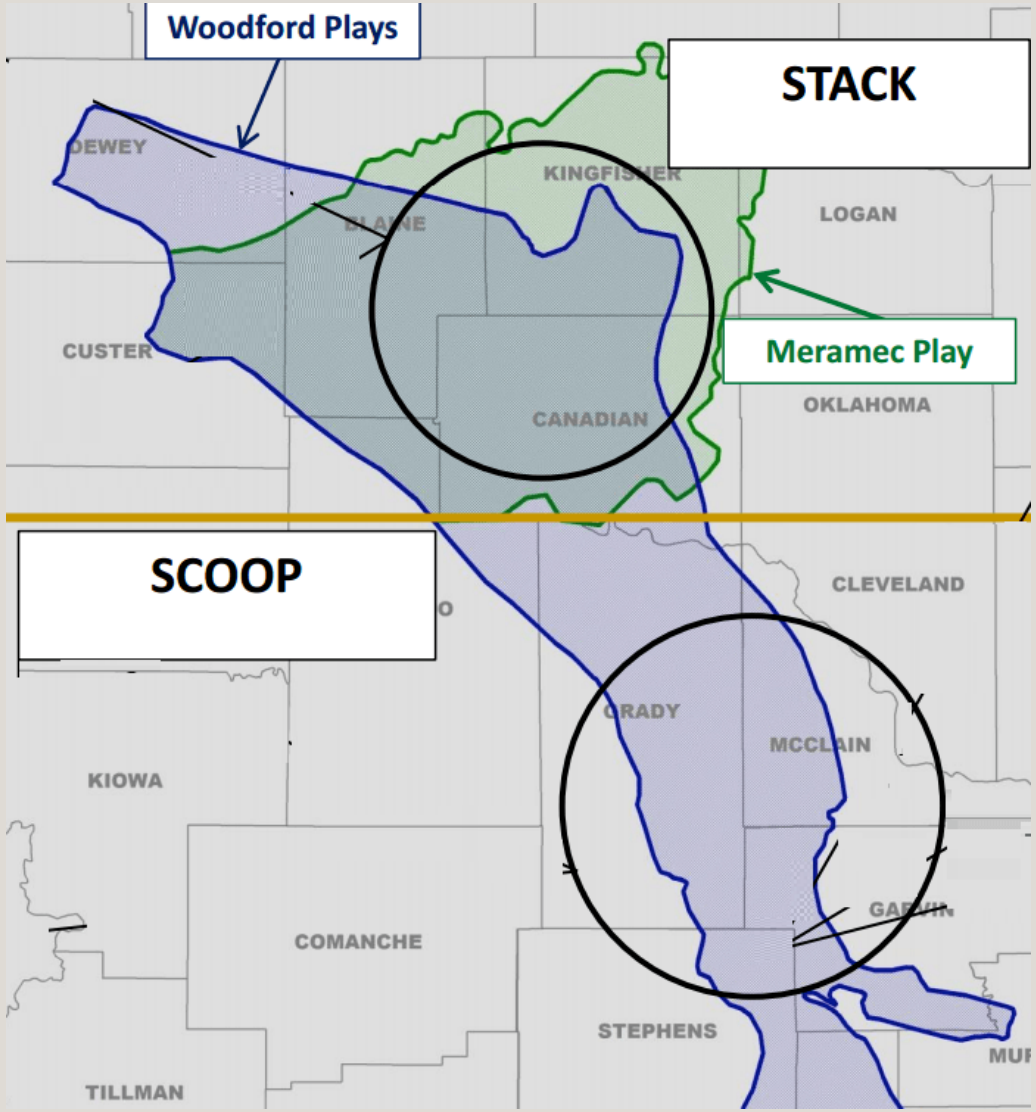
1. Reduce challenges to water re-use through targeted regulations and legislation:
   - Remove legal ambiguity about ownership of produced water
   - Establish bonding requirements for water impoundments without being an impediment
   - Make right-of-way for pipelines for recycled/re-used water easier 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.

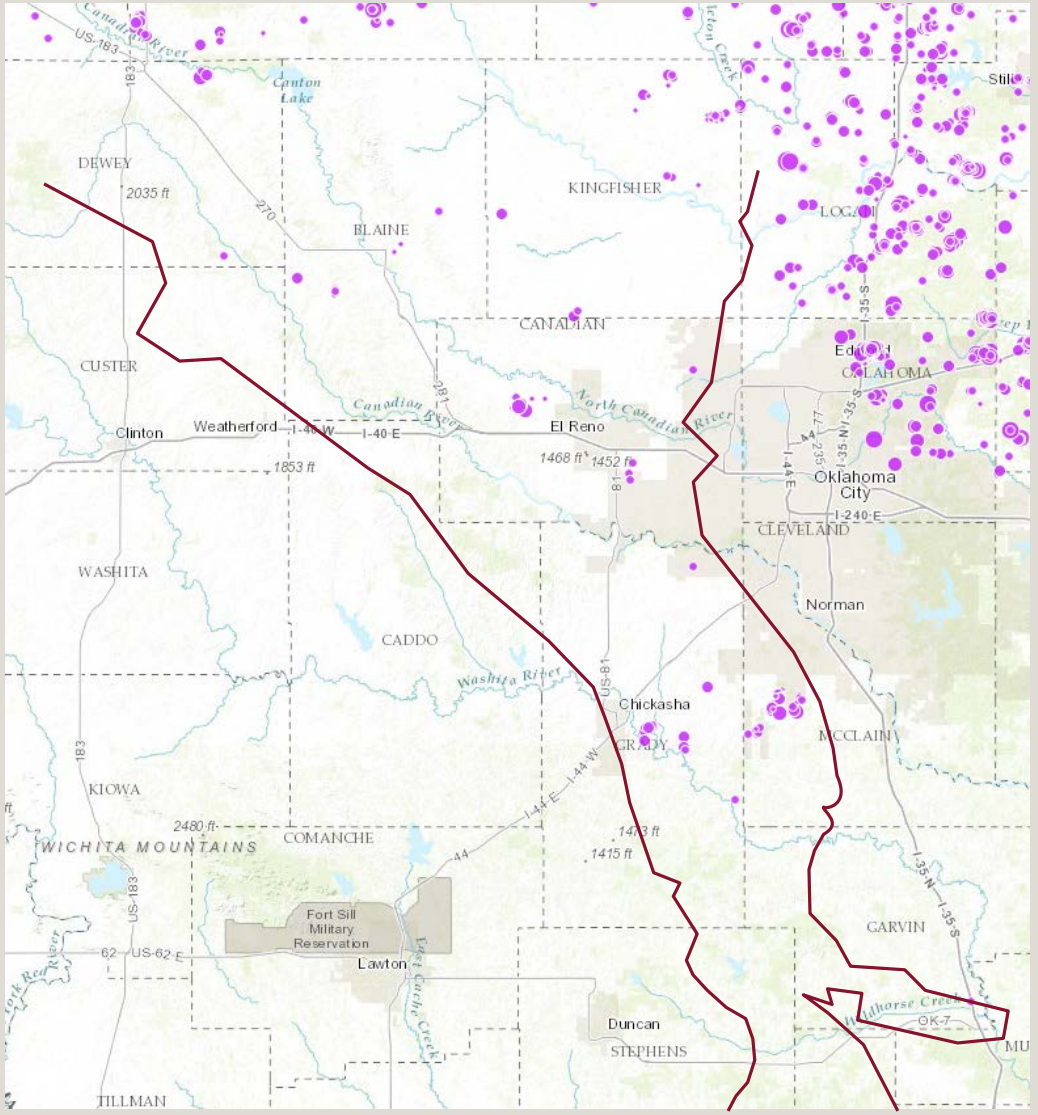
Earthquakes associated with hydraulic fracturing





18 STACK & SCOOP Play Areas

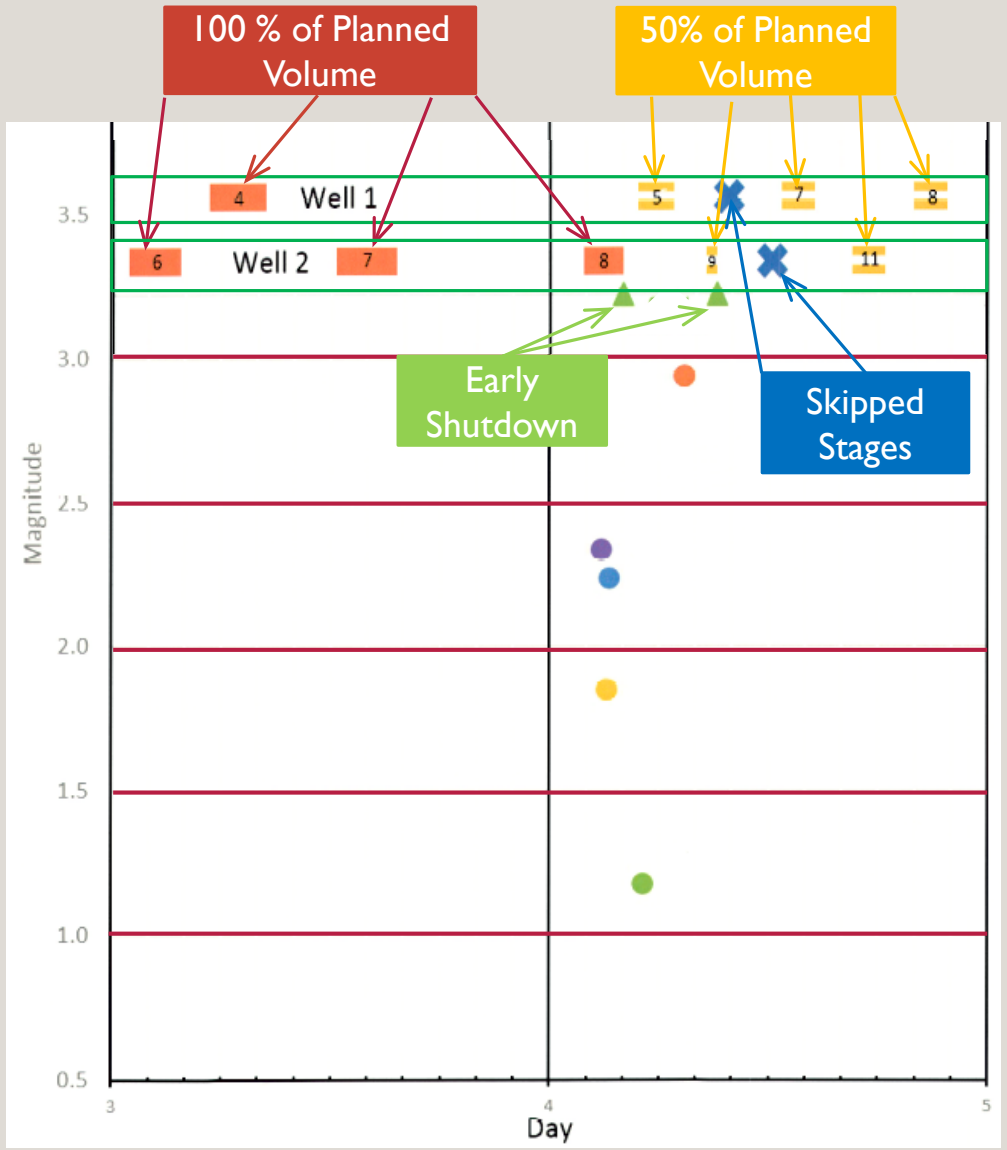


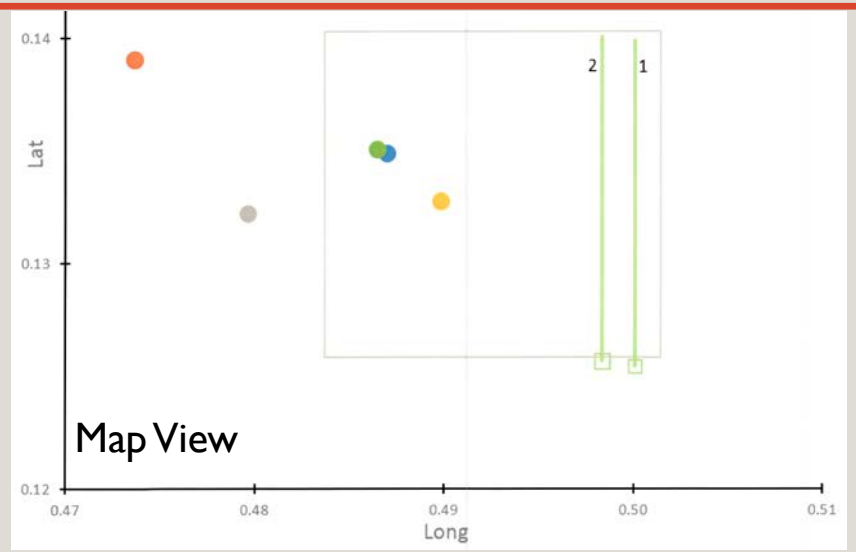


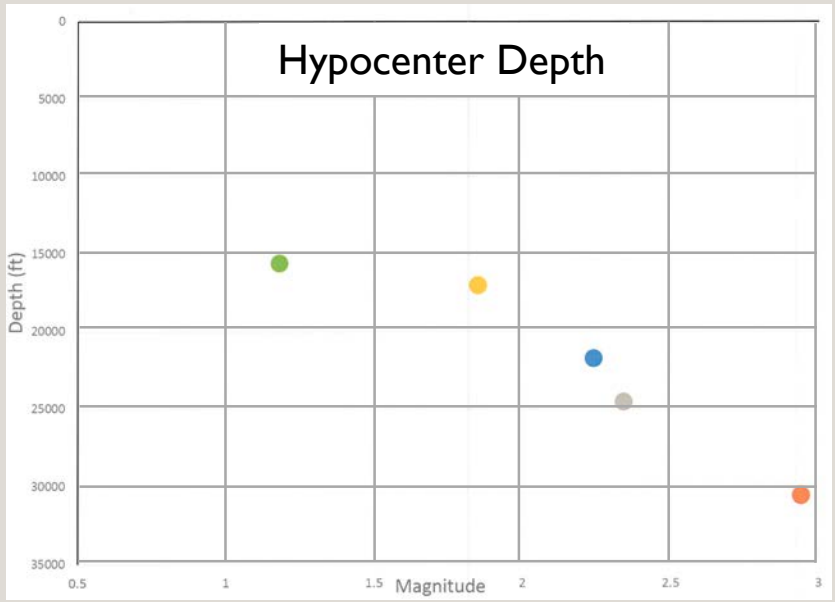
19 OCC well completion guidance on seismicity

- Action following anomalous seismic activity ≤2 km from completion operations
- Stoplight system, if Oklahoma Geological Survey reports magnitude ≥2.5; ≥3.0M; ≥3.5M earthquake
- 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

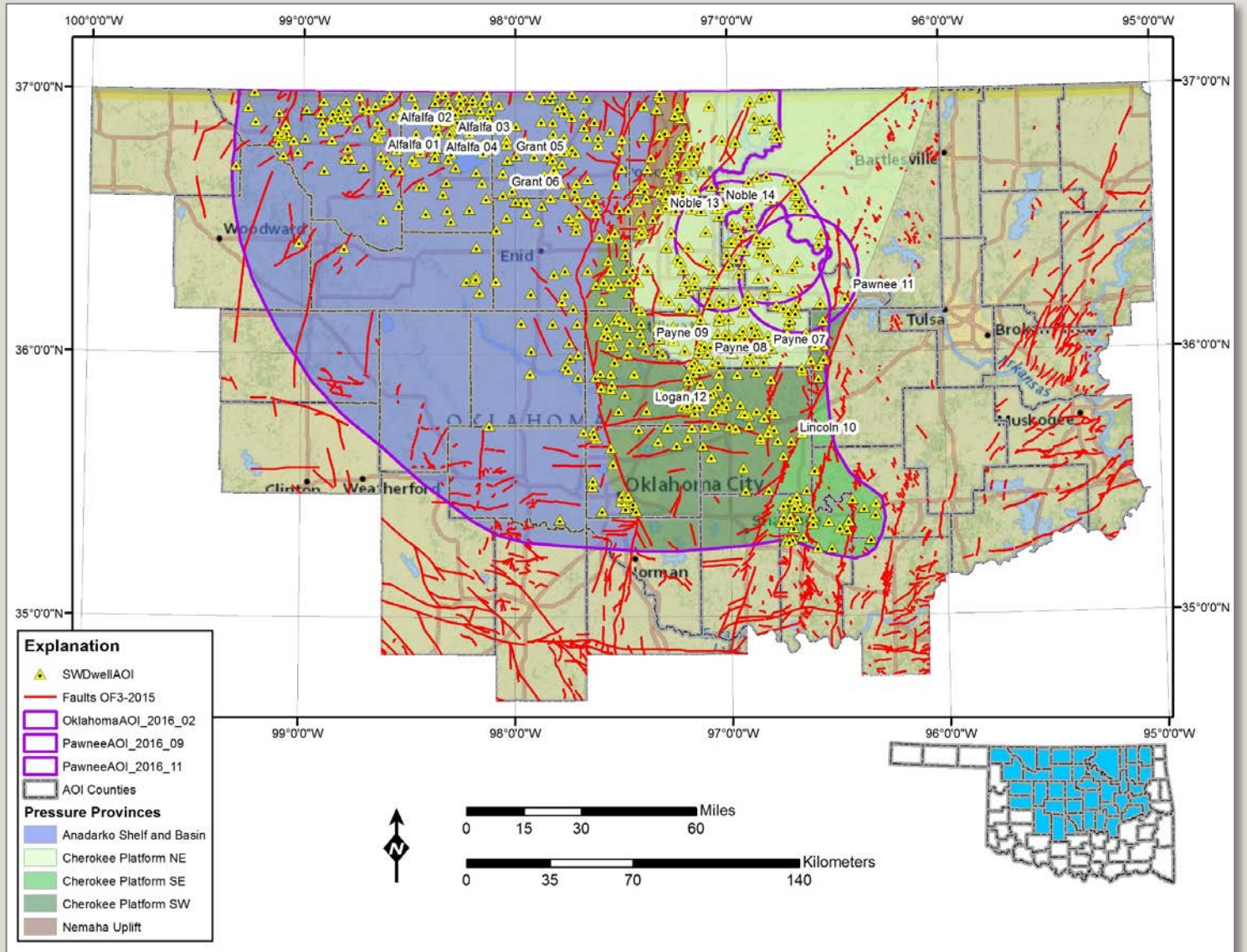
Recent example: Response to earthquakes induced by hydraulic fracturing







21 OGS-Industry collaboration on pressure monitoring



Continuous measurement of hydrostatic head in 14 shut-in UIC Class II (salt water disposal) wells completed in the Arbuckle Group provides insight into induced seismicity

22 Mewbourne College staff engaged on seismicity issue

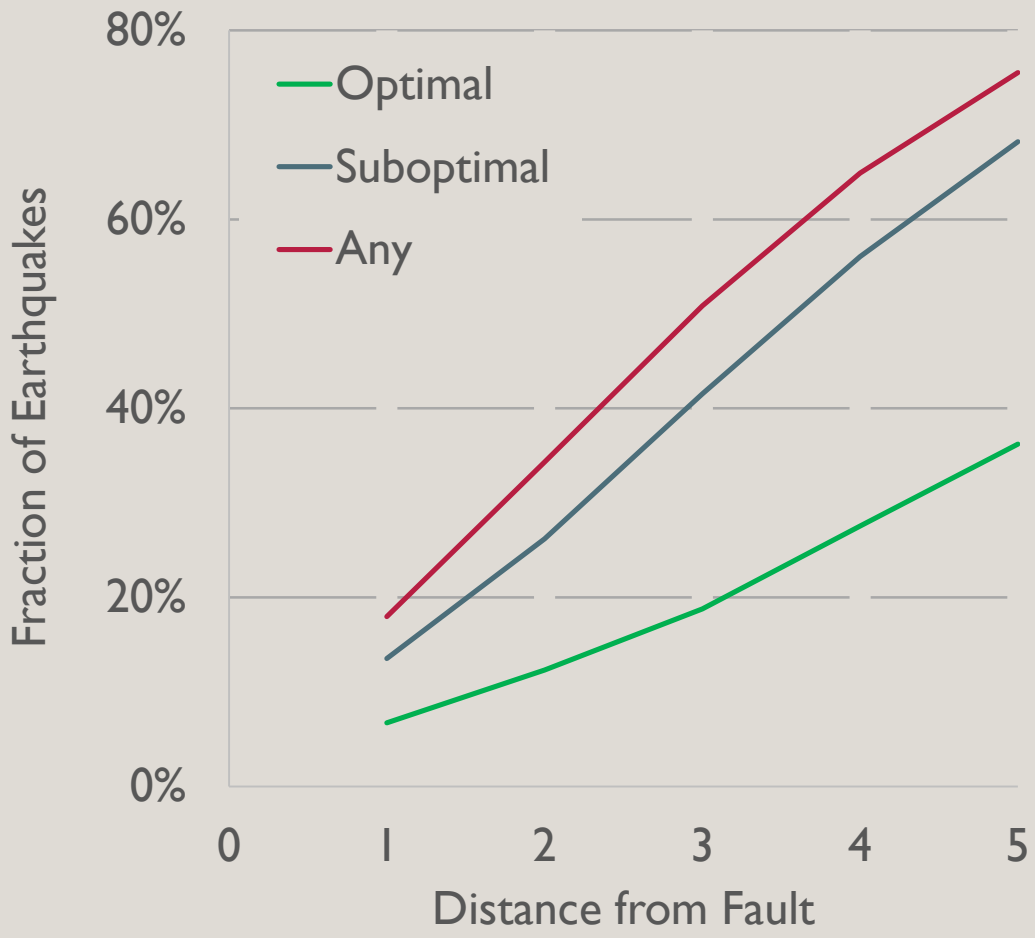
- **Oklahoma Geological Survey**
  - **Seismology**: Jacob Walter, Jefferson Chang, Fernando Ferrer, Andrew Thiel, Isaac Woelfel
  - **Hydrogeology, Geology, Geophysics**: Kyle Murray, Ella Walker, Jordan Williams, Kevin Crain, Steve Holloway,
  - **Publications & Outreach**: Ted Satterfield
- **Conoco-Phillips School of Geology and Geophysics**
  - **Seismology**: Xiaowei Chen, Nori Nakata
  - **Geology**: Douglas Elmore, Matthew Pranter,
  - **Geophysics**: Kurt Marfurt

Major additional funding sources

- Research Partnership to Secure Energy for America (RPSEA)
- U. S. Department of Energy
- Oklahoma Secretary of Energy and Environment (through Recovery Act)
- Oklahoma Governor's Emergency Fund

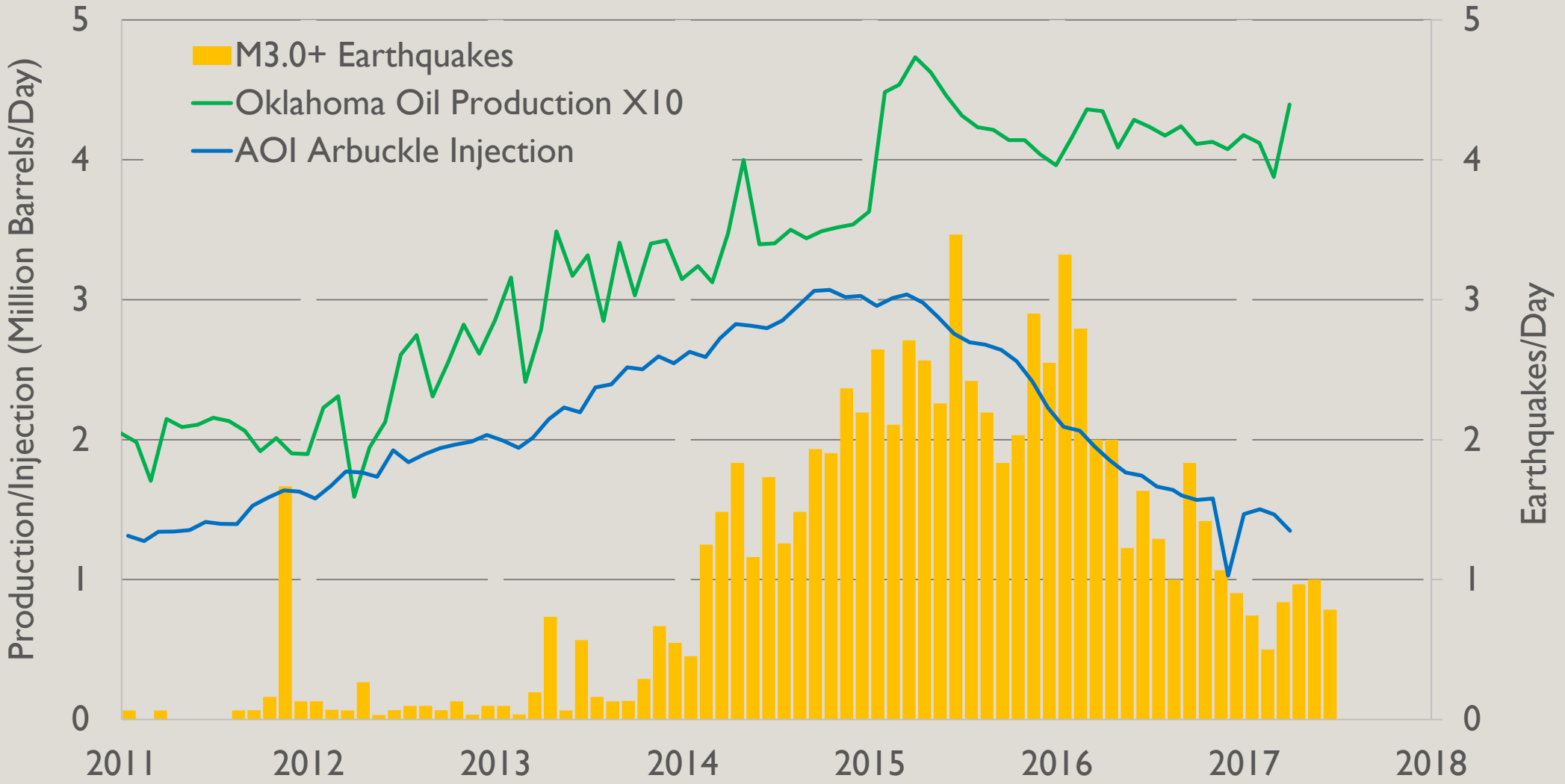
Backup Material

Location of OK earthquakes and known faults

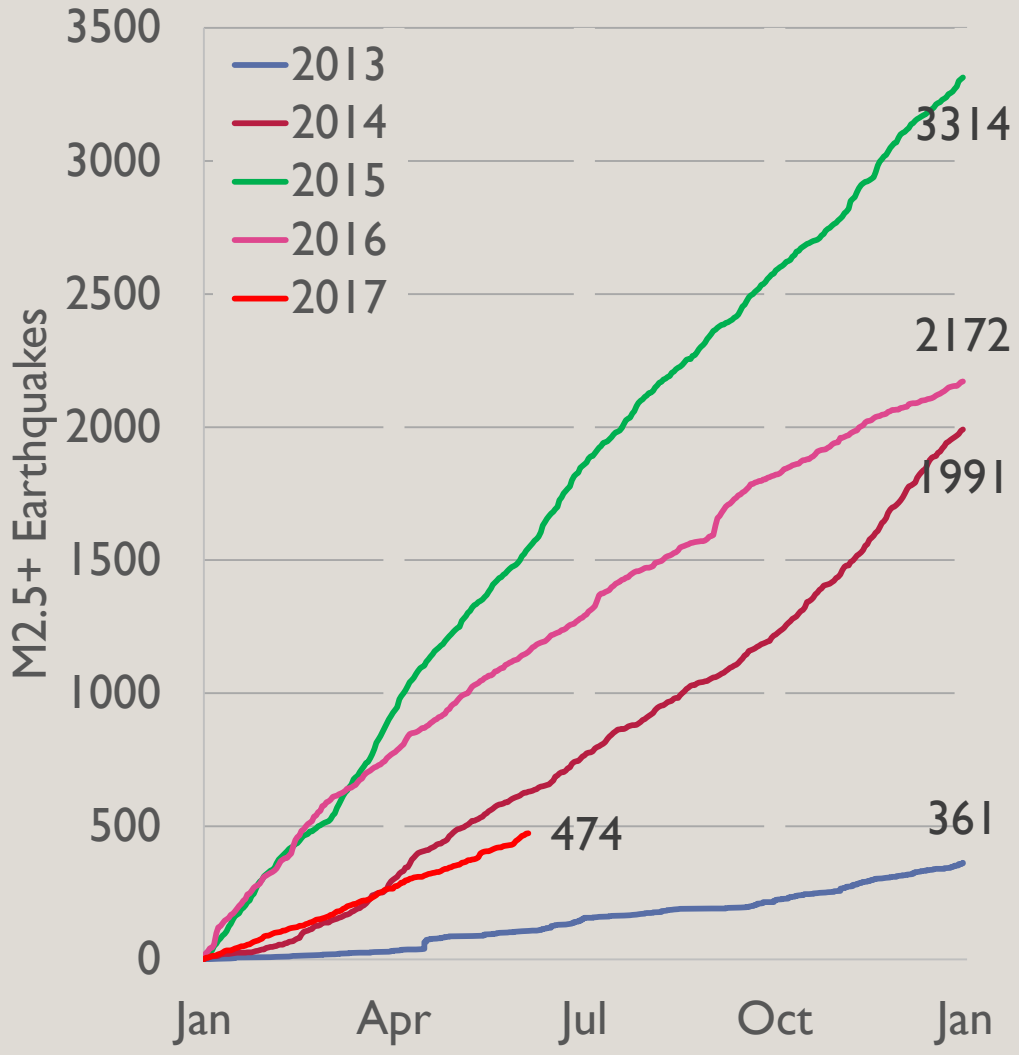


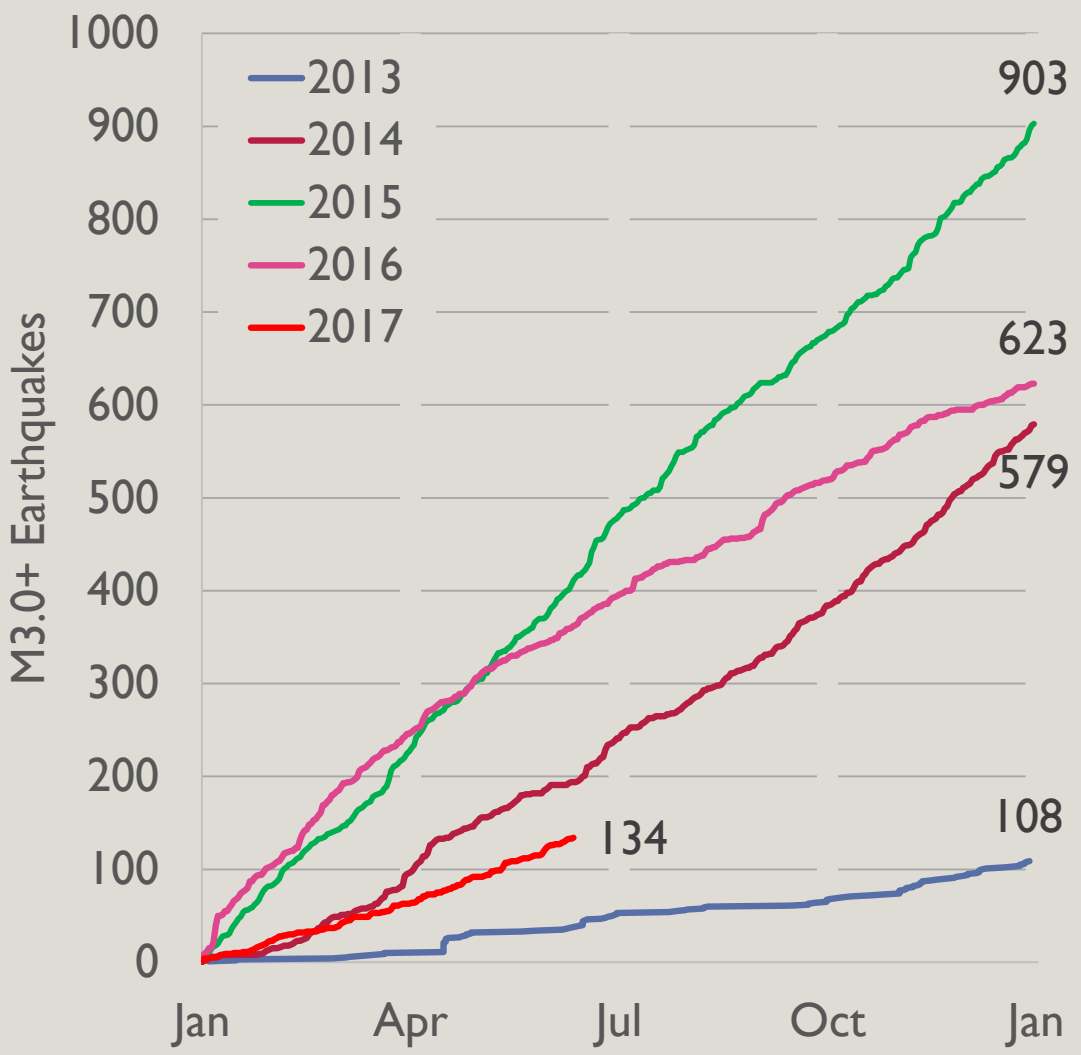
- 80% of earthquakes within 5 km of a known fault
- But only 34% of earthquakes within 2 km of any known fault
- 36% of earthquakes within 5 km of an optimally oriented fault
- 12% of earthquakes are within 2 km of an optimally oriented fault

26 Earthquakes, Oil and Water

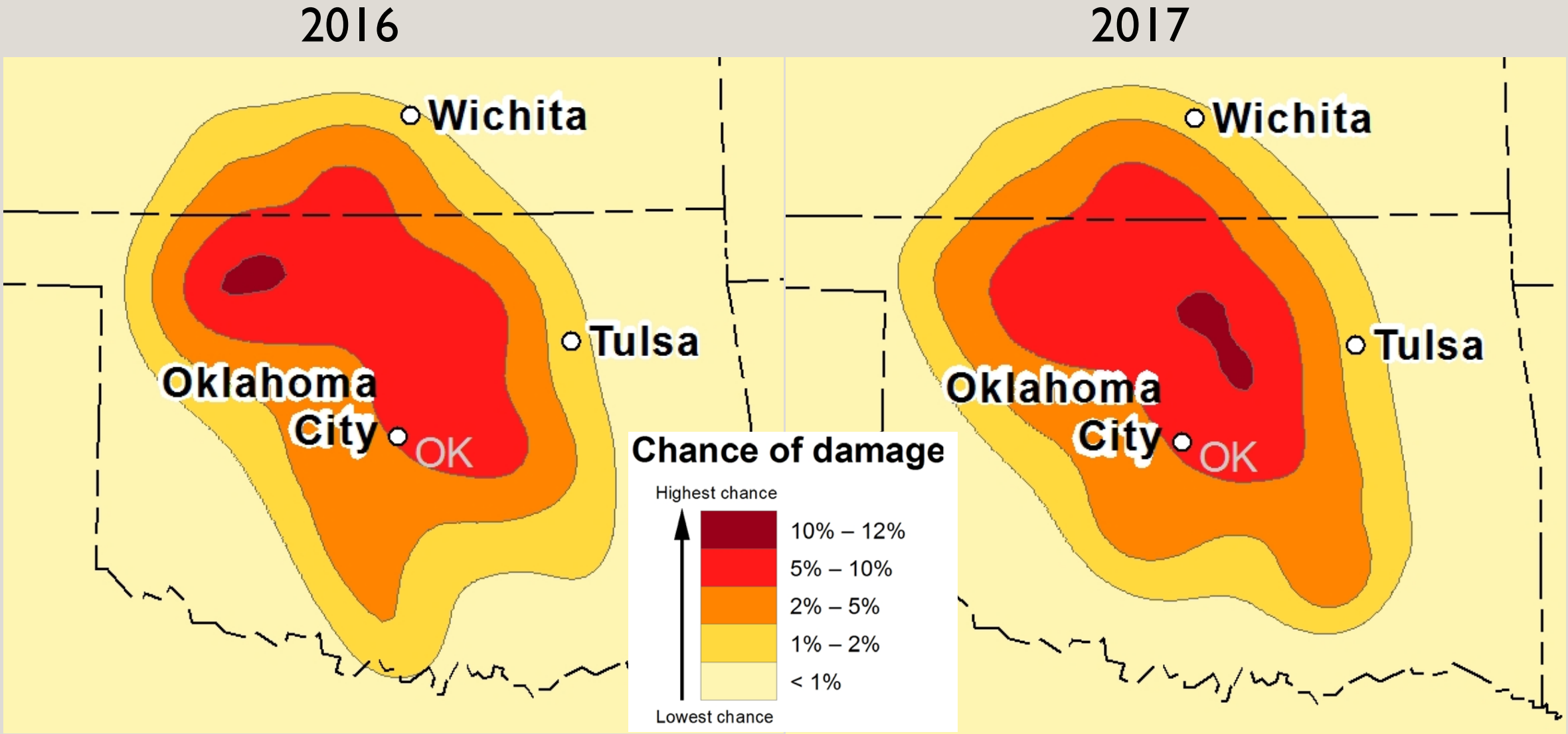


Earthquake Comparison | Year-to-Year





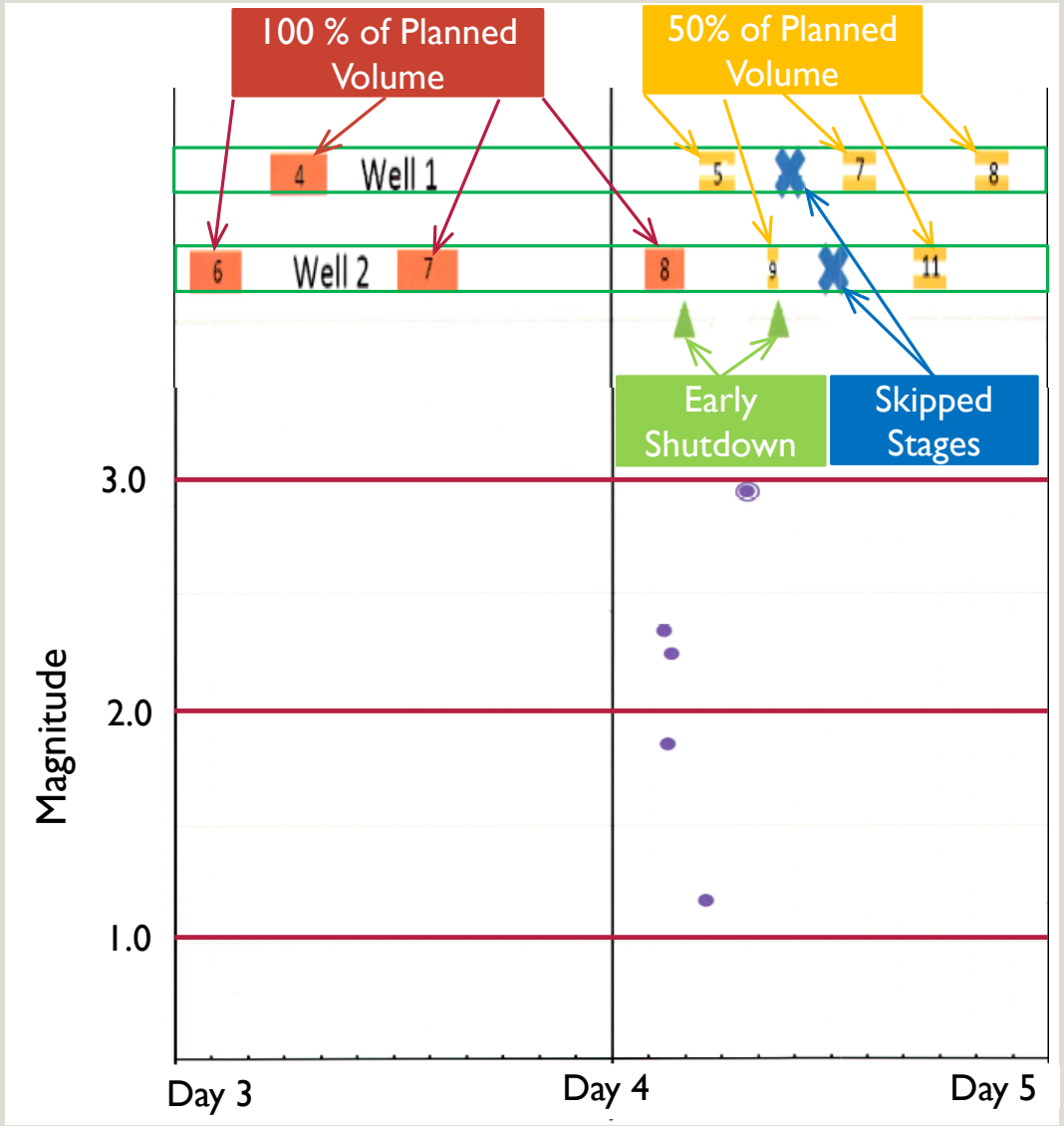
28 USGS One-Year Hazard Forecast

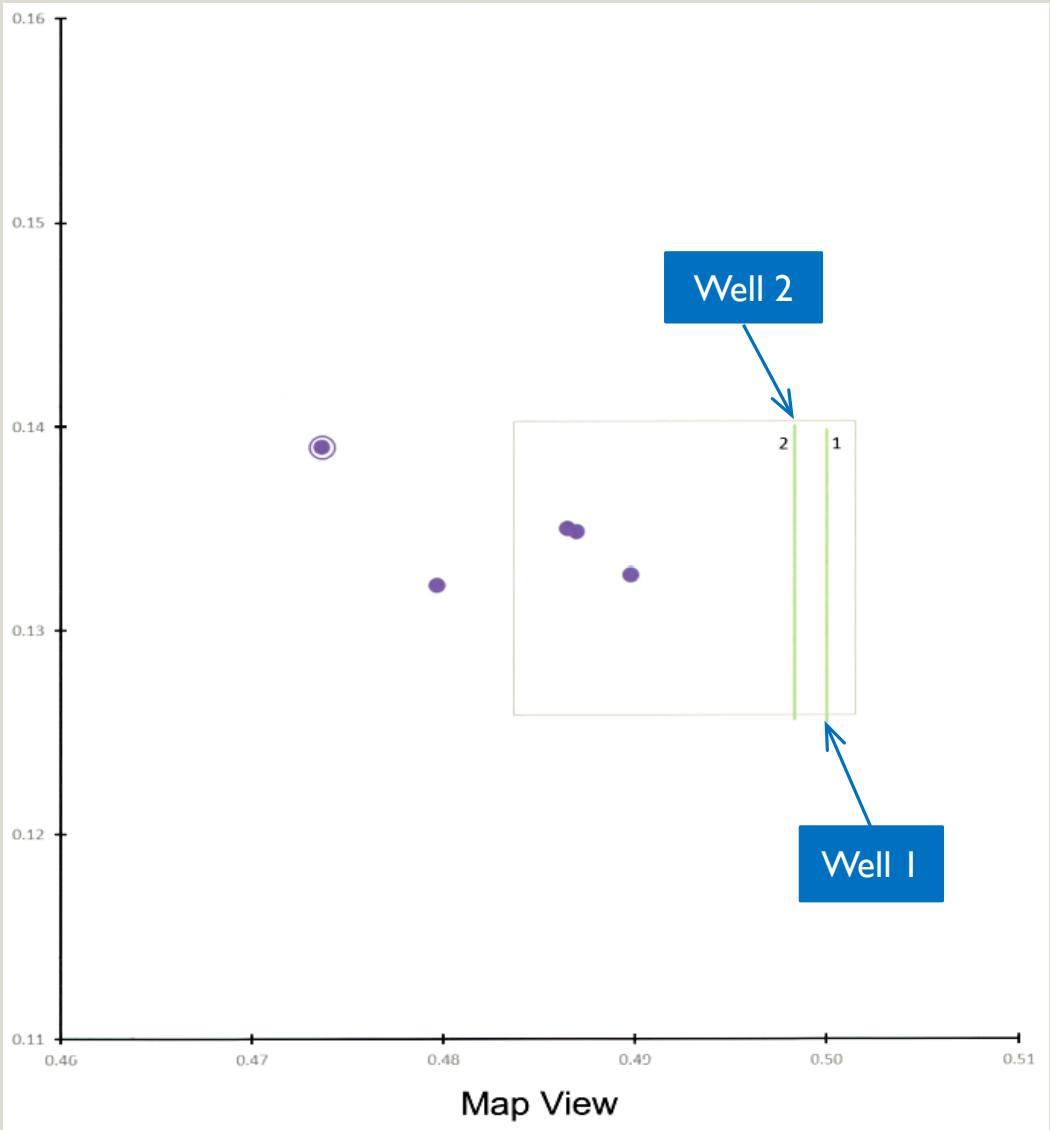


29 Summary: Induced Seismicity in Oklahoma

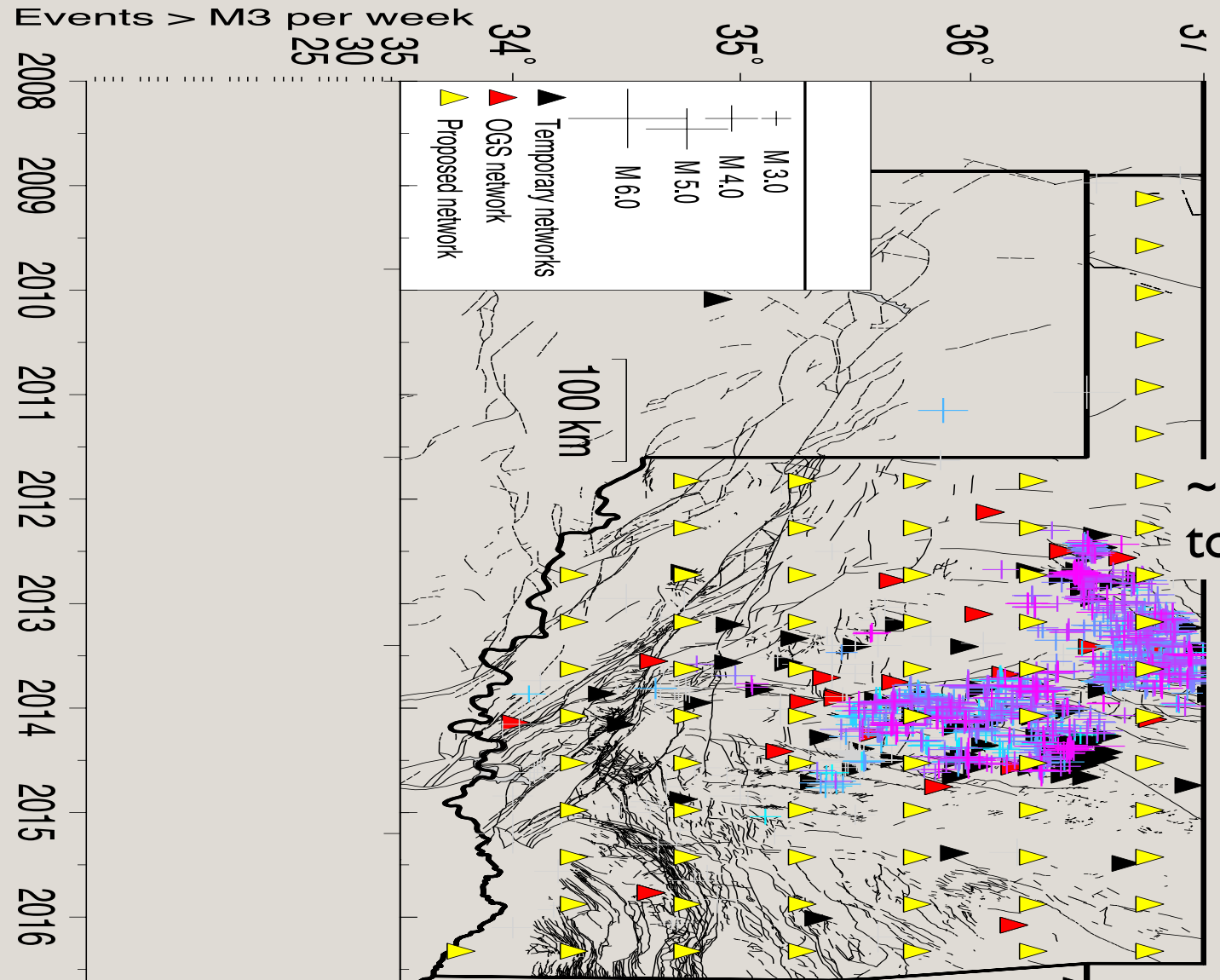
- No documented case of induced seismicity close to Oklahoma in earthquake rate or affected area
- Only 34% of earthquakes occur within 2 km of any known fault.
- It is not clear the density of faulting is greater in Oklahoma than elsewhere in the mid-continent
- Majority of recent earthquakes in central and north-central Oklahoma likely triggered by injection of produced water in SWD wells
- Hydraulic fracturing flowback water <5% of SWD volume in Arbuckle
- Drop in earthquake frequency since mid-2015 likely results from decreases in injection in Area of Interest driven by oil price and Corporation Commission directives
- Small number of lower magnitude earthquakes apparently associated with hydraulic fracturing manageable through a stoplight system

Recent Example: Action in Response to Earthquakes Induced by Hydraulic Fracturing



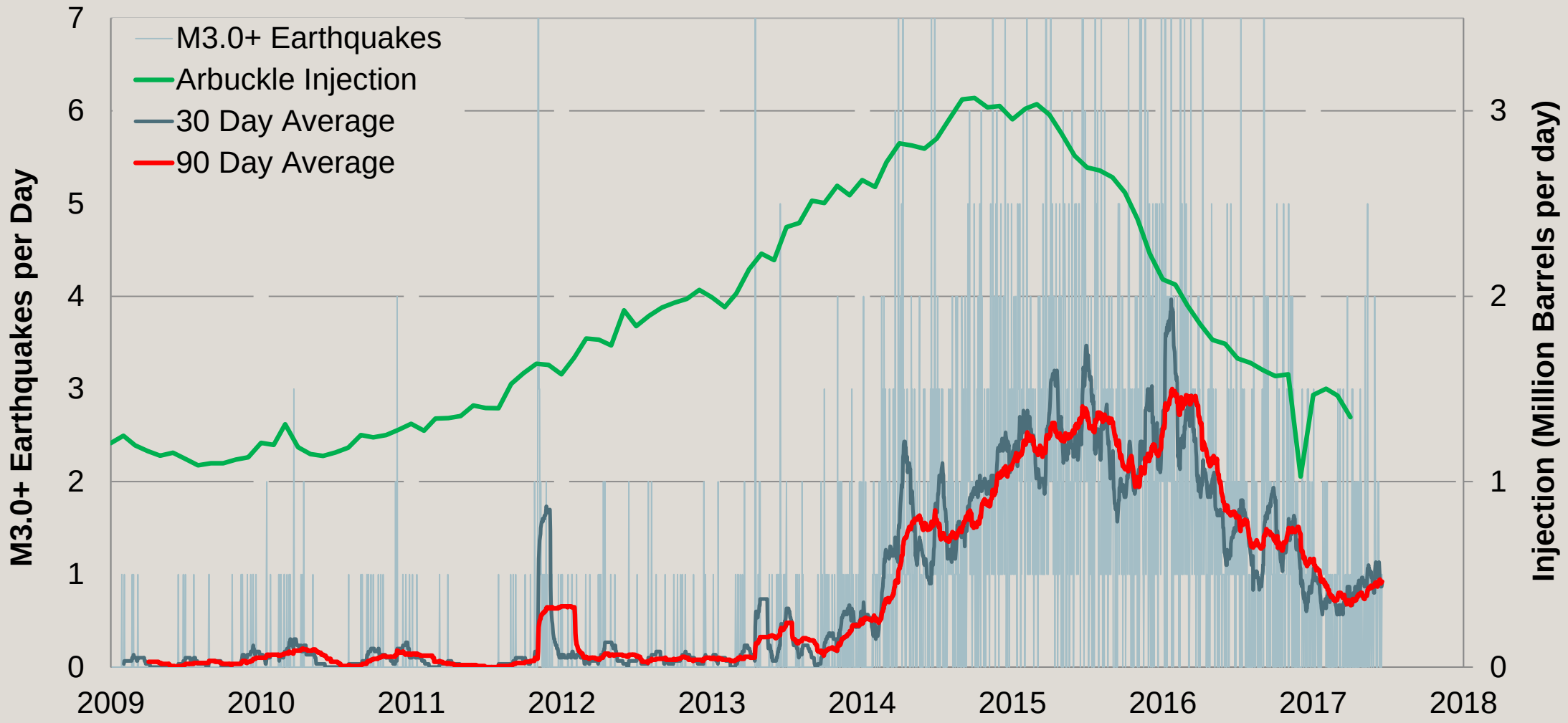


OGS vision:
A comprehensive high-quality seismic network



~$3.5 million total cost

32 Oklahoma M3.0+ earthquakes



33 OCC Directives on Injection