Oklahoma Earthquakes: An Update with Questions about Regulatory Adequacy of Scientific Interpretations*

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Abstract

The frequency of earthquakes in Oklahoma peaked in 2015, with 903 M3.0+ earthquakes, declined to 619 in 2016, and is declining further in 2017, to a projected 302 M3.0+ earthquakes for 2017 (as of October). However, seismic moment peaked in 2016, with three earthquakes of M5.0+, unprecedented in Oklahoma's recorded history. Seismic energy release is distinctly lower in 2017; a remarkable seismic lull in January and February has been followed by a return to levels similar to late 2016.

Rising seismicity has been attributed to greatly increased disposal of saline formation water from high water cut wells into under pressured and relatively permeable Arbuckle Group sedimentary rocks overlying Precambrian crystalline basement (for example, Walsh and Zoback, 2015). Pressure communication from the Arbuckle Group to faults in the basement is interpreted to have reduced stress on favorably aligned faults. More recently, poroelastic effects have been interpreted to play a role as well (Barbour et al. 2017).

Reduction in frequency results from a decrease of >1,000,000 barrels per day of disposal in ~700 Arbuckle disposal wells in the seismic Area of Interest (AOI). Reductions in disposal occurred due to 1) reduced production driven by a significant oil price drop since 2014, and 2) shut in or reduced injection directed by the Oklahoma Corporation Commission. A recent model suggests that seismicity will decline toward background levels in a few years (Langenbruch and Zoback, 2017a), although these results have been debated (Goebel and others, 2017; Langenbruch and Zoback, 2017b). It remains uncertain whether the recent flattening/increase lies outside these projections.

At the same time, a second class of earthquakes has been identified outside the main Area of Interest that are associated in location and time with oil and gas well completion activities. These are generally smaller, less frequent, and readily mitigated by operator actions.

A recent issue of Seismological Research Letters highlights diverse new research results on the September 3, 2016 M5.8 Pawnee earthquake, the largest recorded in Oklahoma (Chen and Norikata, eds. 2017). This talk will discuss these and other recent research results on the nature of seismicity in Oklahoma. It will describe the evolution of Oklahoma seismicity and the regulatory actions taken to reduce it. It will also describe recent investigations of regional variation in earthquake frequency within the AOI.

Selected References

Cantner, K., 2018, Induced Seismicity: https://www.earthmagazine.org/article/ground-shaking-research-how-humans-trigger-earthquakes, Web Accessed June 19, 2018.

Darold, A.P, A.H. Holland, J.K. Morris, and A.R. Gibson, 2015, Oklahoma Earthquake Summary Report 2014: Oklahoma Geological Survey Open File Report 1-2015, 46 pages.

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U.S. Department of Energy, 2018, Energy Information Administration: https://www.eia.gov/dnav/pet/pet_pri_spt_s1_m.htm, Web Accessed June 19, 2018.

Walsh, F.R., and M.D. Zoback, 2015, Oklahoma's recent earthquakes and saltwater disposal: Sci. Adv. 2015; 1:e1500195, 18 June 2015.

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AAPG Annual Convention and Exposition

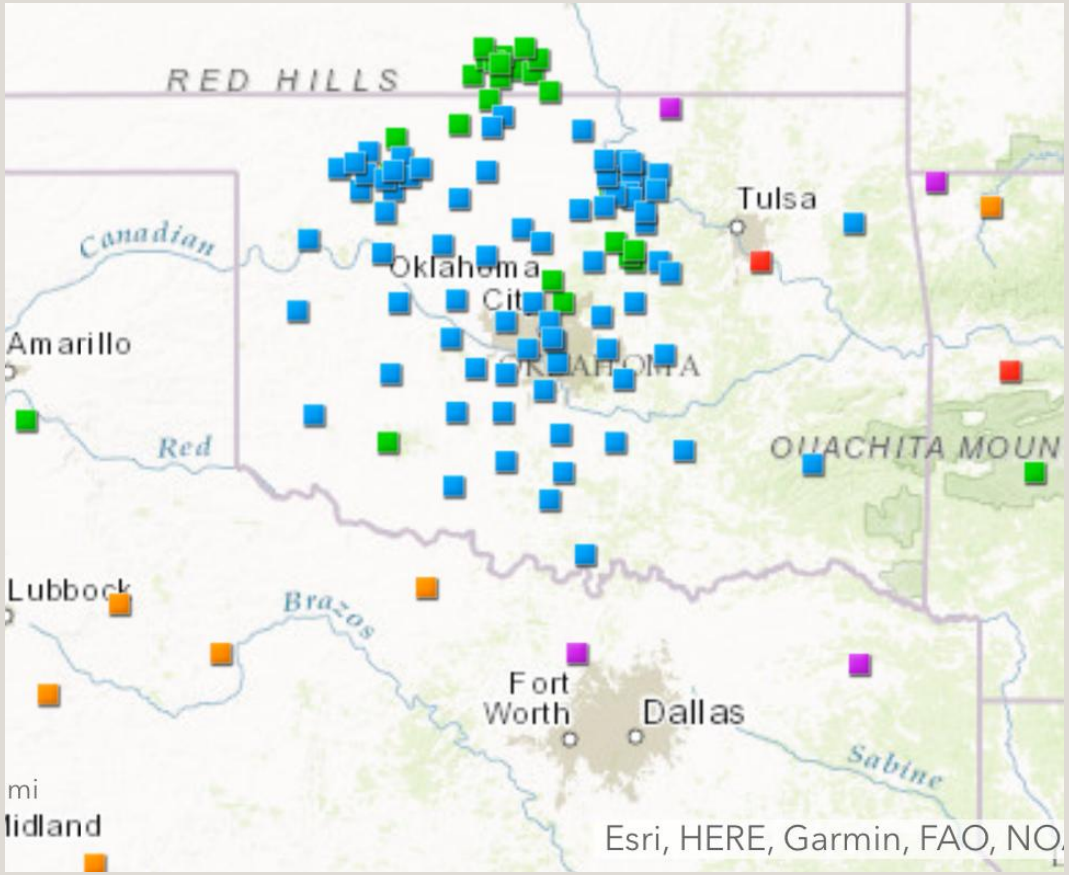
Salt Lake City

May 21, 2018

Outline

- OGS seismic network and research team
- Induced seismicity in Oklahoma
- Patterns of seismicity and science-based regulatory actions
  - Regulatory action must be prudent and based on full range of science, reasonable scenarios, recognized uncertainty
  - Decisions taken with incomplete information can still be prudent
  - Geologic structure and petroleum development history are critical to understanding seismic activity
  - Simple tests may be able to validate more complicated models

Multi-disciplinary response to seismicity at OU



- **Oklahoma Geological Survey**
  - **Seismology**: Jacob Walter, State Seismologist, Jefferson Chang, Fernando Ferrer, Andrew Thiel, Peter Dotray, Isaac Woelfel
  - **Hydrogeology, Geology**: Kyle Murray
  - **Publications & Outreach**: Ted Satterfield, Molly Yunker
- **Conoco-Phillips School of Geology and Geophysics**
  - **Seismology**: Xiaowei Chen, Nori Nakata, Michael Behm
  - **Geology**: Douglas Elmore, Matthew Pranter
  - **Geophysics**: Kurt Marfurt
- **Mewbourne School of Petroleum & Geological Engineering**
  - **Petroleum Engineering:** Zulfiquar Reza

Human activity can induce earthquakes

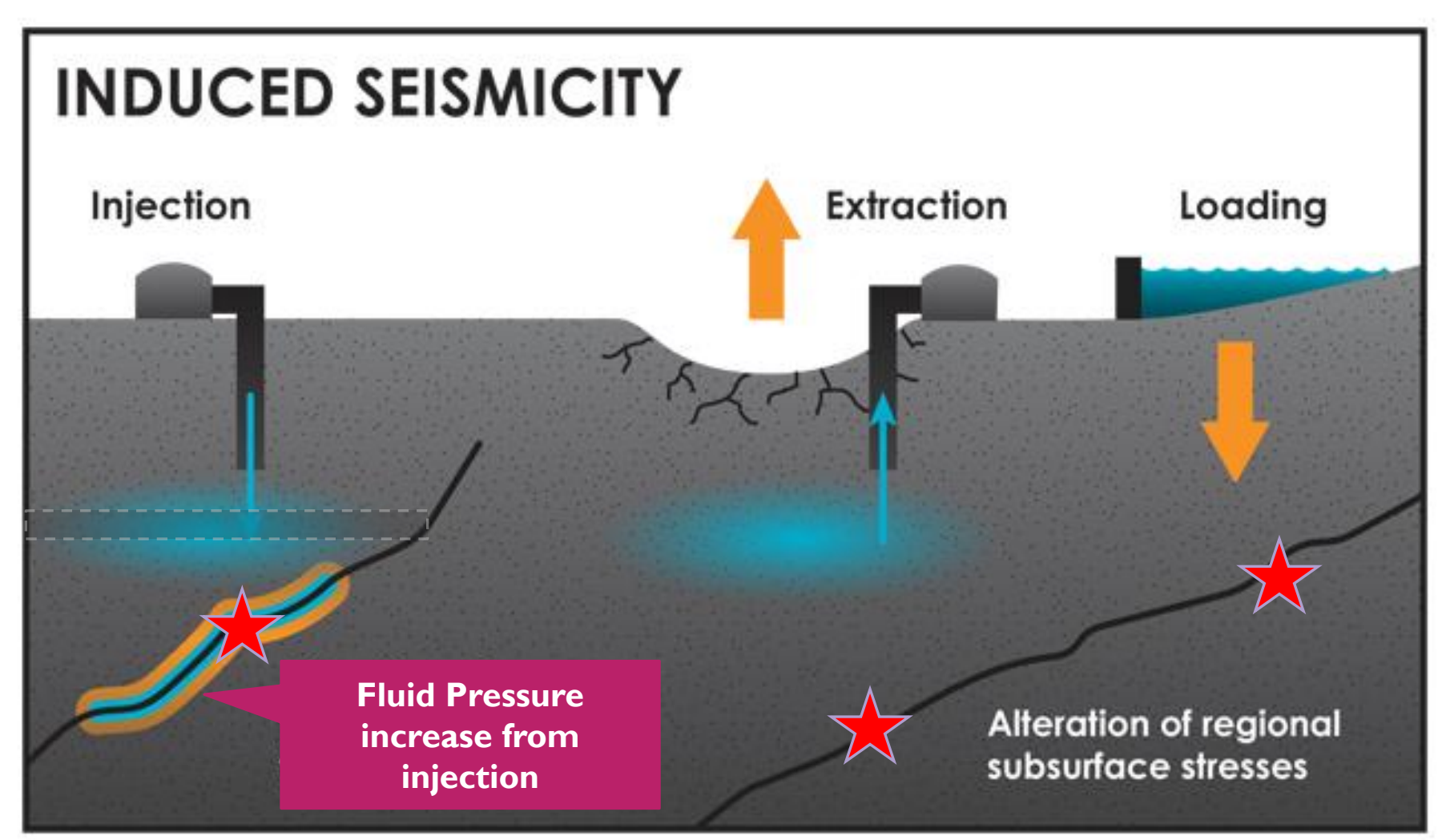
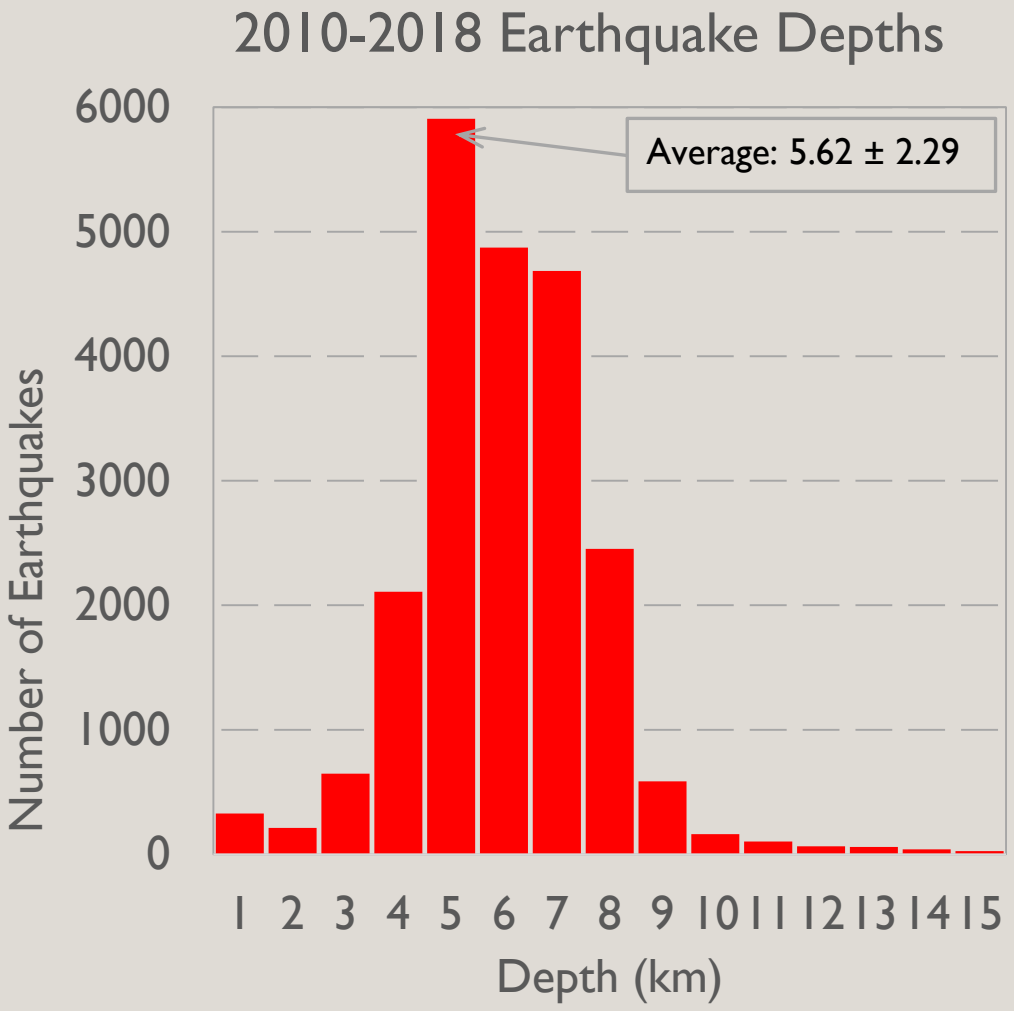
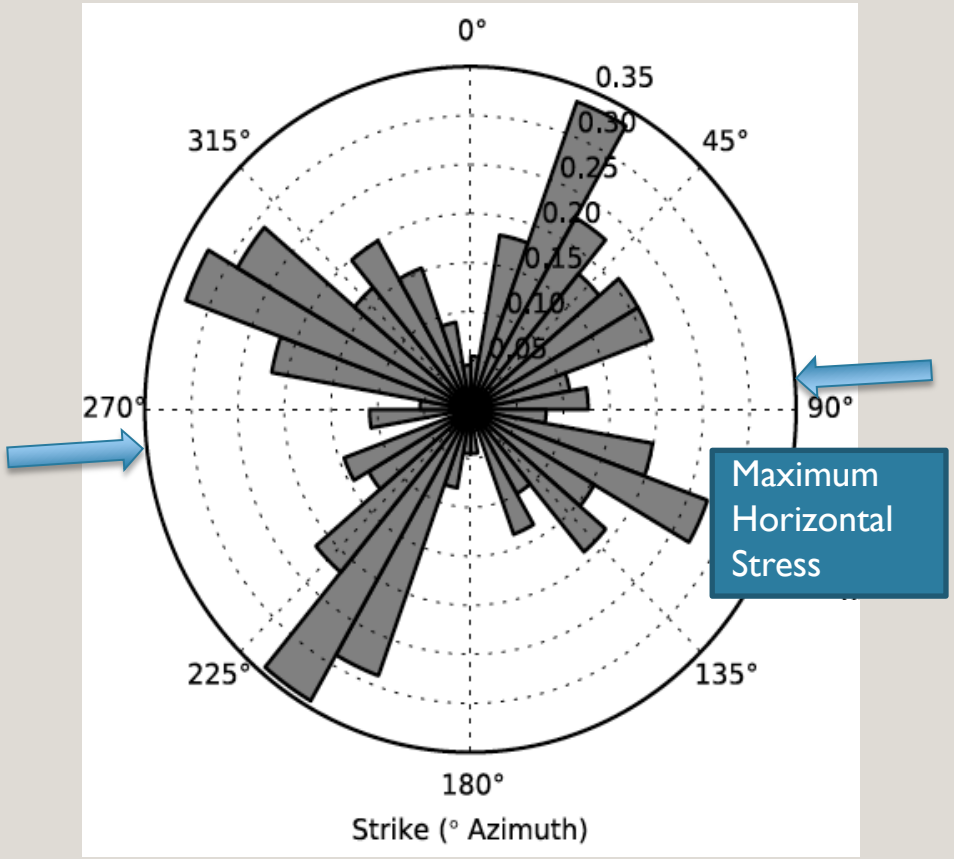


Figure modified from: http://www.earthmagazine.org/article/ground-shaking-research-how-humans-trigger-earthquakes

OK earthquakes occur in basement, on optimally aligned faults



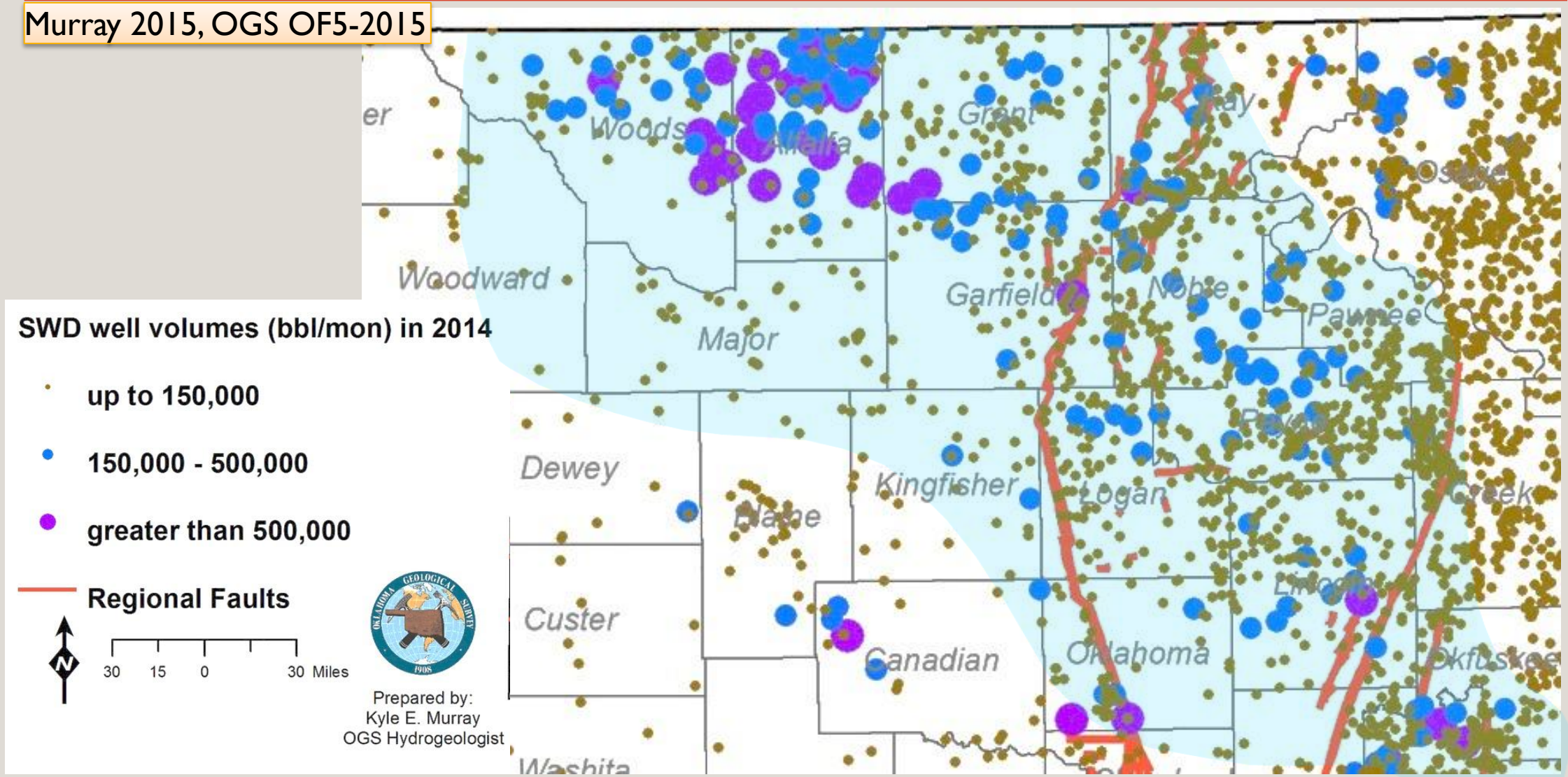
Active Fault Orientations 2014



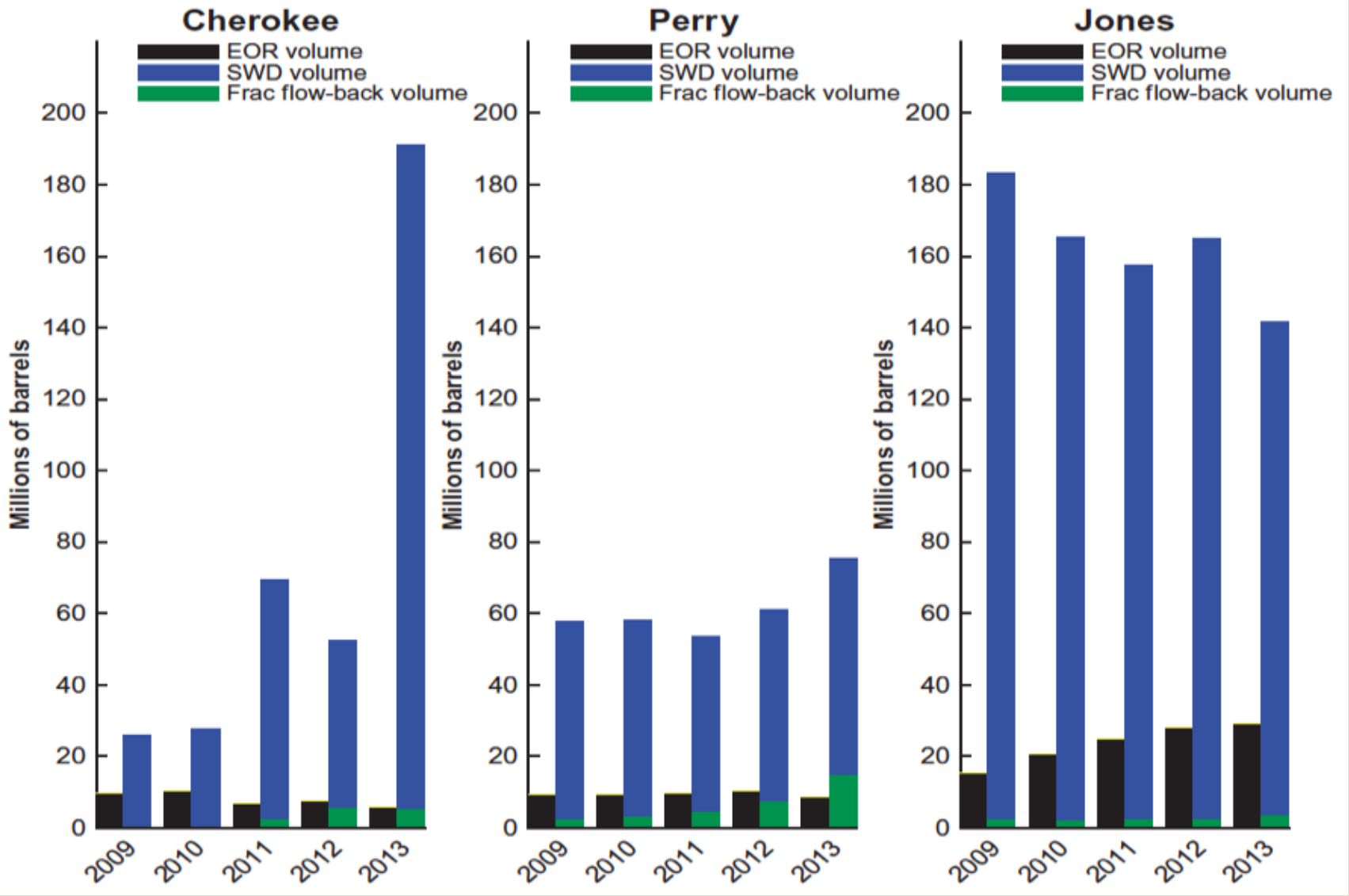
OGS OF1-2015

Earthquakes occur in areas of large volume disposal wells

Murray 2015, OGS OF5-2015

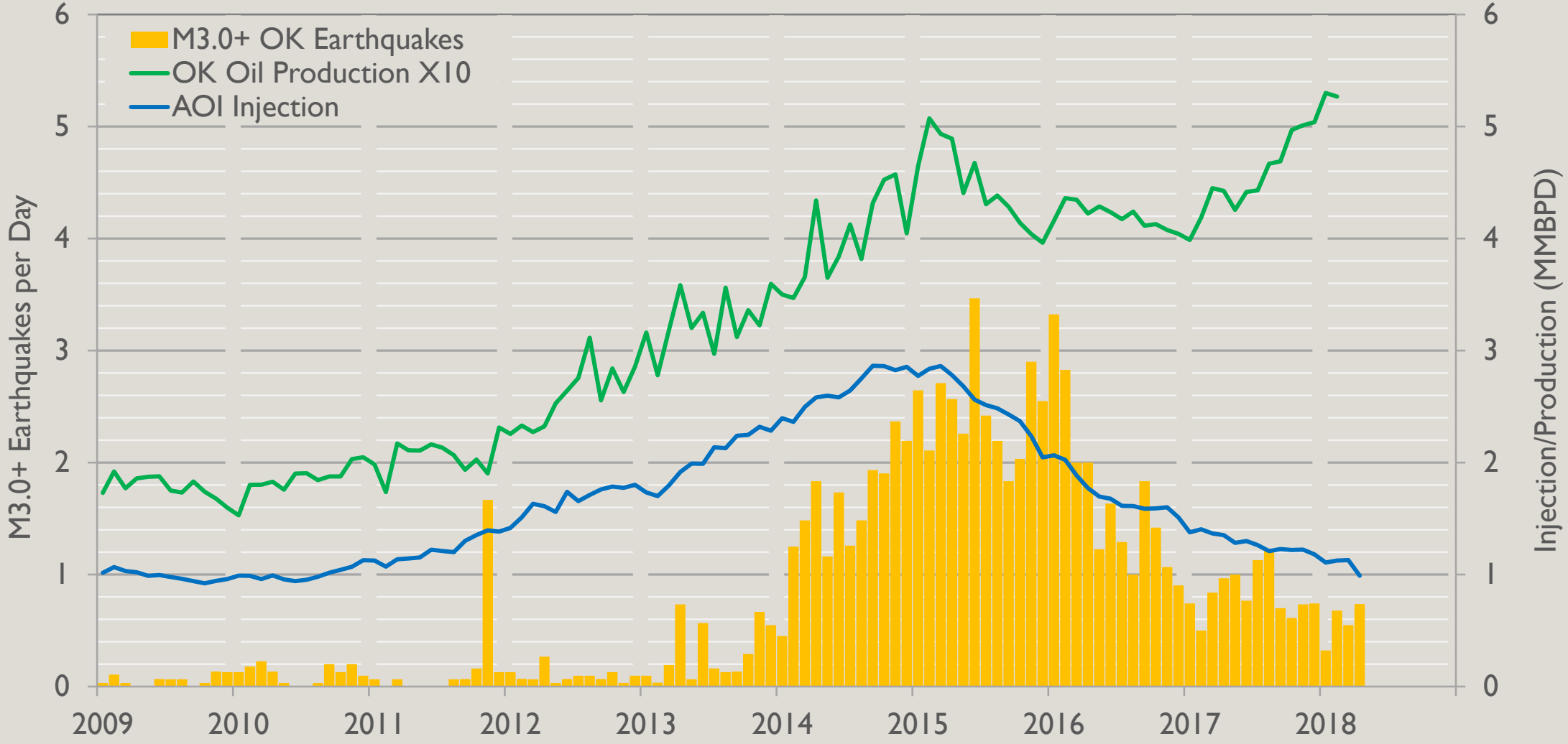


Disposal contains <5% flowback water from hydraulic fracturing

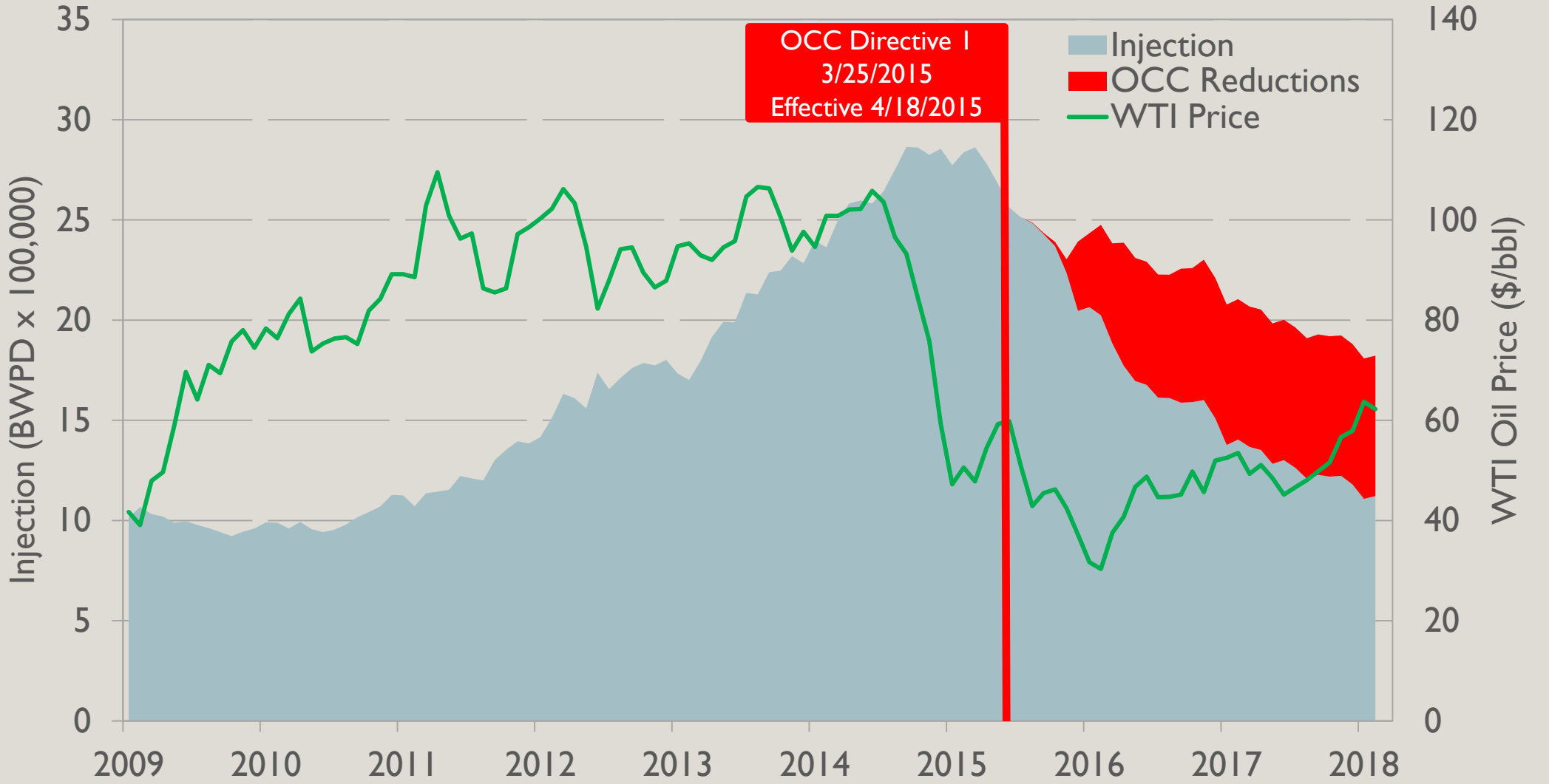


Source: Walsh, F. R., and Zoback, M. D. (2015) *Oklahoma's recent earthquakes and saltwater disposal.* Sci. Adv. 2015; 1:e1500195, 18 June 2015

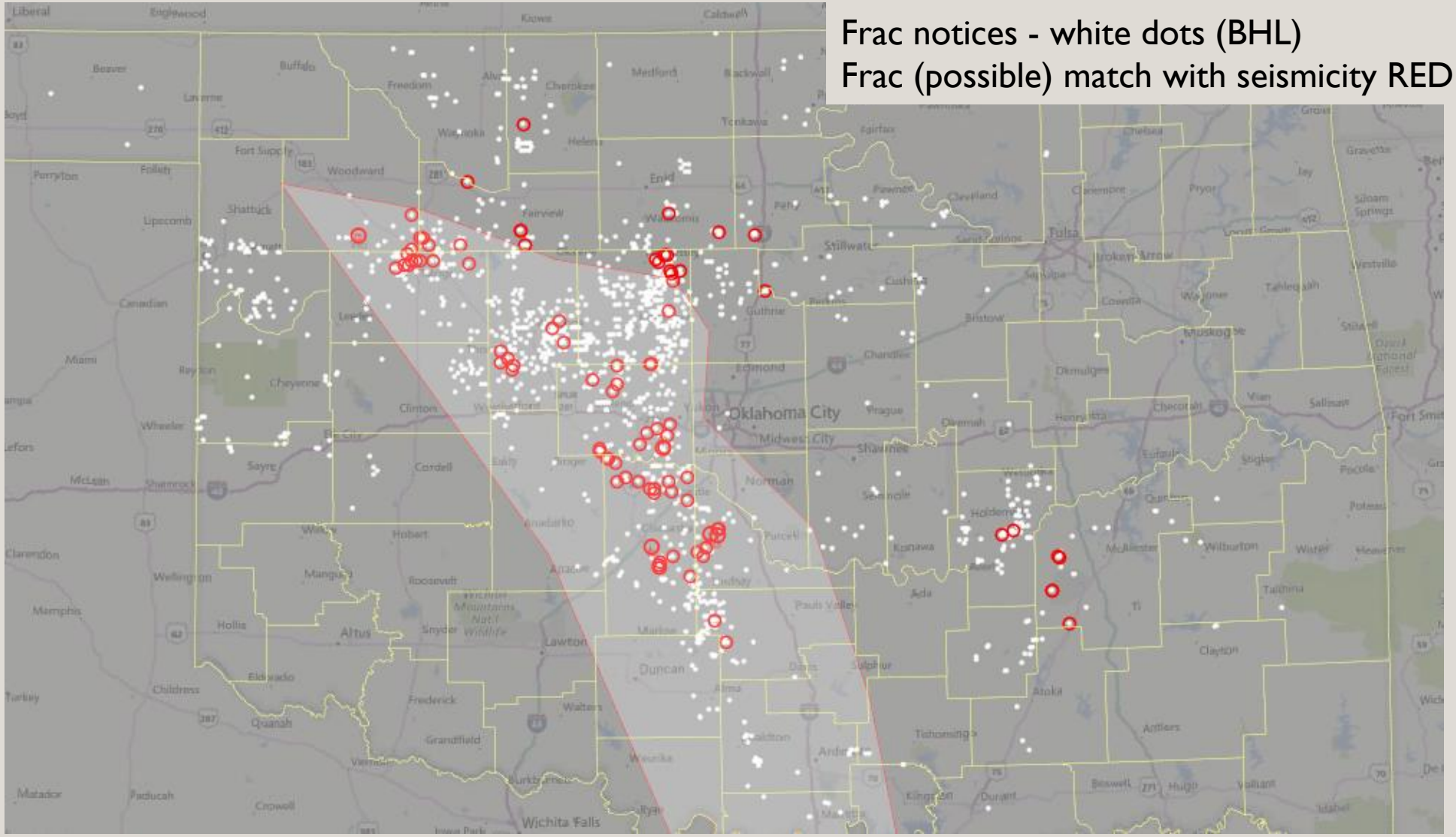
Earthquakes, Injection, Oil Production



Oil price, injection rate and OCC directed reductions

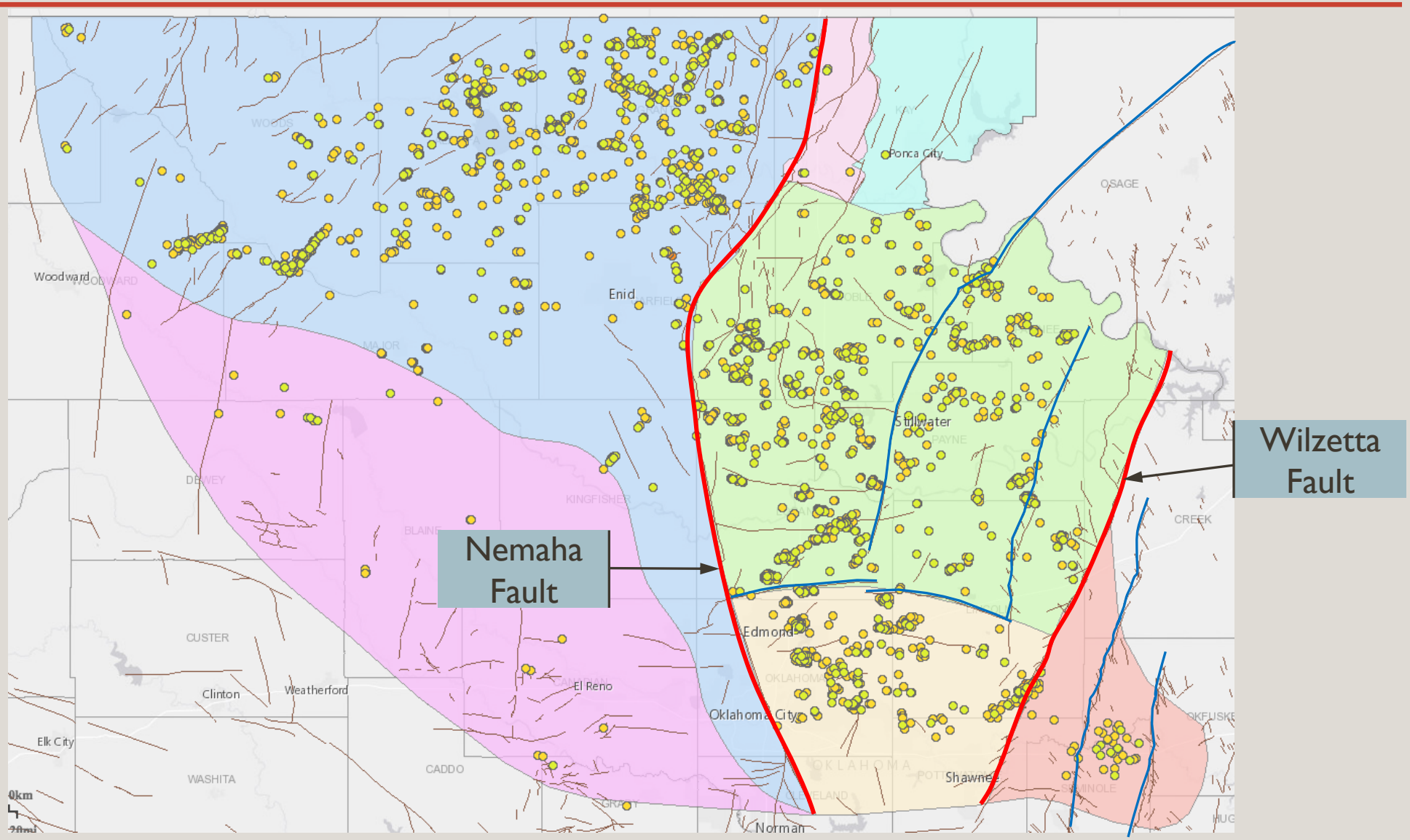


Anomalous seismicity associated with completion operations – a different population

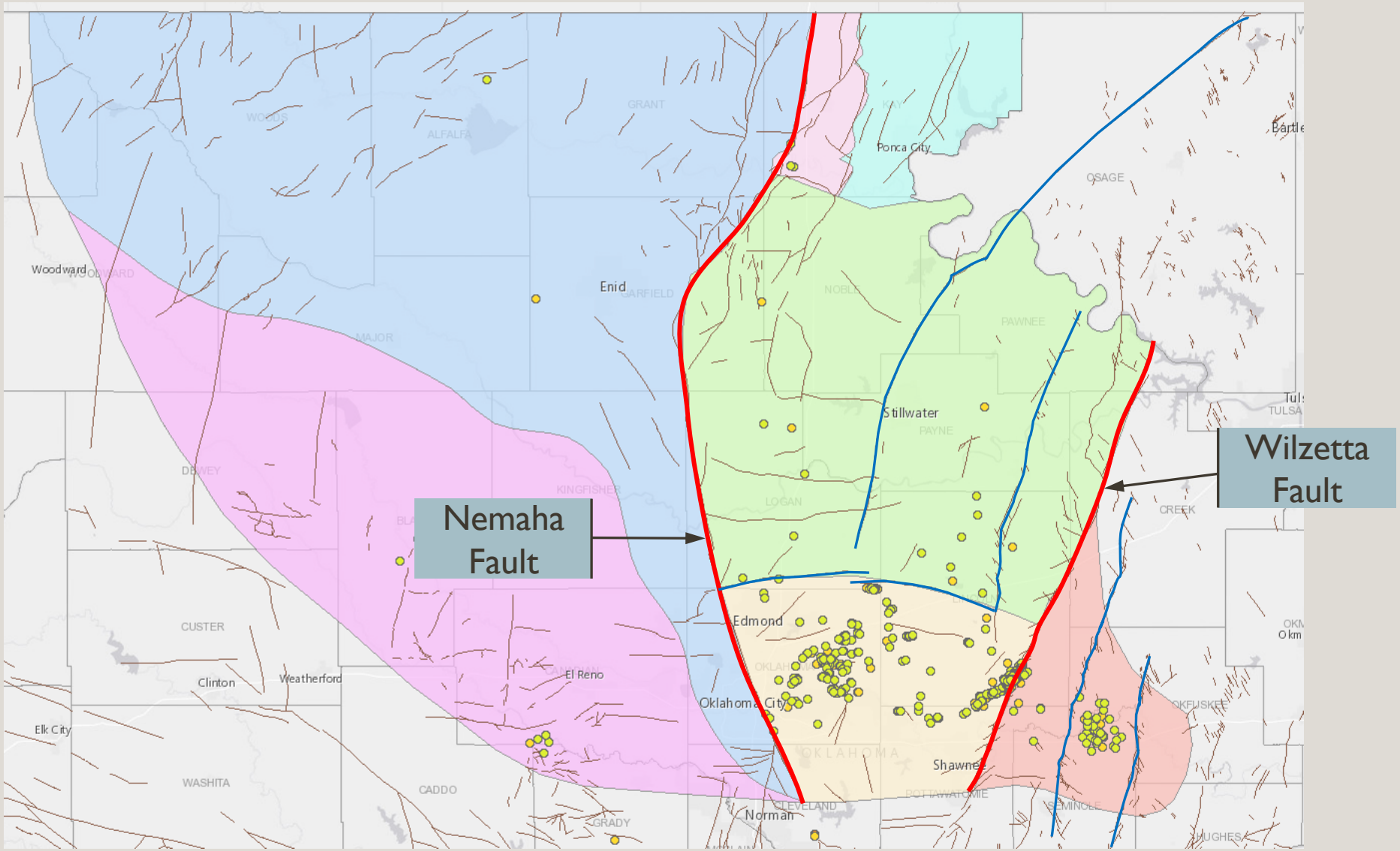


Frac notices - white dots (BHL)
Frac (possible) match with seismicity RED dots

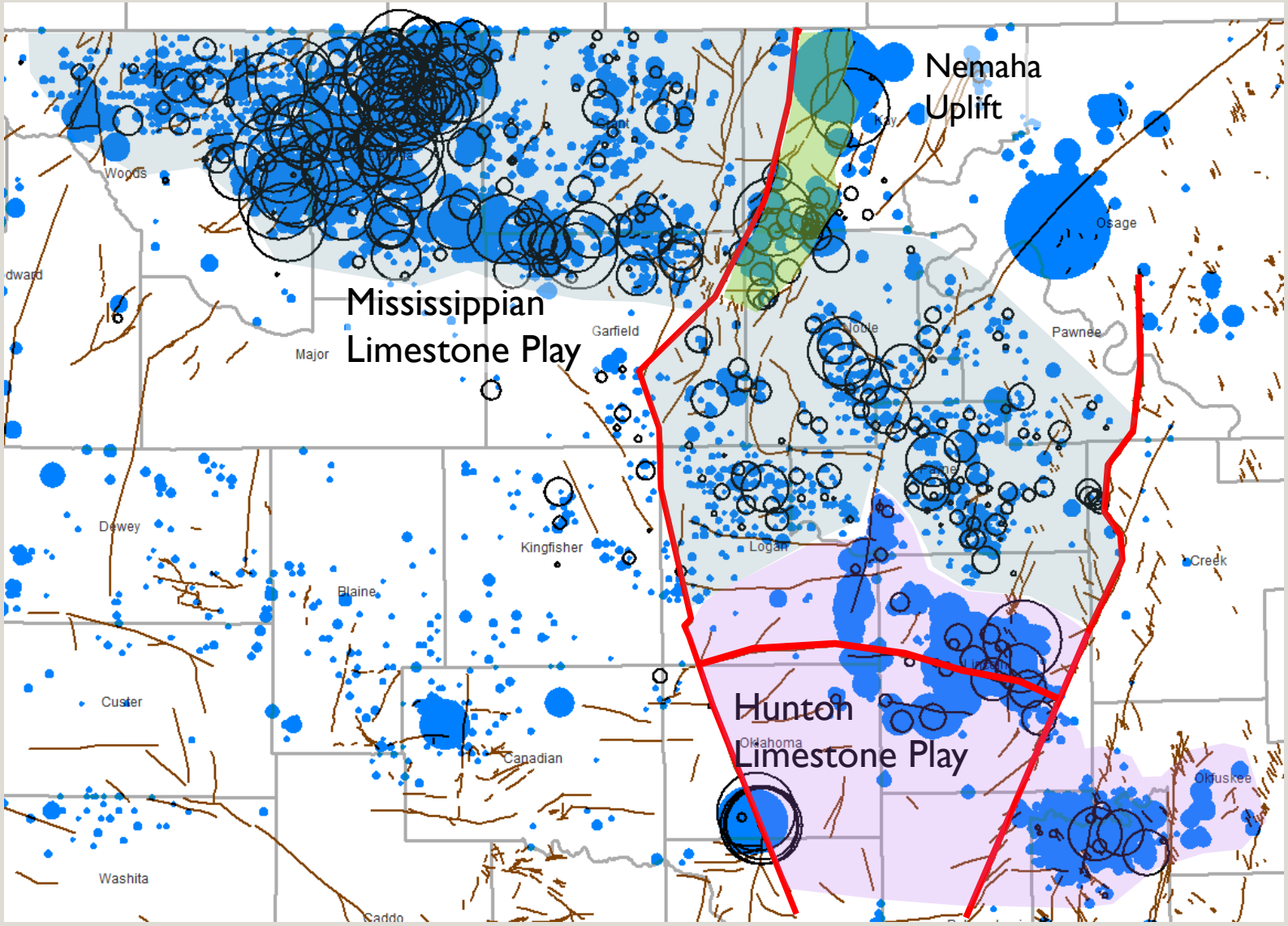
Have we recognized all the important faults?



2009-2012 M2.5+ earthquakes



Petroleum development history affects seismicity

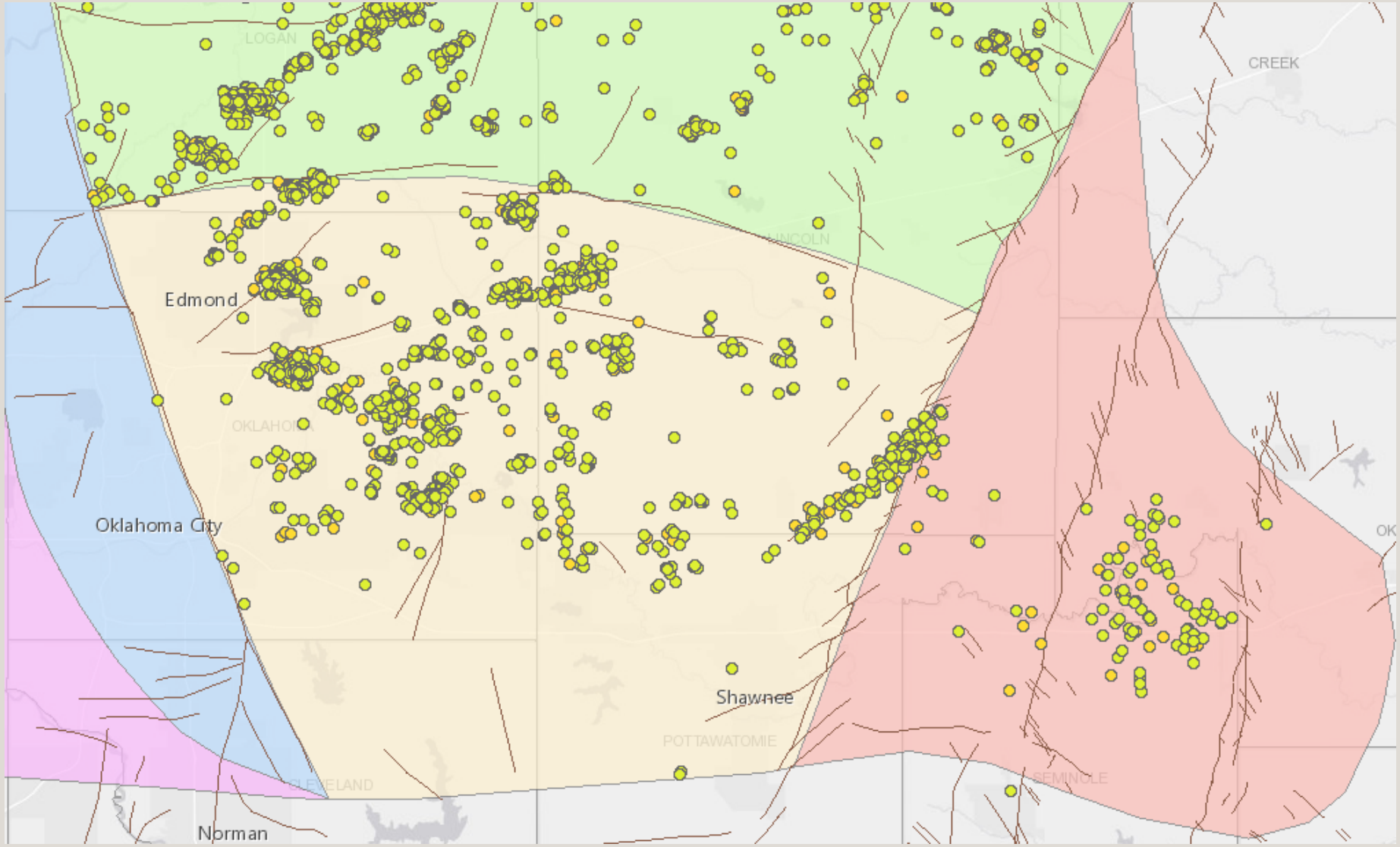


Initial Water Production

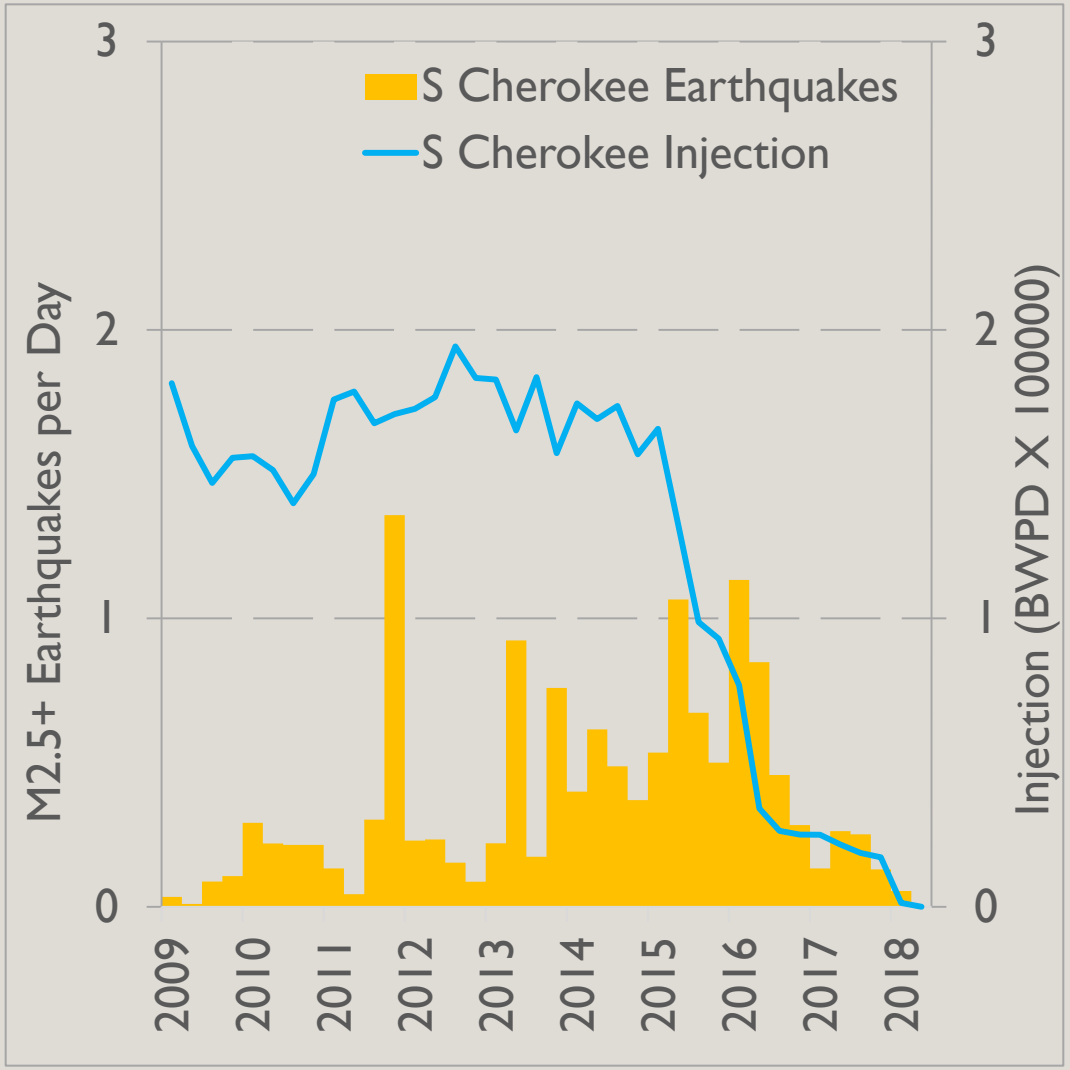
Cumulative Injection

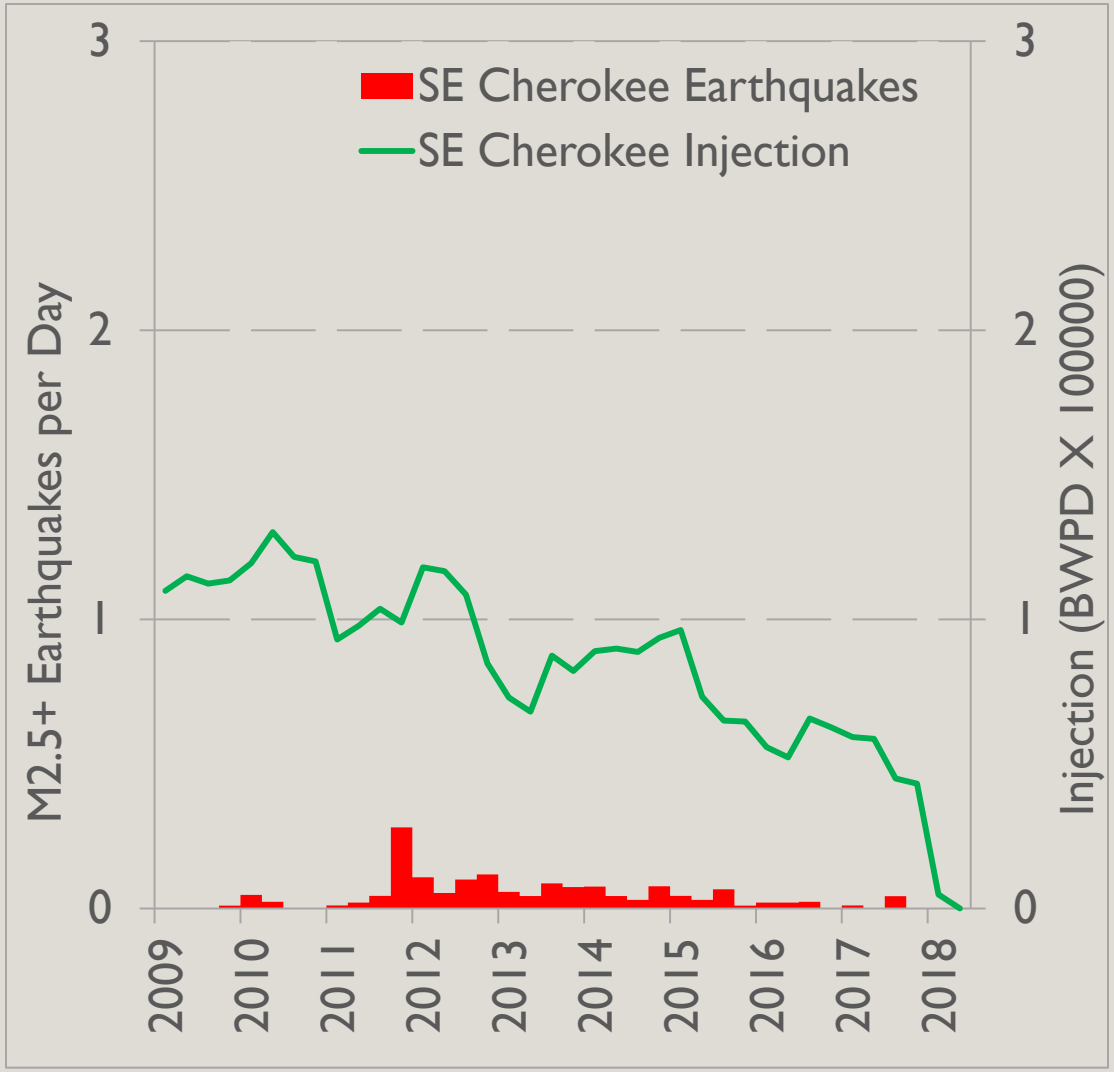
Figure Courtesy of
Anna Stafford, IPA LLC

M2.5+ earthquakes, S, SE Cherokee Platform

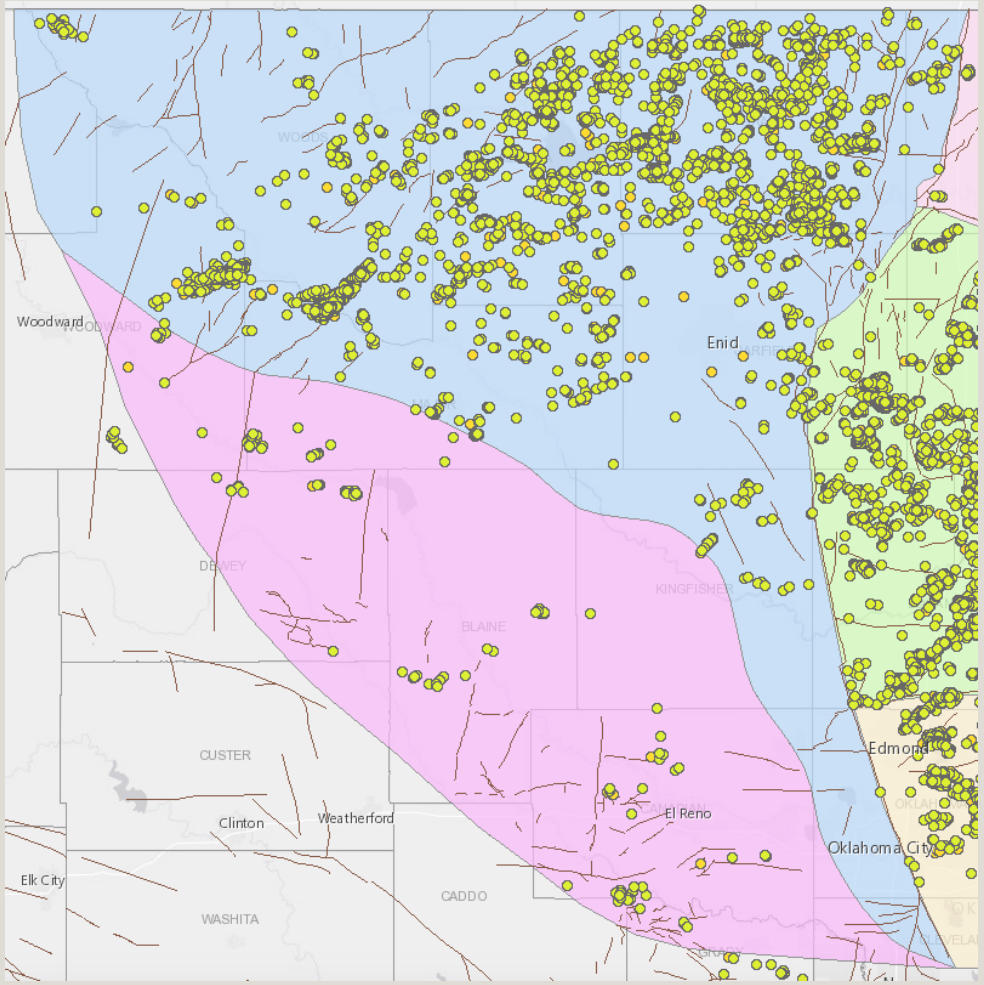


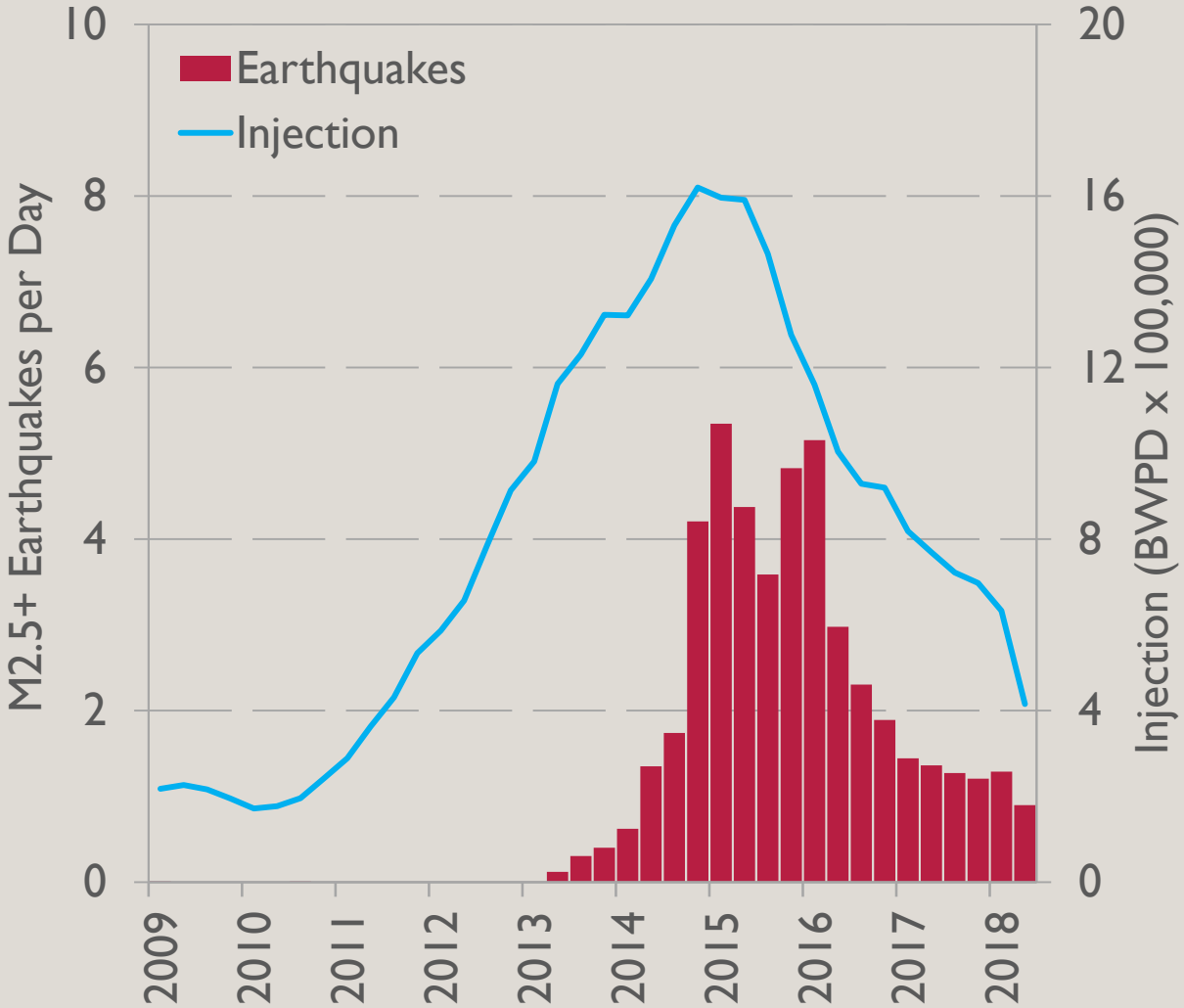
M2.5+ earthquakes, S, SE Cherokee Platform



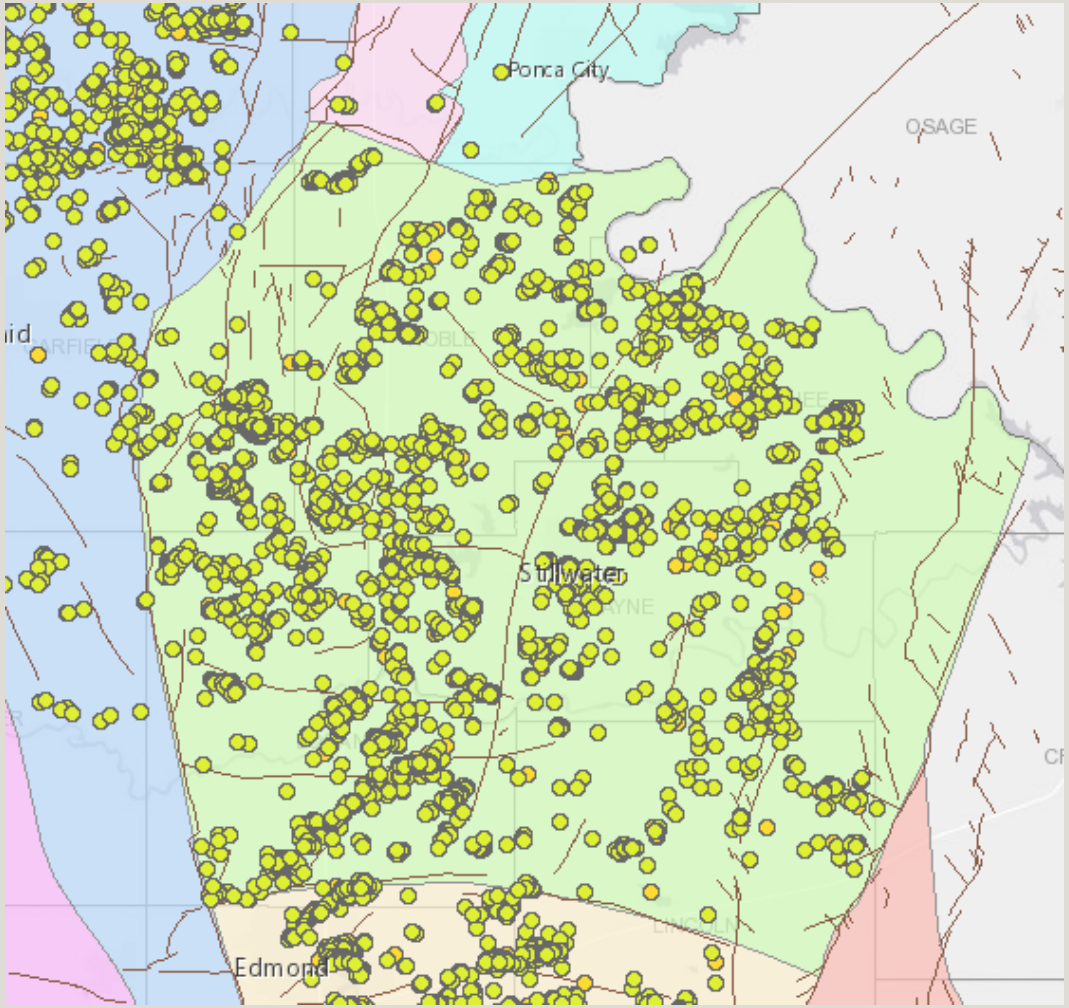


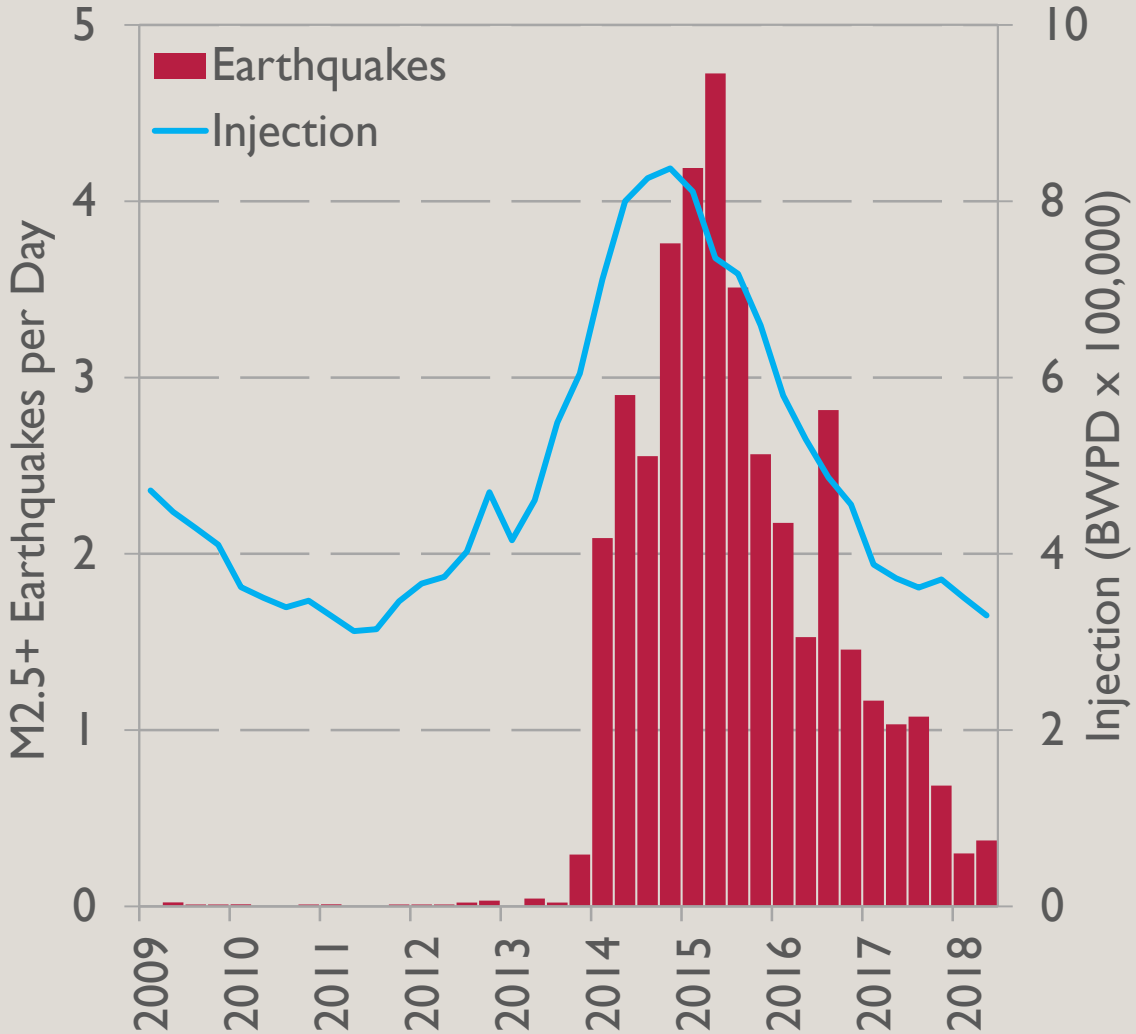
Anadarko Shelf M2.5+ earthquakes



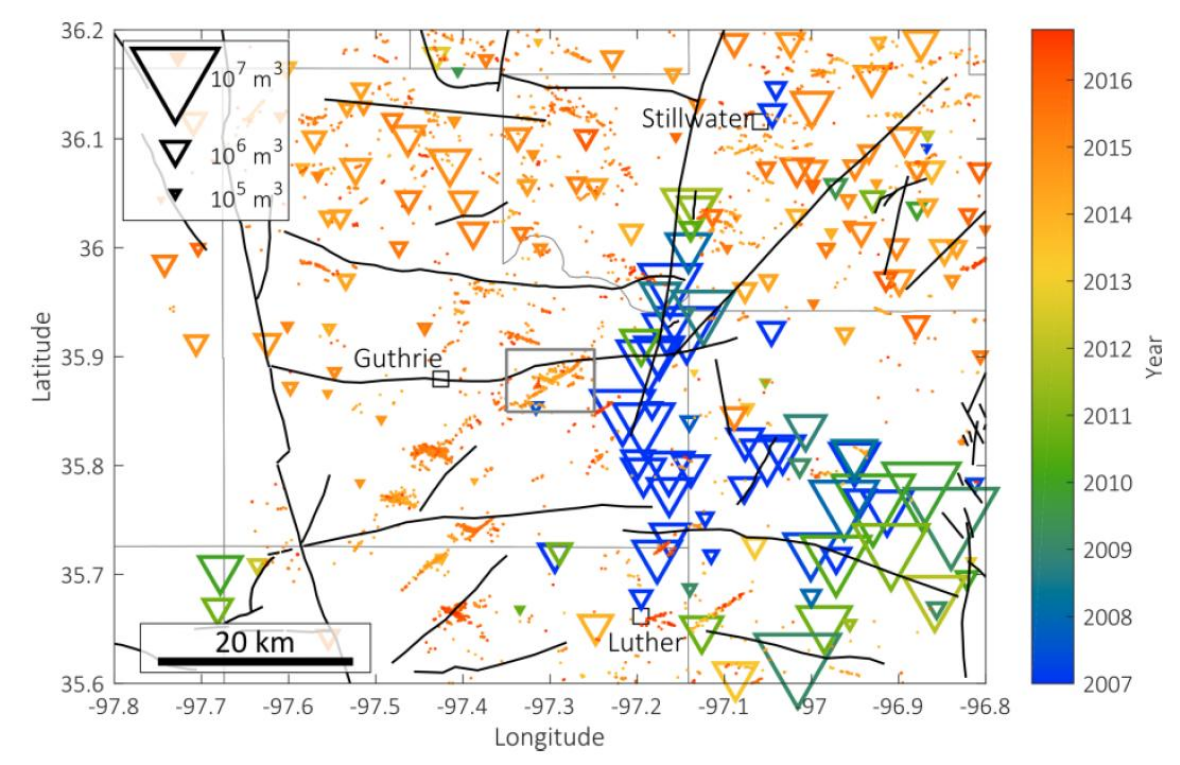


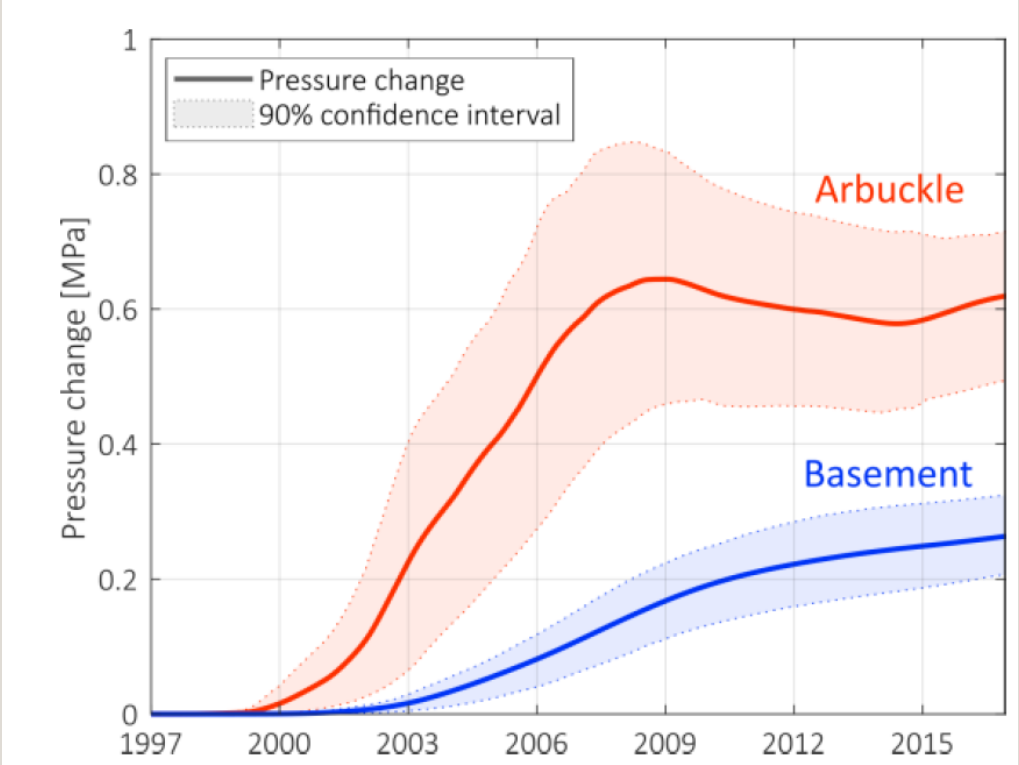
Central Cherokee Shelf M2.5+ earthquakes





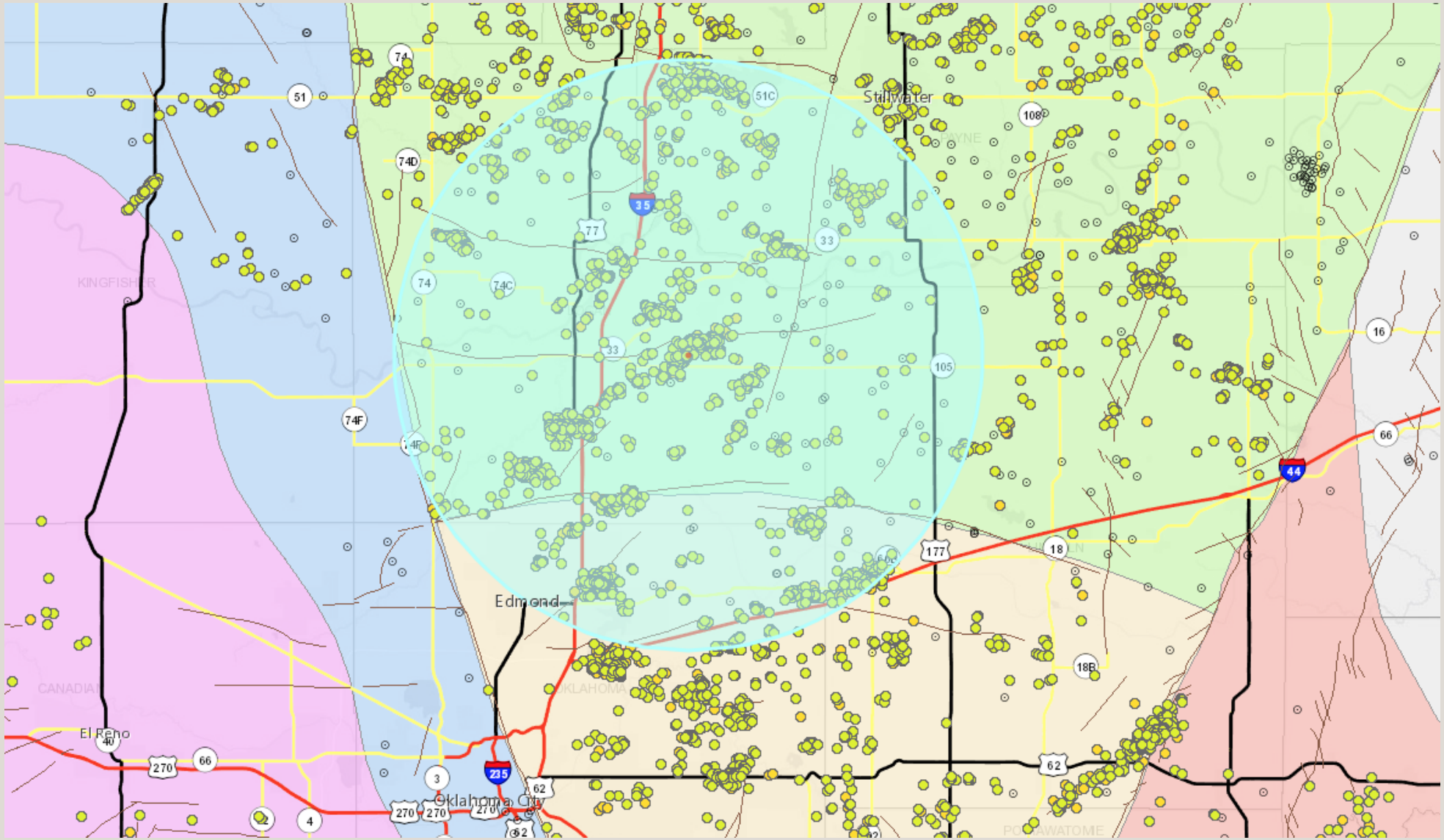
Schoenball et al. 2018



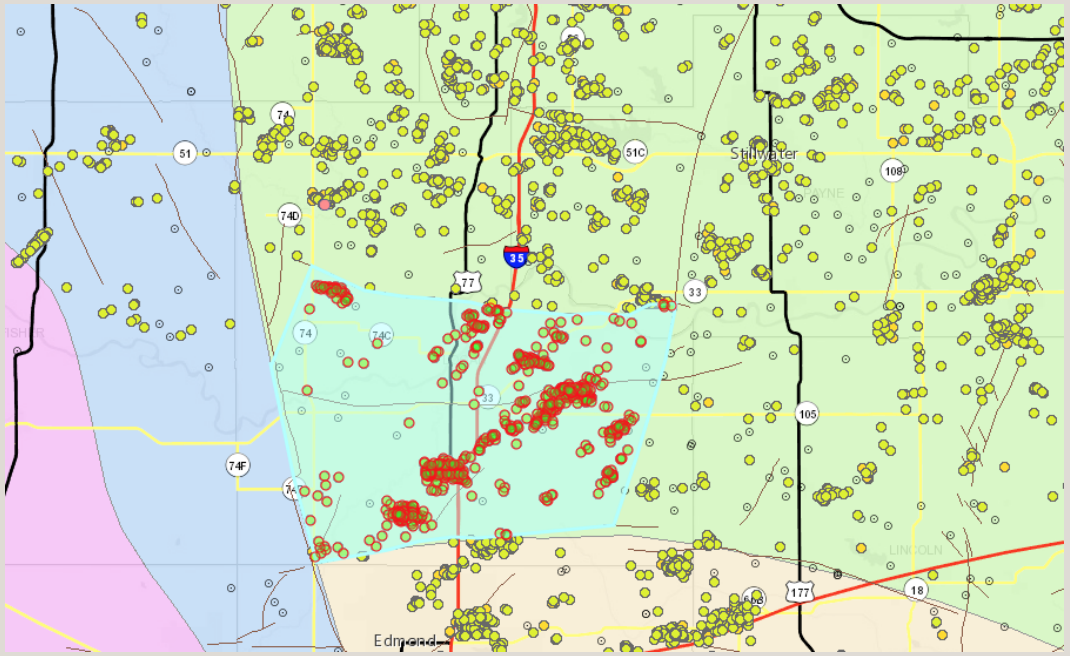


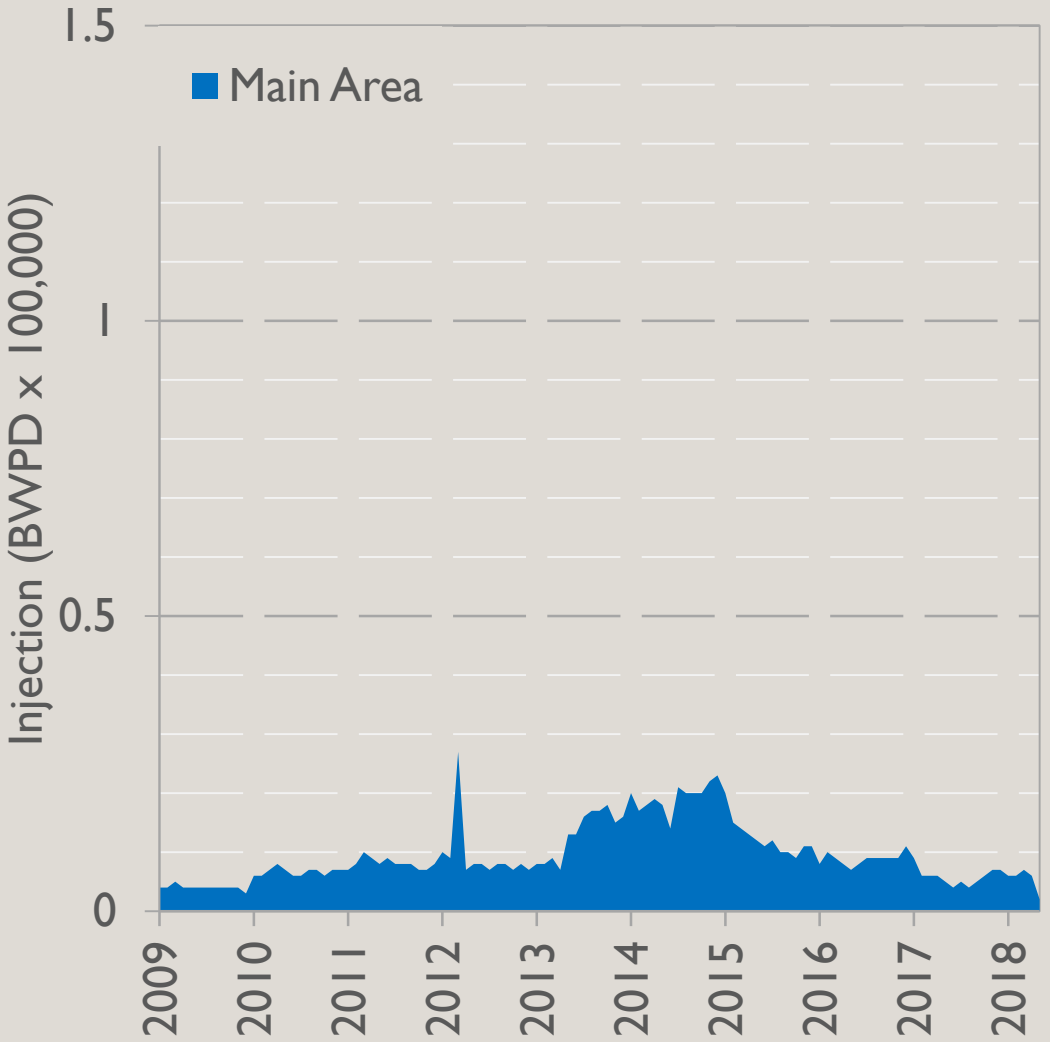
- Basement pore pressure change depends on injection in wells east of the area investigated
- N-S fault serves as high permeability fluid conduit for disposal wells
- Pressure diffusion to basement takes years to exceed critical pressure to induce slip
- Measured pressure in Arbuckle and calibrated models needed to evaluate future induced seismic hazard

30 km radius transects significant faults

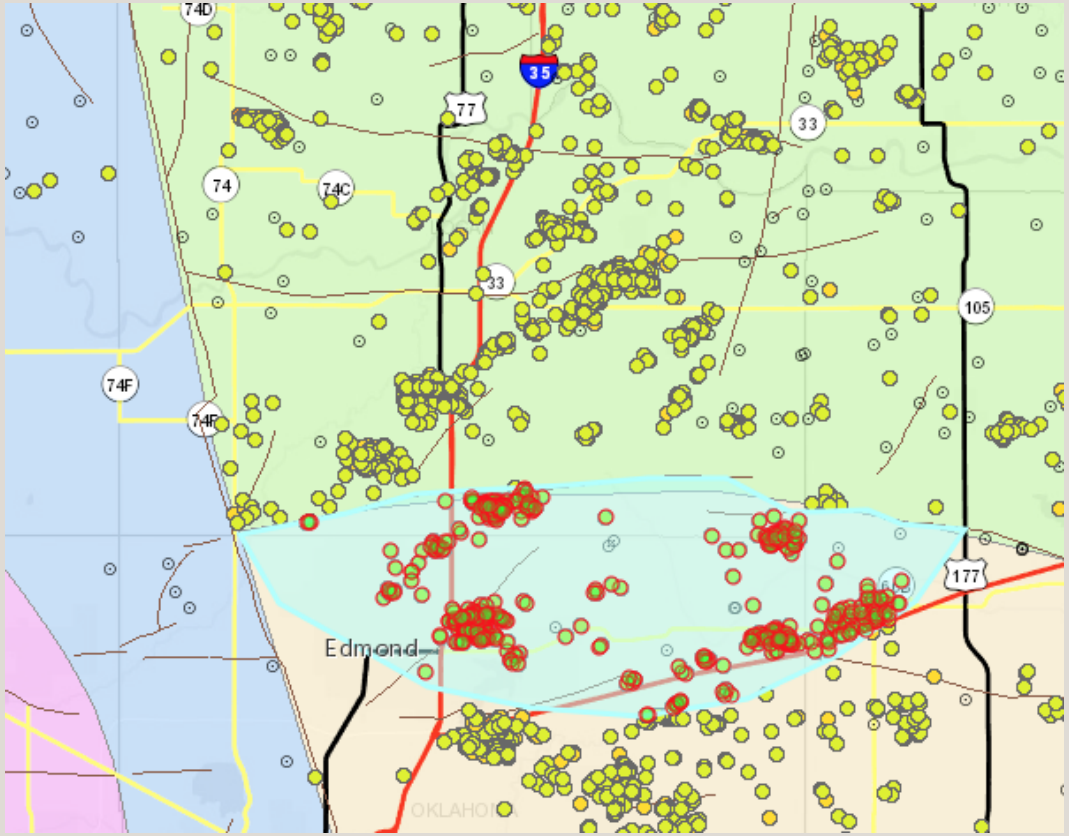


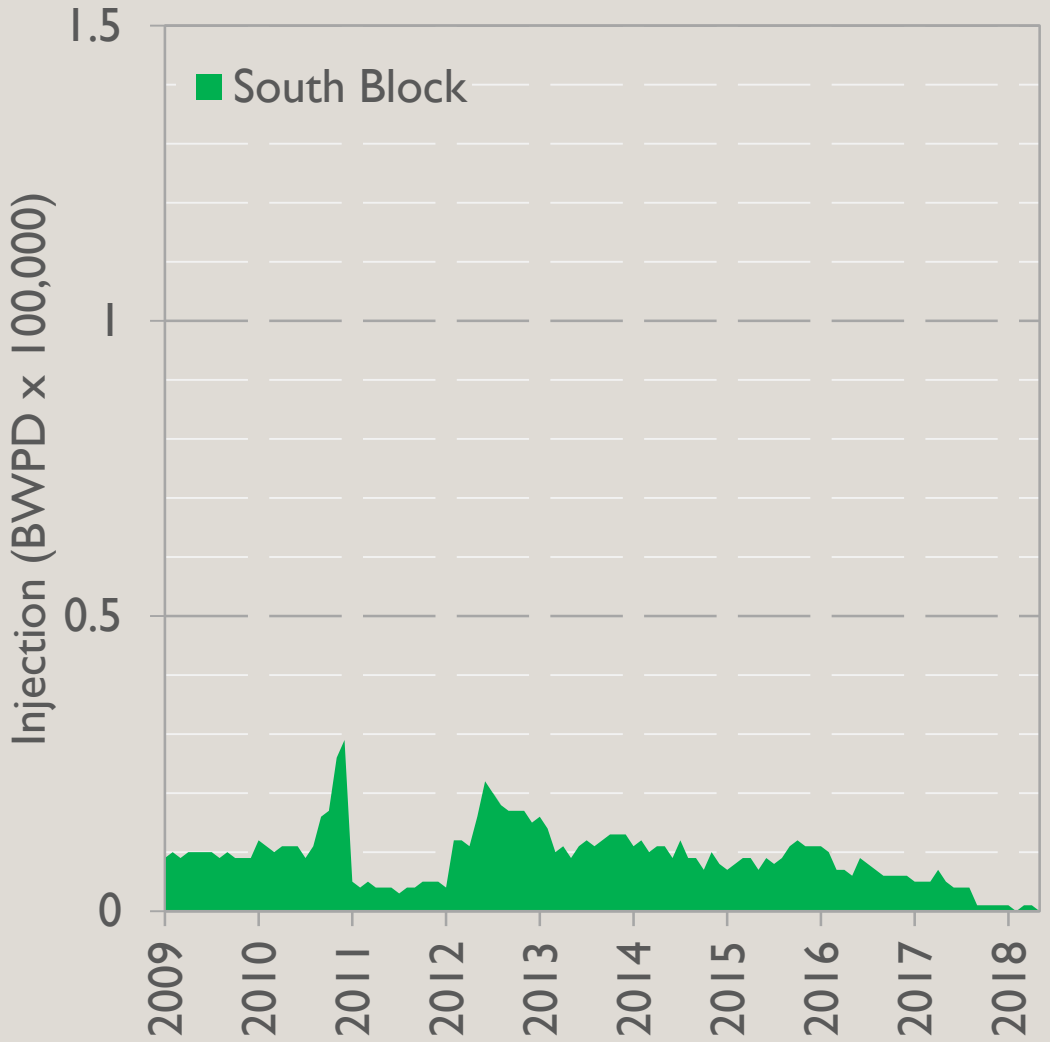
Main area


Stillwater
Edmond
35
77
74
74D
74C
74F
51
51C
33
105
177
18
108

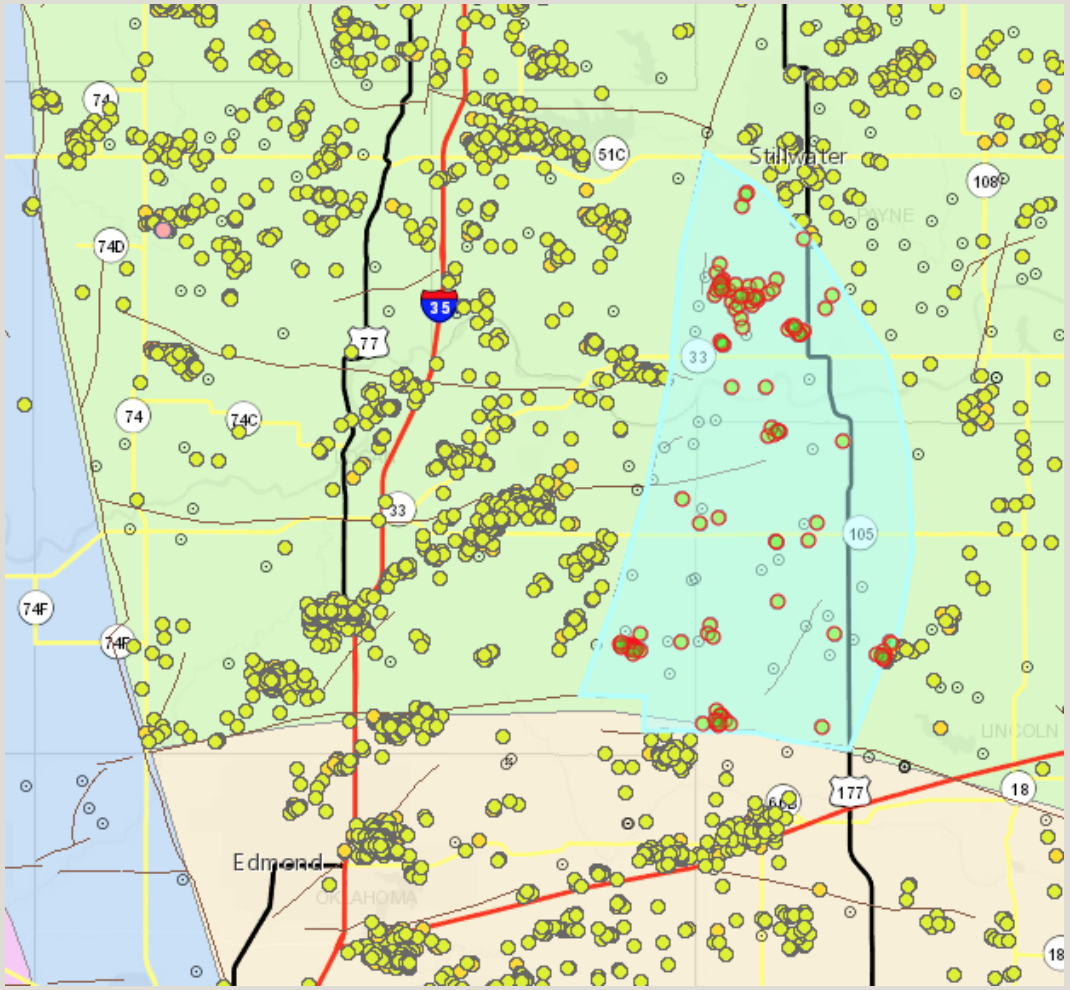

1.5
1
0.5
0
Main Area
Injection (BWPD x 100,000)
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018

South Block


74D
35
77
33
74
74C
33
105
74F
74F
177
Edmond
OKLAHOMA


1.5
1
0.5
0
Injection (BWPD x 100,000)
South Block
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018

East Block


74
51C
Stillwater
108
74D
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77
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74C
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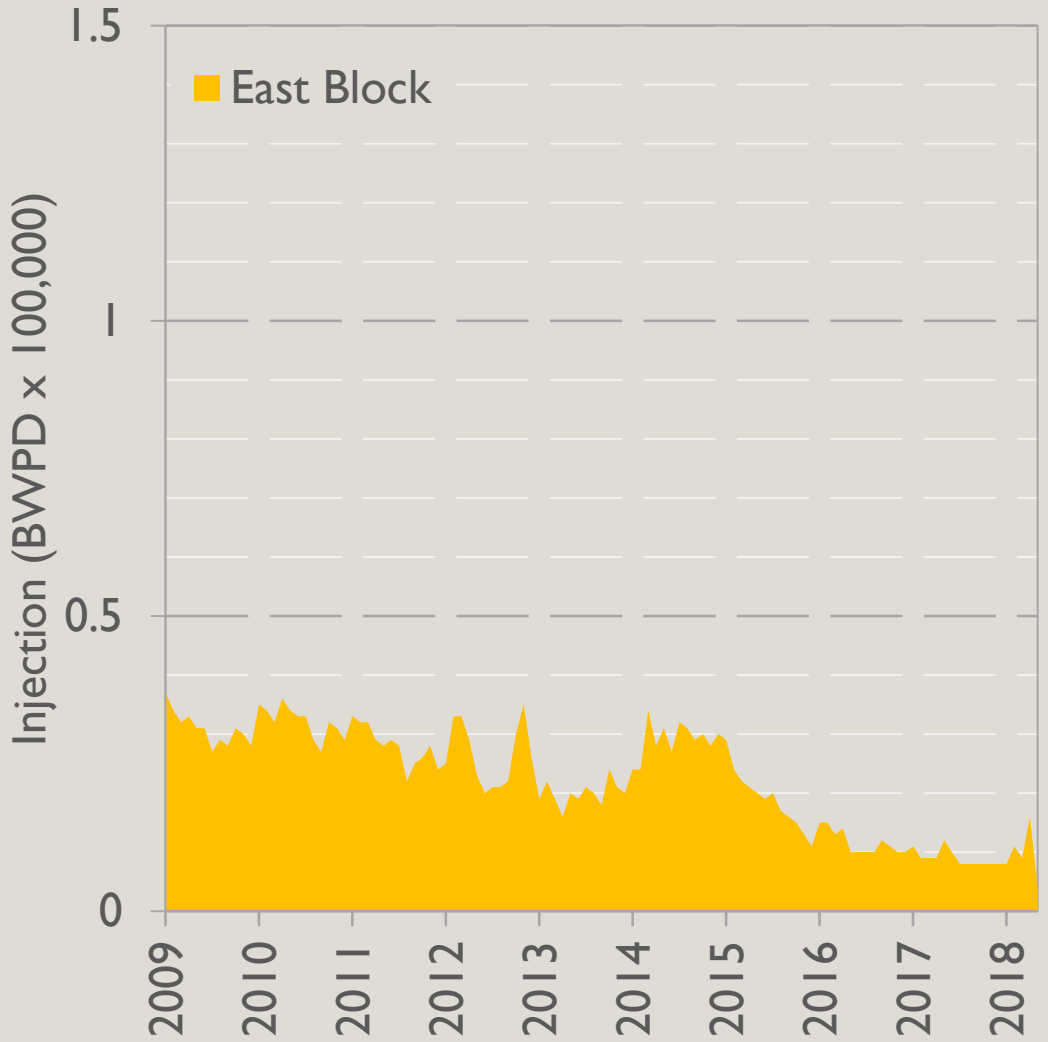
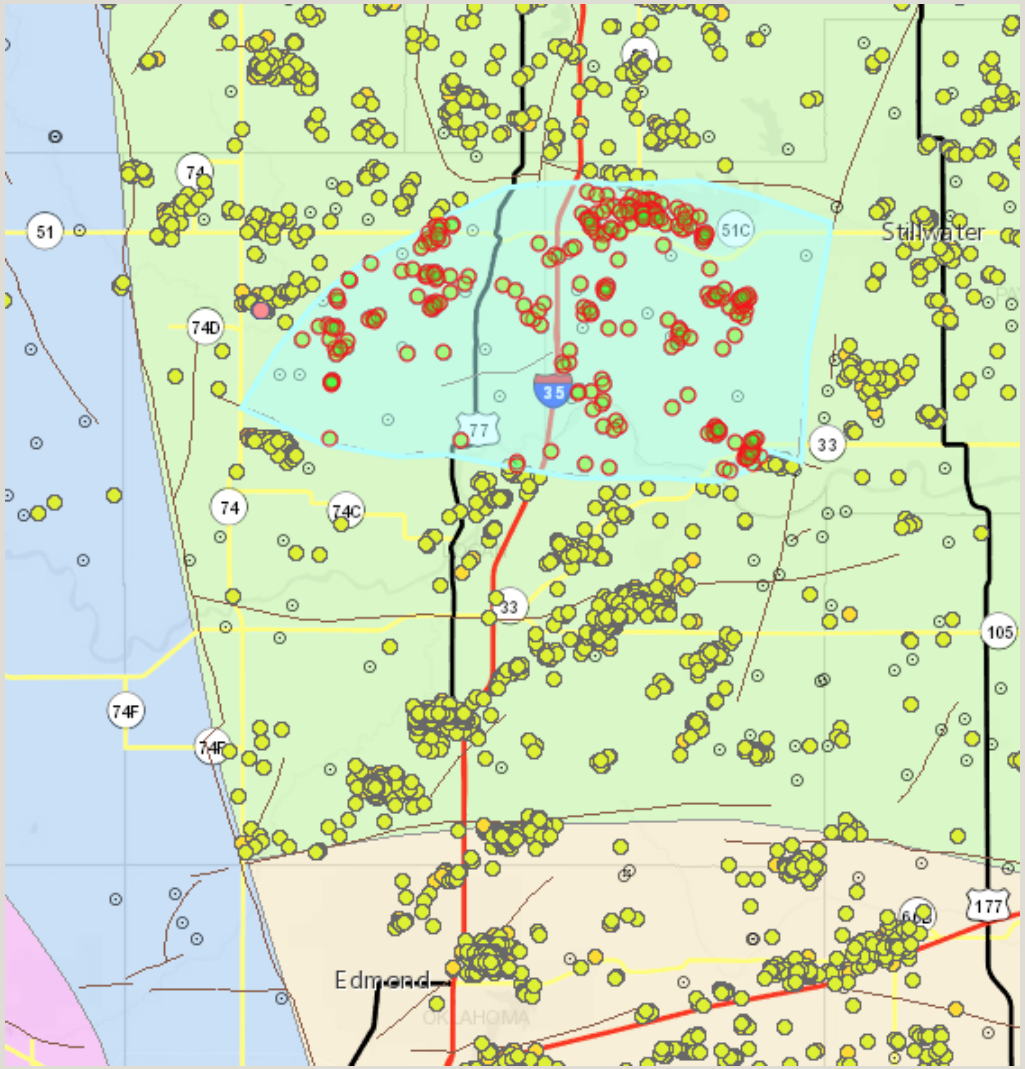
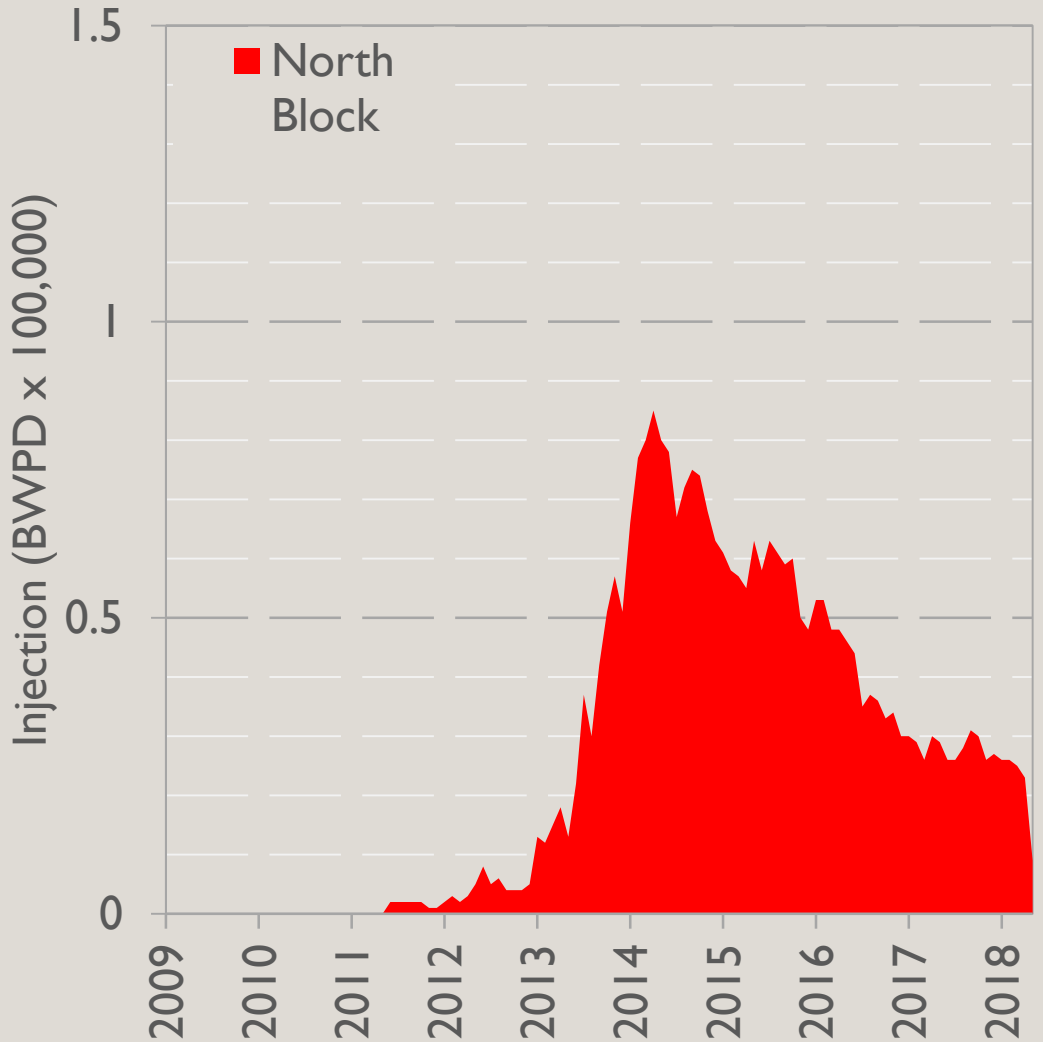
74F
74F
177
18
Edmond
OKLAHOMA
LINCOLN
18

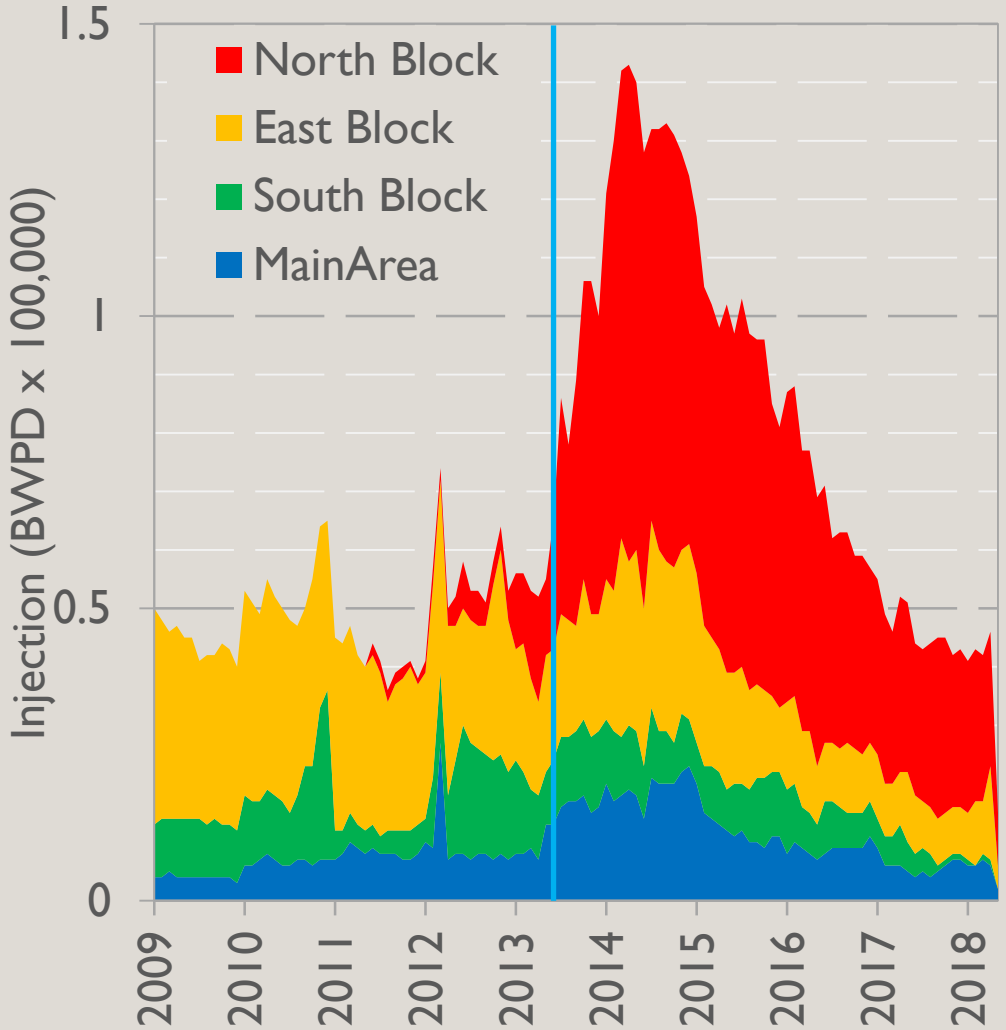

East Block
Injection (BWPD x 100,000)
1.5
1
0.5
0
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018

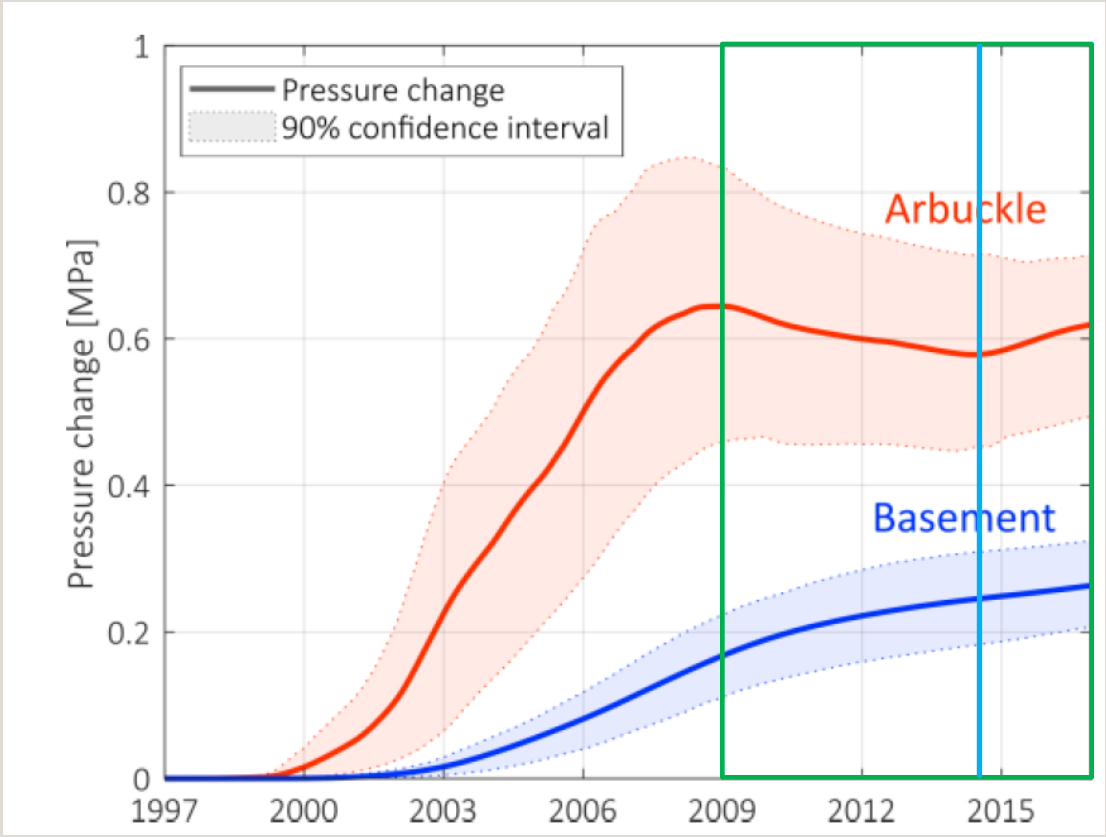
North Block


74
51
51C
Stillwater
74D
35
77
33
74
74C
33
105
74F
74F
177
Edmond
OKLAHOMA

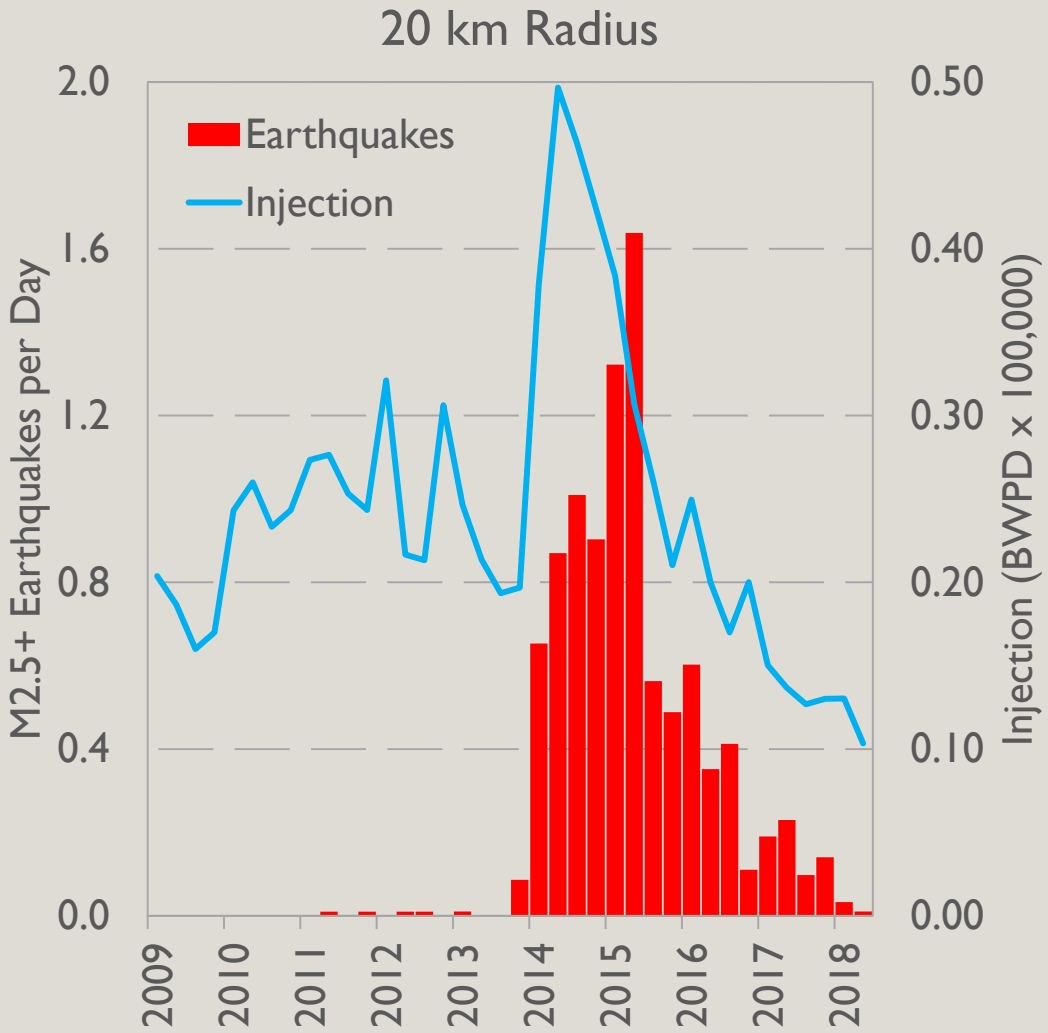

1.5
1
0.5
0
Injection (BWPD x 100,000)
North Block
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018

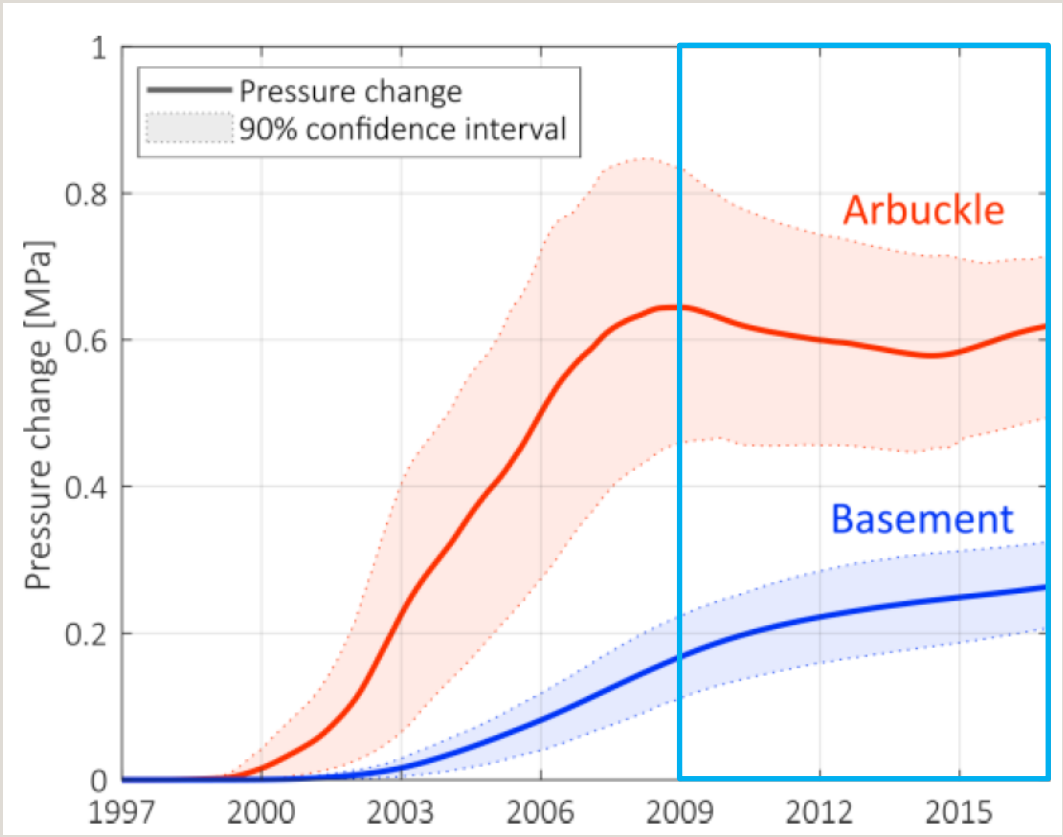
External water sources are likely important





If basement pressure time lag is large, why does seismicity decline from mid-2015?





Conclusions

- Seismicity in Oklahoma is declining in most areas
  - Injection induced seismicity down >75% from peak
  - Completion-related seismicity may still be rising with completion rate
  - We are not out of the woods yet
- Understanding has advanced for both categories of earthquakes
  - Hazard estimates for two categories of earthquakes should be treated separately
  - Some controlling geologic structures are well-recognized; others not adequately evaluated
  - Structural and petroleum geology provide important input on critical relationships
  - Relatively complex well-calibrated models will be necessary to evaluate seismic hazards
  - Scientific support for rational decision-making must provide answers that acknowledge uncertainty

References

- Cantner, K. , Induced Seismicity, downloaded at https://www.earthmagazine.org/article/ground-shaking-research-how-humans-trigger-earthquakes , June 19, 2018, and modified
- Darold, A. P, Holland, A. H, Morris, J. K, and Gibson, A. R., 2015, *Oklahoma Earthquake Summary Report 2014*, Oklahoma Geological Survey Open File Report 1-2015, 46 pages.
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- U. S. Department of Energy – Energy Information Administration, downloaded at https://www.eia.gov/dnav/pet/pet_pri_spt_s1_m.htm June 19, 2018
- Walsh, F. R., and Zoback, M. D., 2015, *Oklahoma's recent earthquakes and saltwater disposal,* Sci. Adv. 2015; 1:e1500195, 18 June 2015