



OKLAHOMA GEOLOGICAL SURVEY

A State Agency For Research and Public Service

Oklahoma Earthquakes and Injection of Produced Water

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March 23, 2016



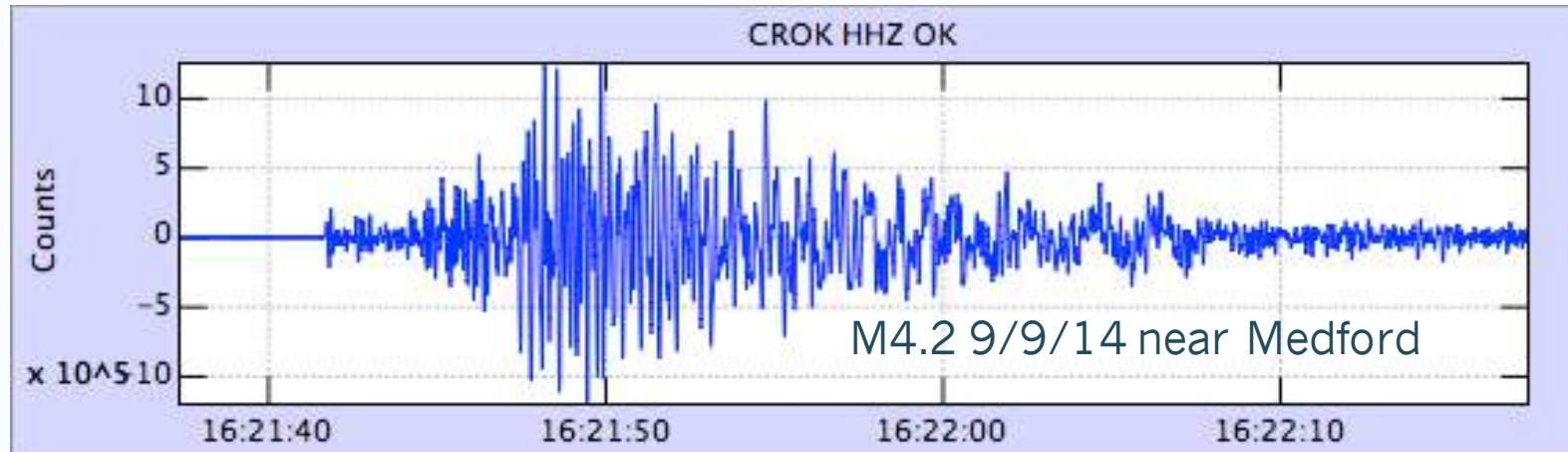
The Oklahoma Geological Survey is a state agency for research and public service located on the Norman Campus of the University of Oklahoma and affiliated with the OU College of Earth and Energy. The Survey is chartered in the Oklahoma Constitution and is charged with investigating the state's land, 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

Acknowledgments

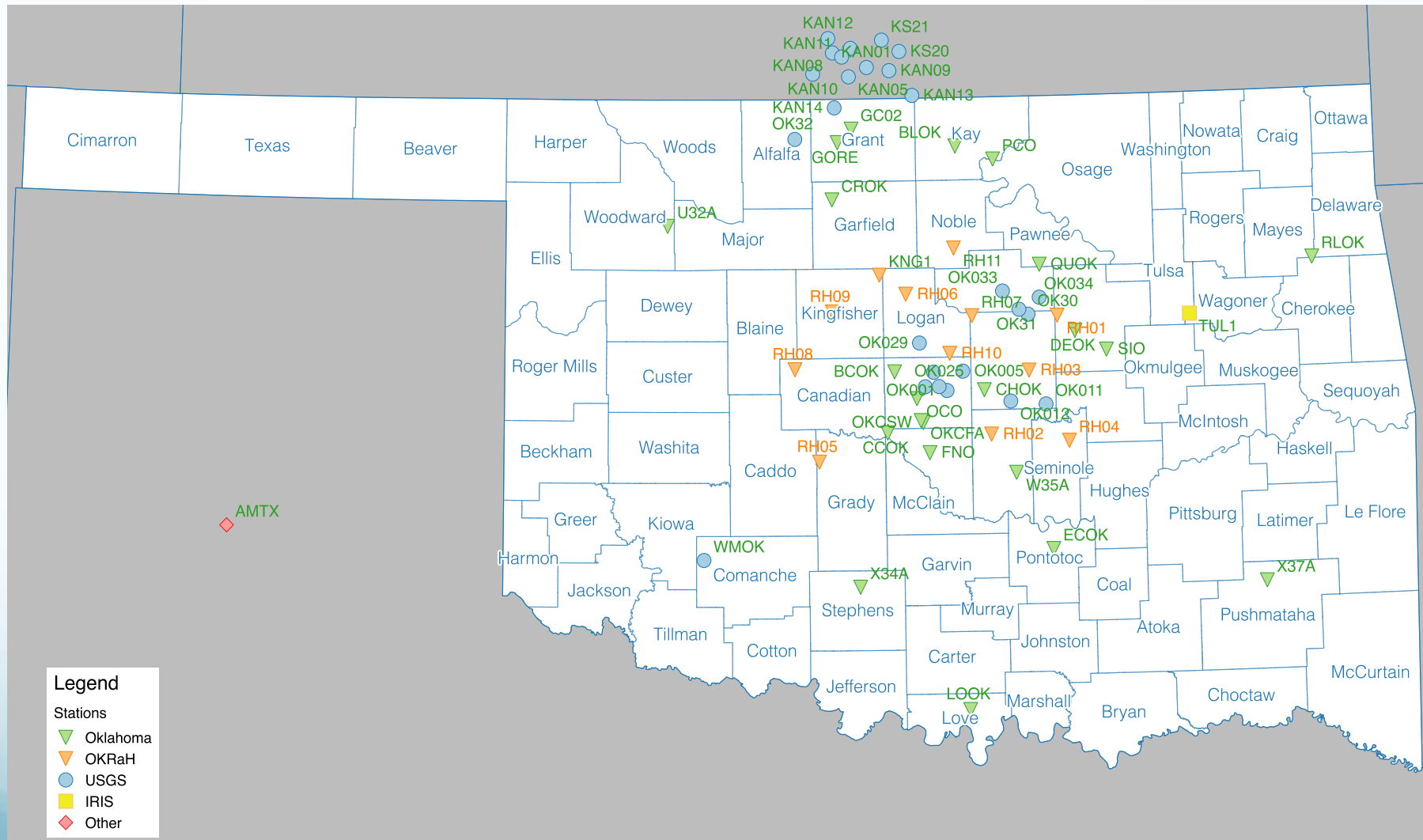
- **OGS Staff Engaged on the Seismicity Issue**
 - **Publications & Outreach:** Ted Satterfield, Jennifer Morris
 - **Seismology:** Jefferson Chang, Fernando Ferrer, Noorulann Ghouse, Junjun Hu, Andrew Thiel, Isaac Woelfel
 - **Hydrogeology, Geology, Geophysics:** Kyle Murray, Richard Andrews, Kevin Crain, Steve Holloway, Jordan Williams

OGS Seismic Monitoring Program



- OGS seismic network began operating in 1978
 - Location, time, & magnitude calculated by seismologists & trained analysts
 - Raw data archived & publicly available at international data management center
 - Two-way real-time sharing with USGS
 - Data available to Corporation Commission, researchers & general public
- Website (<http://www.ou.edu/ogs>) provides:
 - earthquake catalogs, recent earthquake lists
 - maps, research results and educational materials

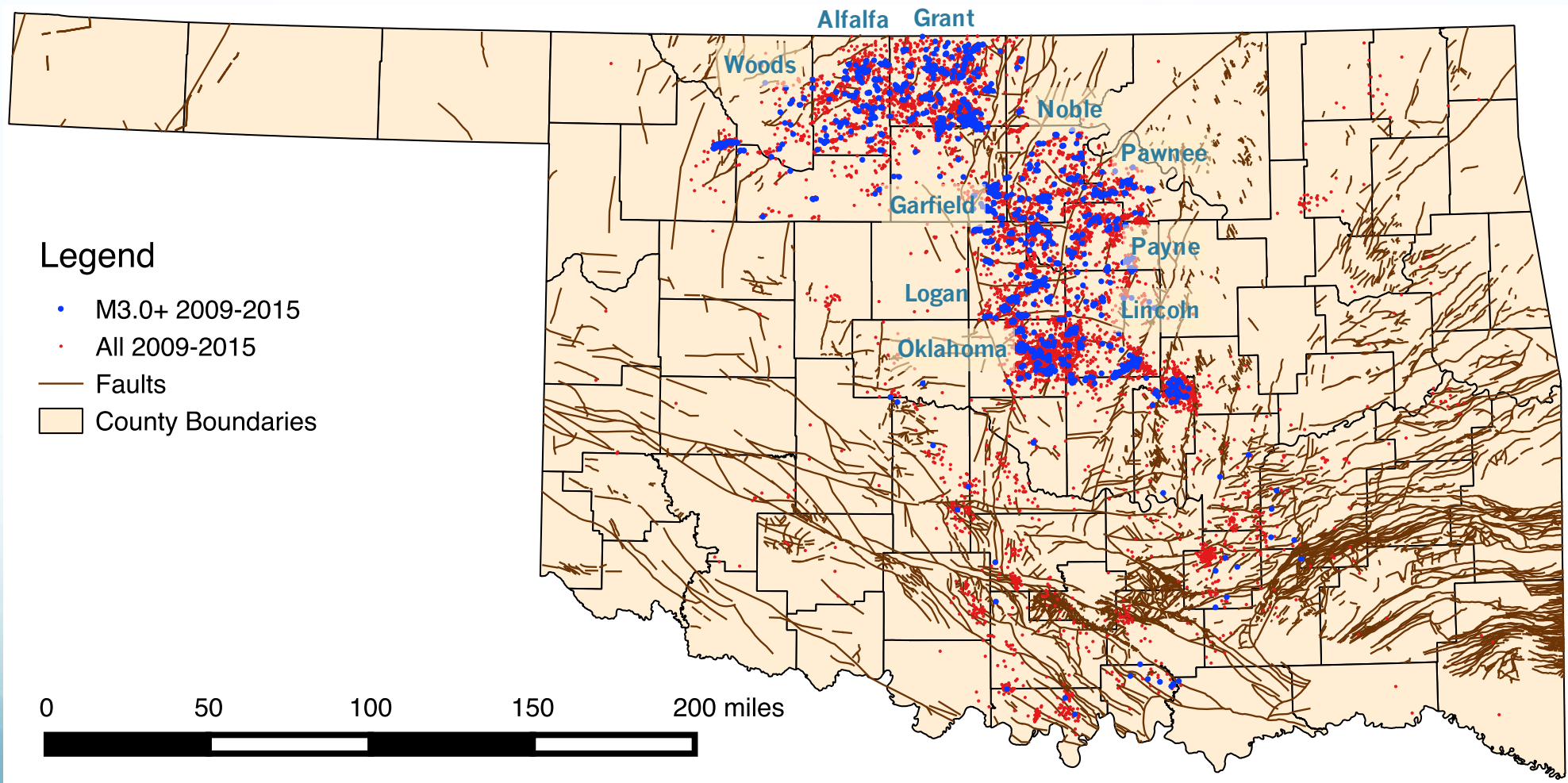
OGS Uses about 50 Stations to Locate Oklahoma Earthquakes



Measuring an Earthquake

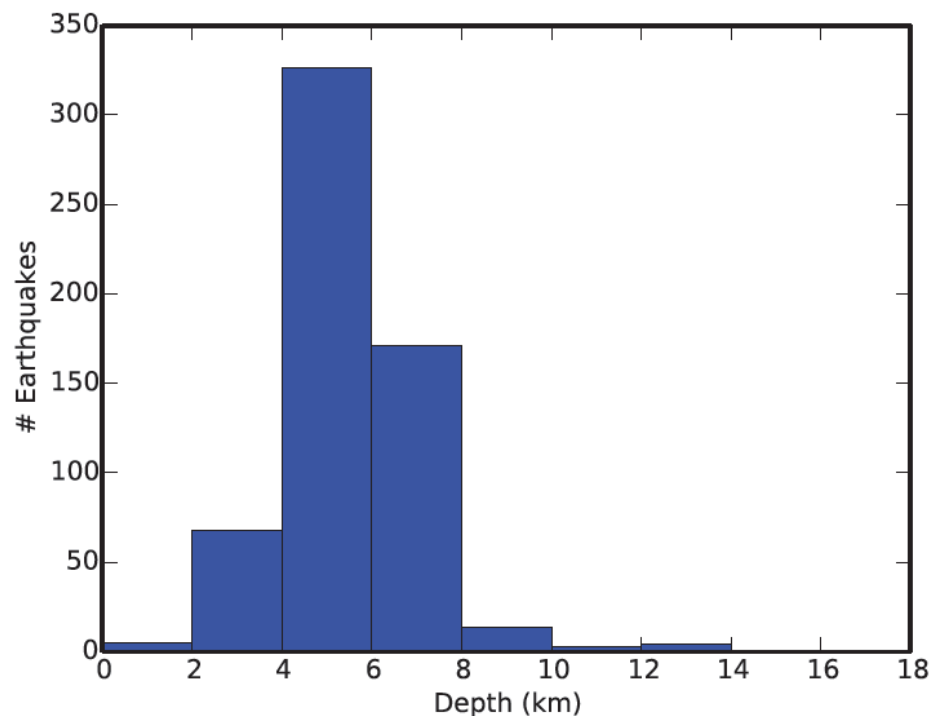
- Magnitude is a scaled estimate of energy released as seismic waves and is proportional to rupture area
- Magnitude measured multiple ways (M_L , m_b , M_w , M_o , M_s)
 - Magnitude estimates rarely the same between different methods
 - All magnitude measures are uncertain
 - Magnitude scales logarithmic (+1 unit of magnitude = ~10 times shaking & ~32 times the energy release)
- Earthquake Intensity is a qualitative estimate (using Modified Mercalli scale ranging from I-XII)

Most Earthquakes Occurring in ~16% of the Area of the State



Earthquakes Occur in the Basement below Oil and Gas Activity

- Average Depth about 5.5 km (~18,000 ft)

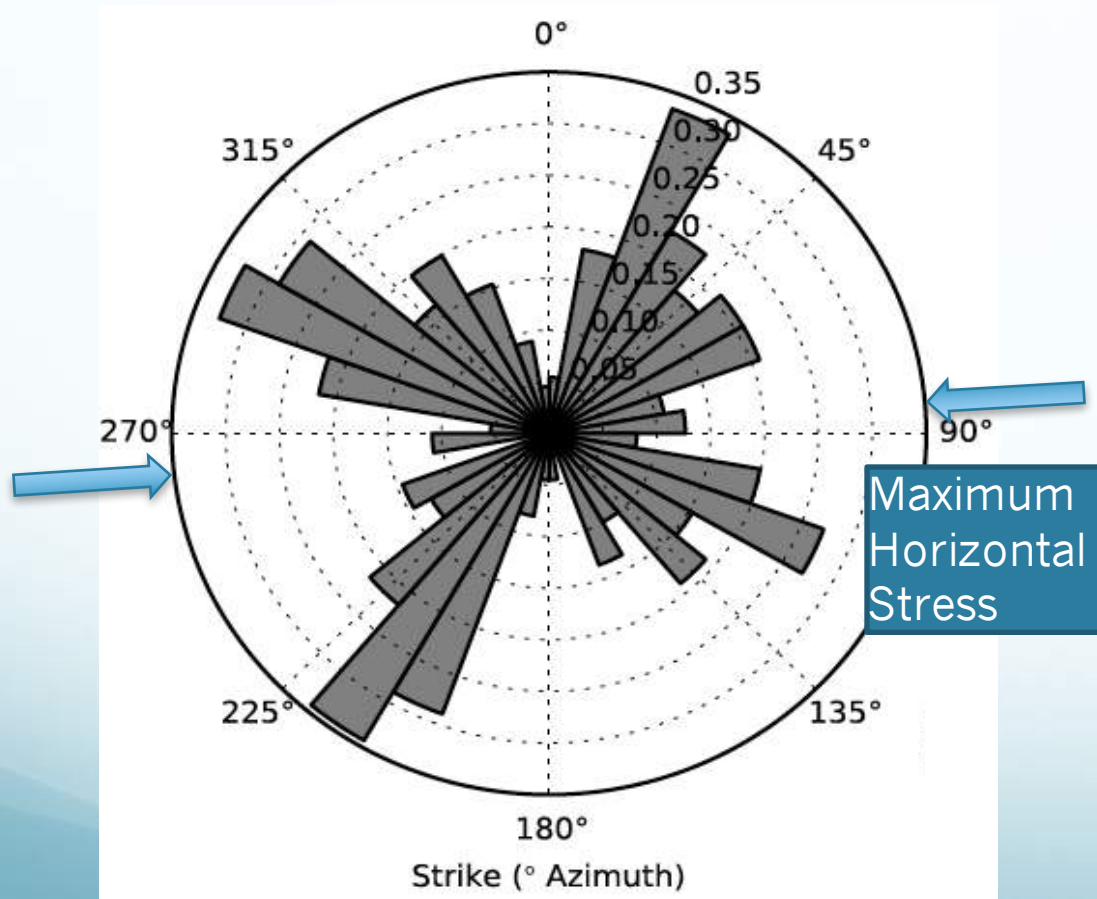


- Most earthquakes occur within crystalline basement
- Deeper than most oil and gas operations
- Many salt water disposal wells may be in communication with crystalline basement

OGS OF1-2015

Earthquakes Occurring on Faults Oriented in Preferred Directions

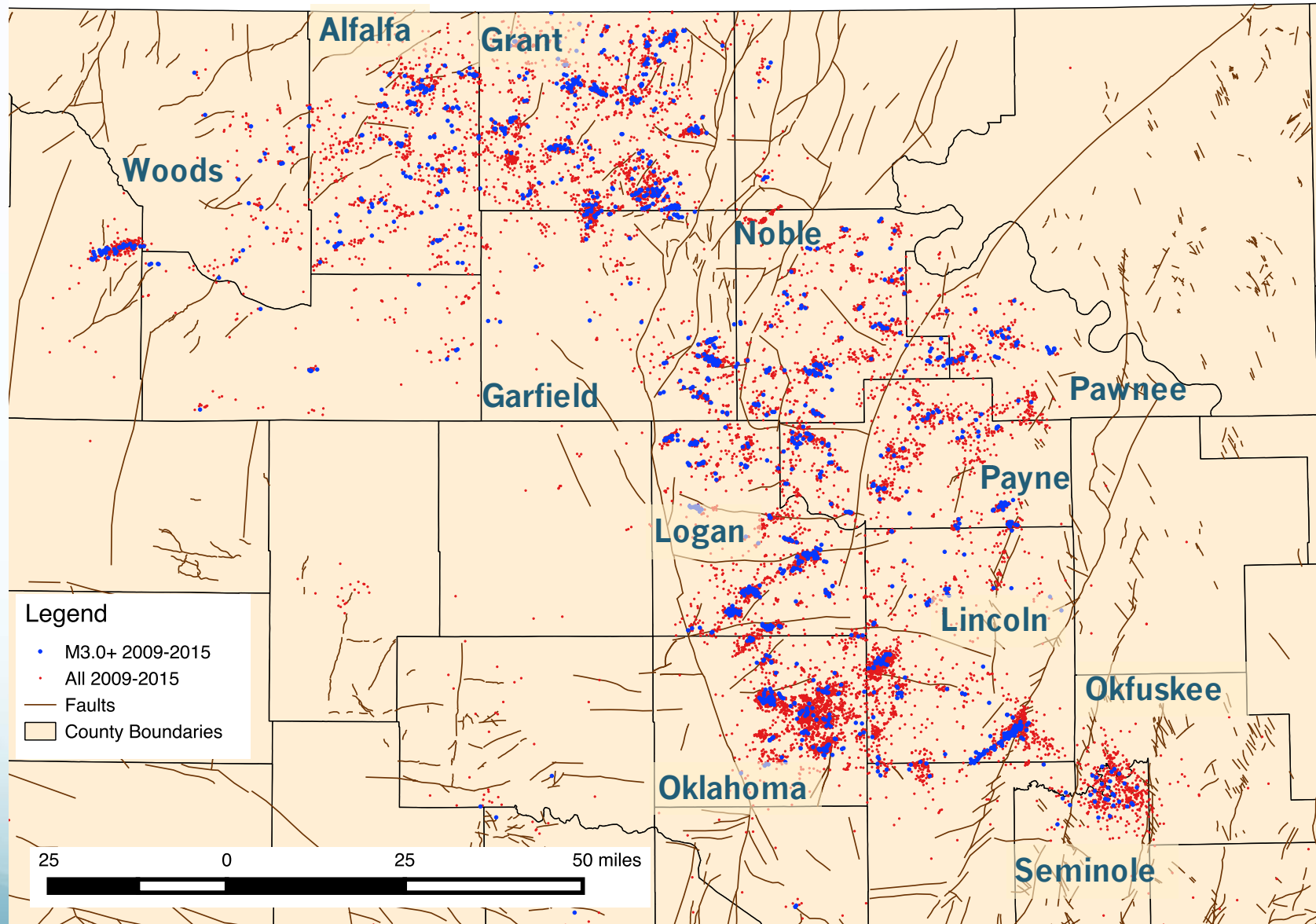
Active Fault Orientations 2014



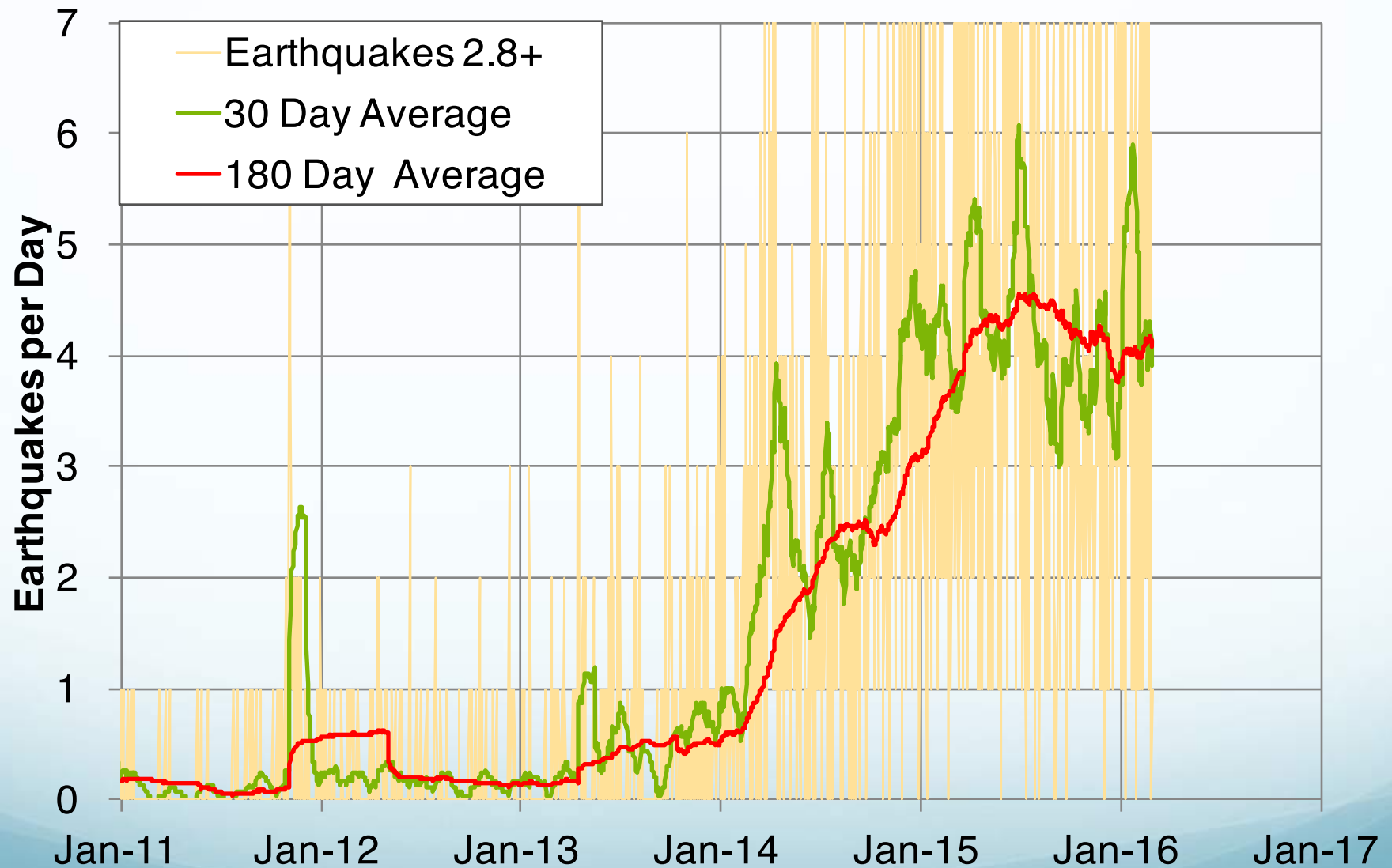
Natural Stresses and Earthquakes

- Earthquakes occur on faults optimally and sub-optimally oriented within Oklahoma's tectonic stress regime (**N85°E**)
- Both triggered and naturally occurring **earthquakes release accumulated tectonic stress** on these faults

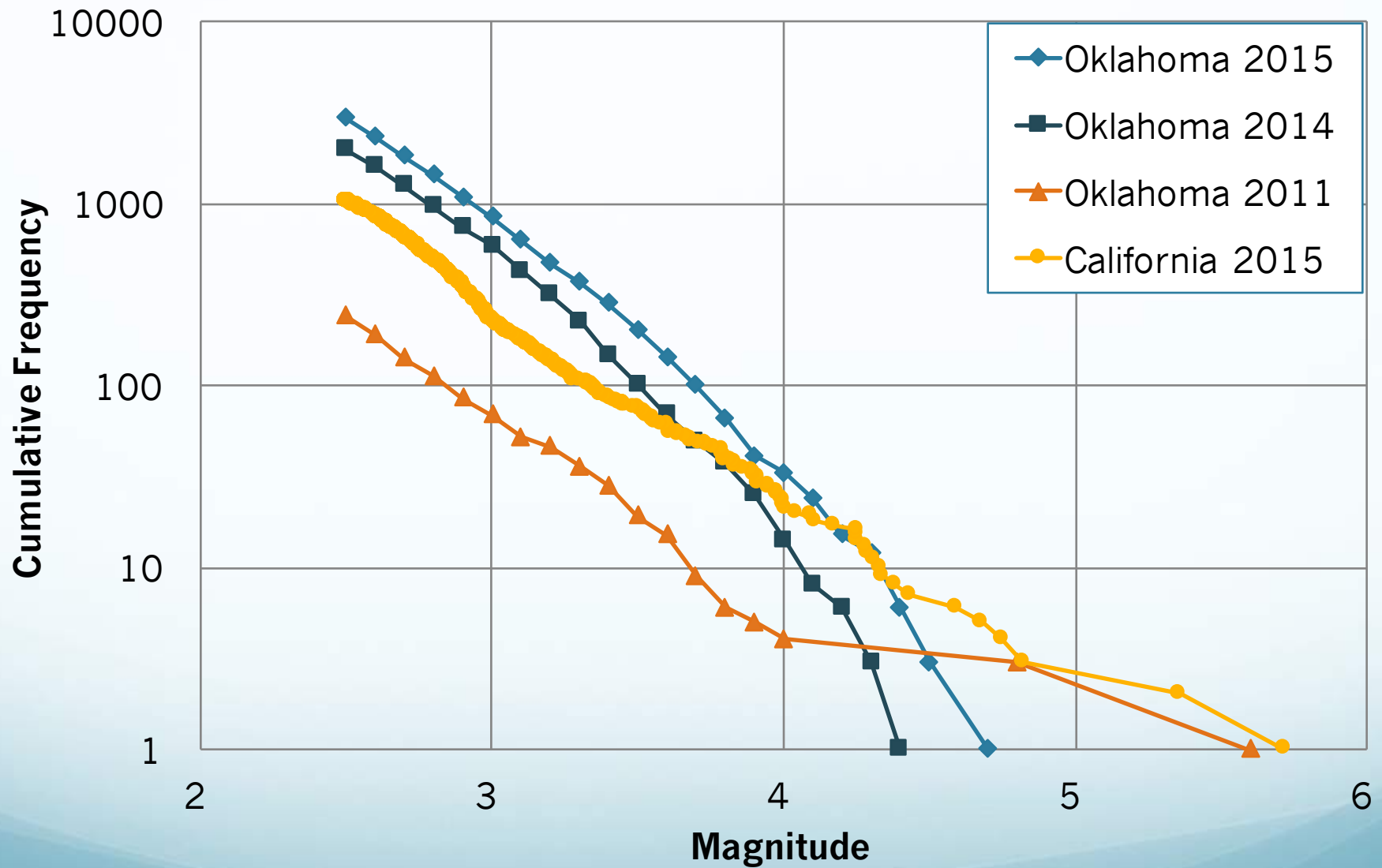
Earthquakes 2009-2015



Oklahoma M2.8+ Earthquakes



Earthquake Capital of the U. S.?



Human Activity Can Induce Earthquakes

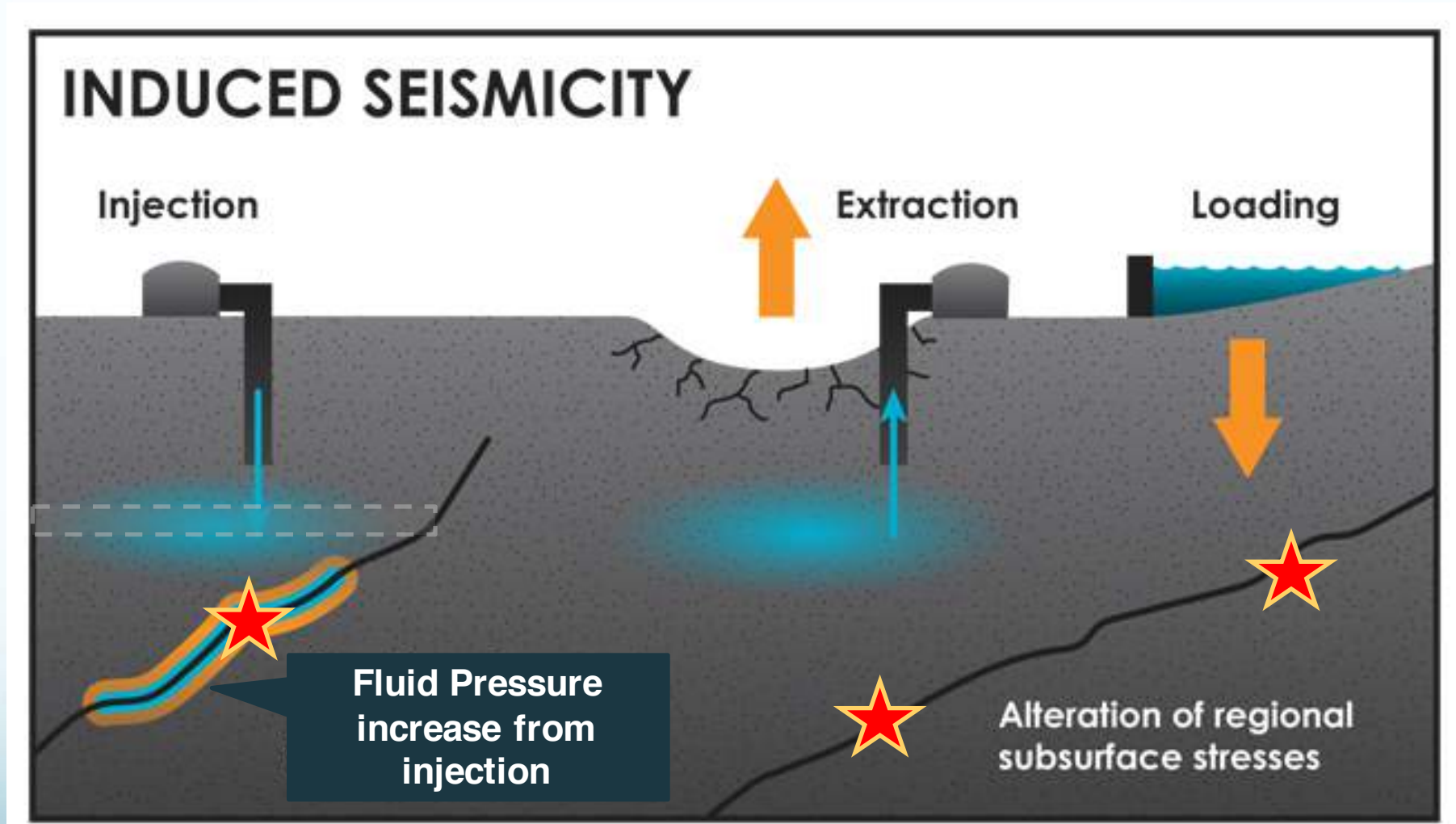
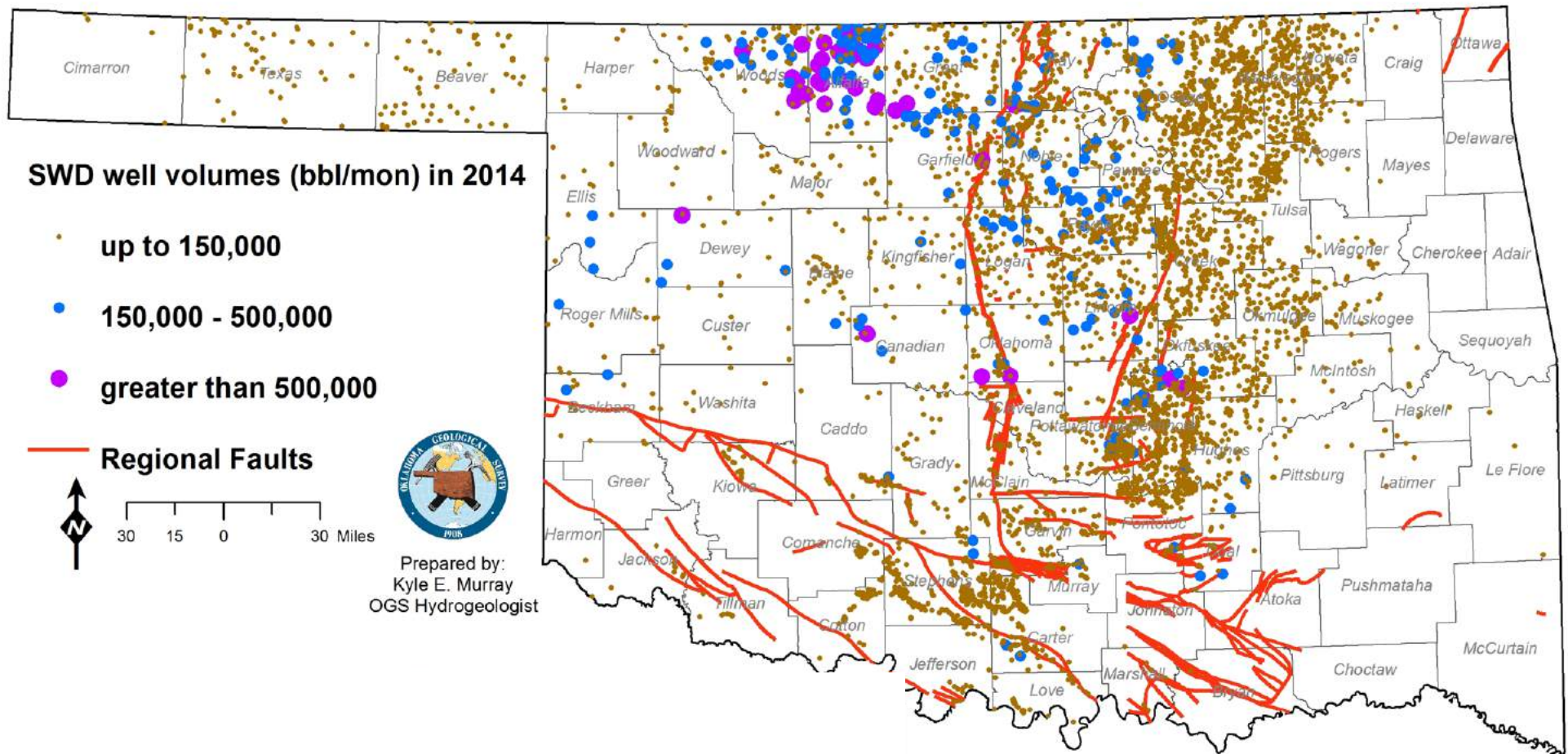


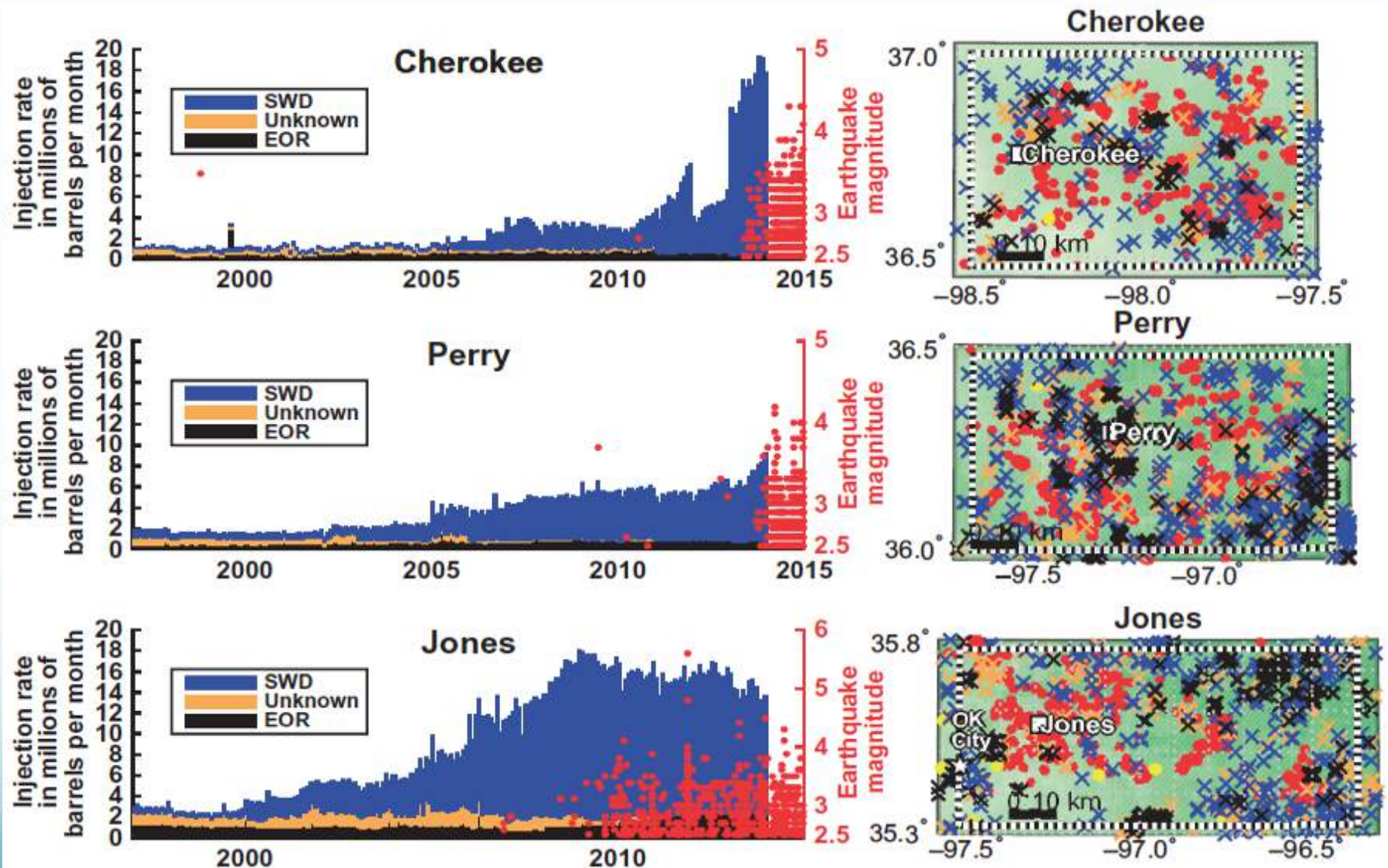
Figure modified from: <http://www.earthmagazine.org/article/ground-shaking-research-how-humans-trigger-earthquakes>

Underground Injection Control (UIC) Class II Injection Salt Water Disposal (SWD) Wells



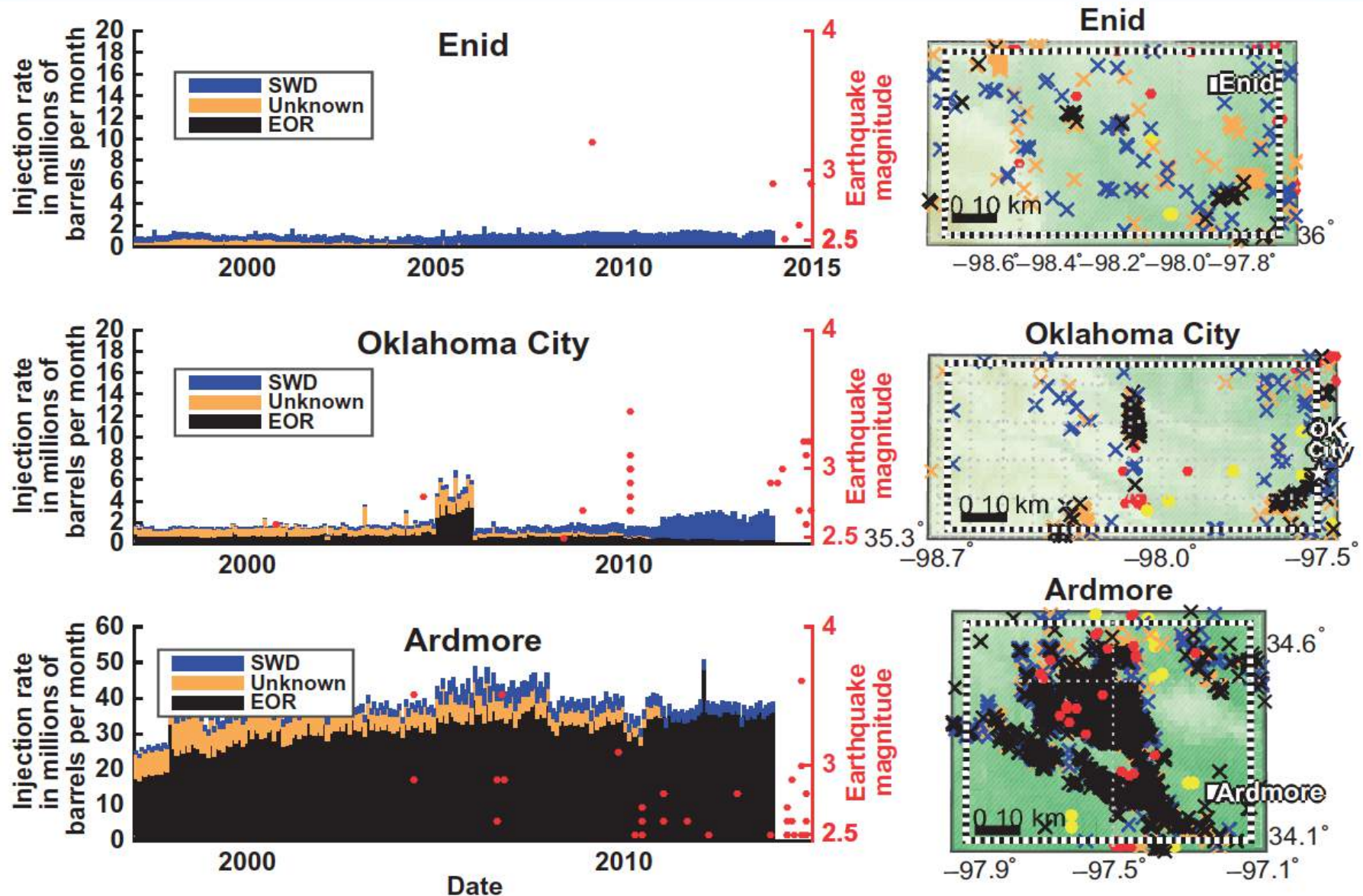
Murray 2014, OGS OF5-2015

Earthquake Activity Occurs Where Deep Injection Increases Substantially



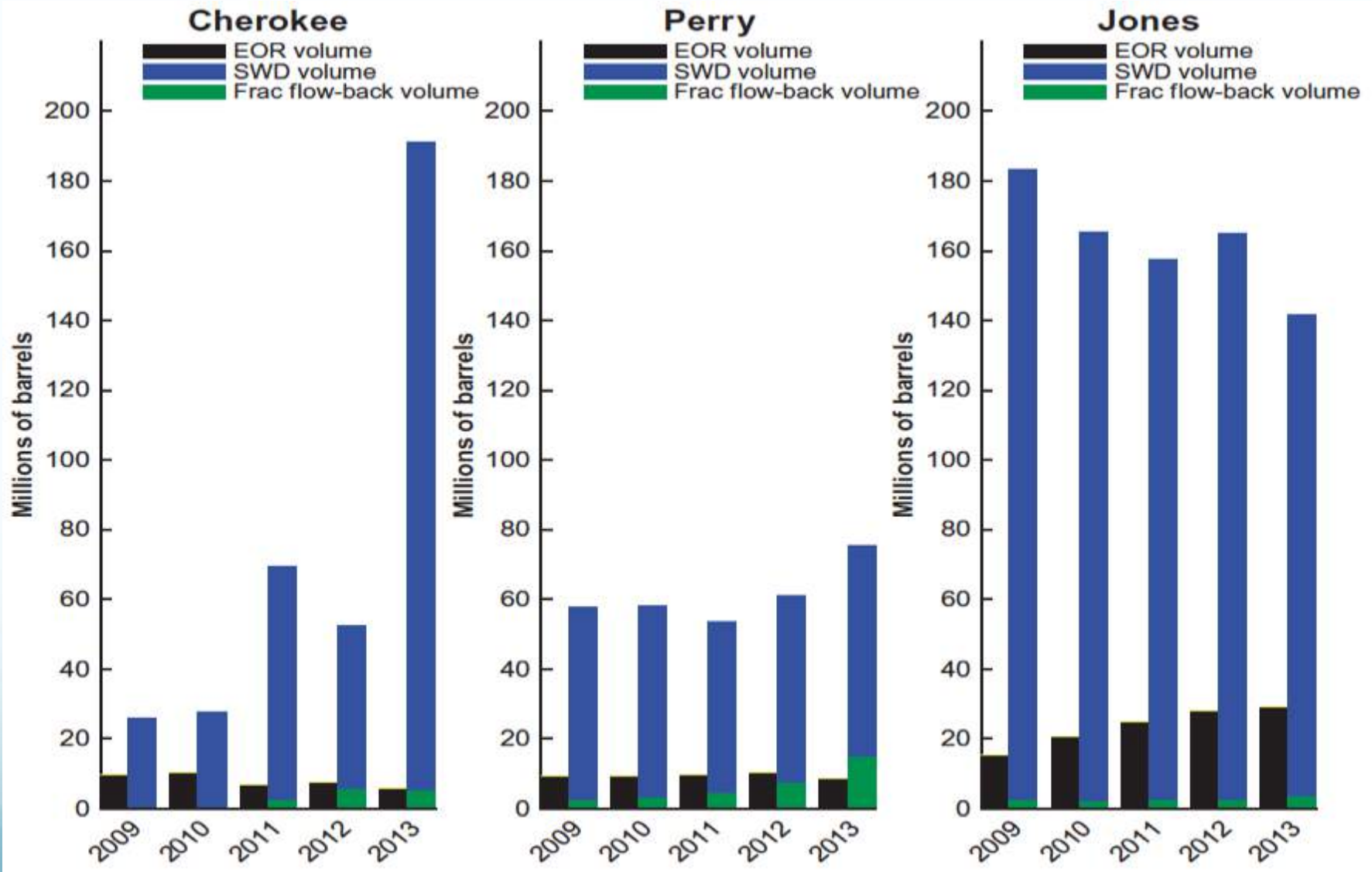
Source: Walsh, F. R., and Zoback, M. D. (2015) Oklahoma's recent earthquakes and saltwater disposal. *Sci. Adv.* 2015; 1:e1500195, 18 June 2015

Areas of Lower SWD Show Lower Earthquake Activity



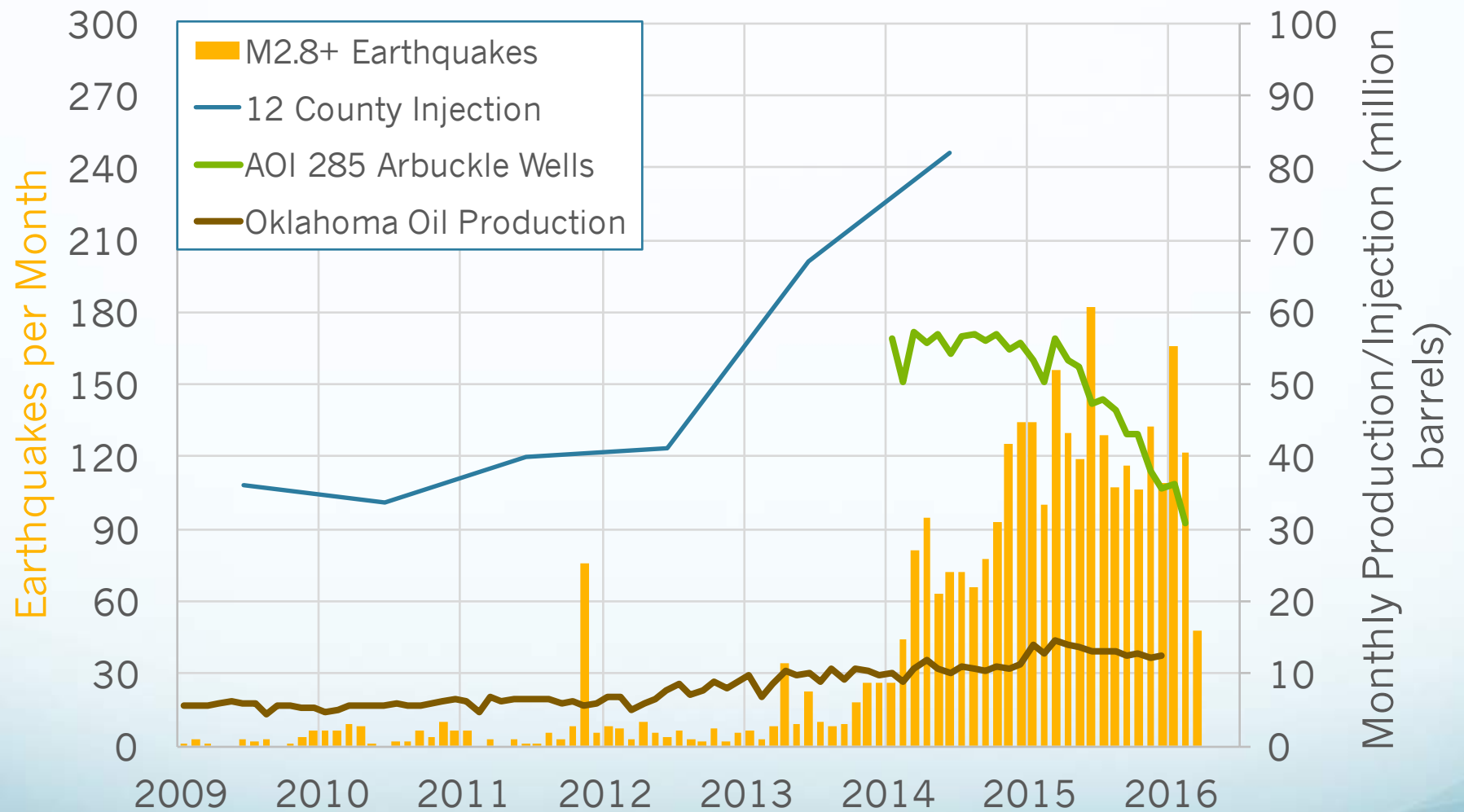
Source: Walsh, F. R., and Zoback, M. D. (2015) Oklahoma's recent earthquakes and saltwater disposal. Sci. Adv. 2015; 1:e1500195, 18 June 2015

SWD Includes Very Little Flowback Water from Hydraulic Fracturing

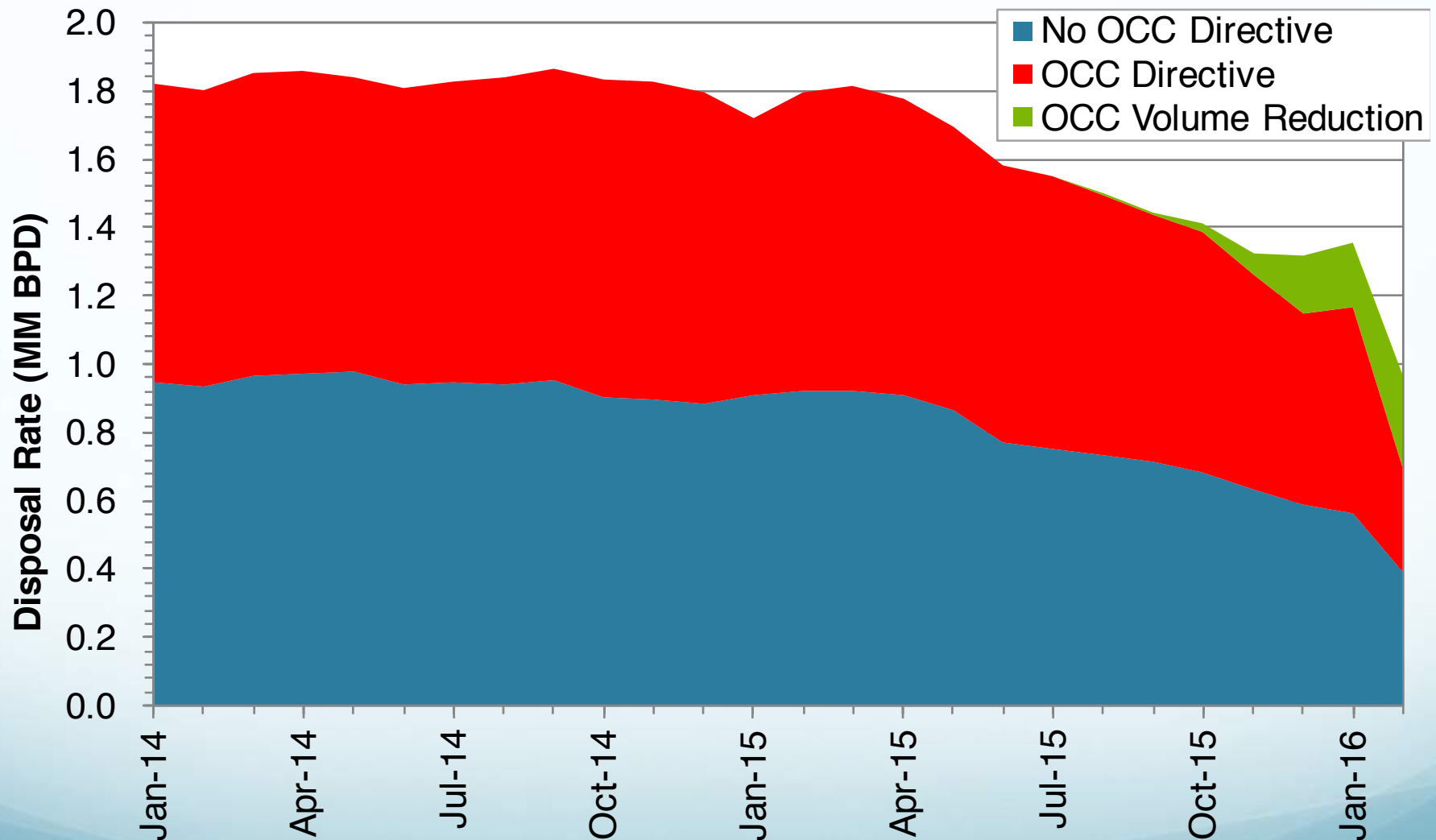


Source: Walsh, F. R., and Zoback, M. D. (2015) Oklahoma's recent earth-quakes and saltwater disposal. Sci. Adv. 2015; 1:e1500195, 18 June 2015

Earthquakes, Oil & Water

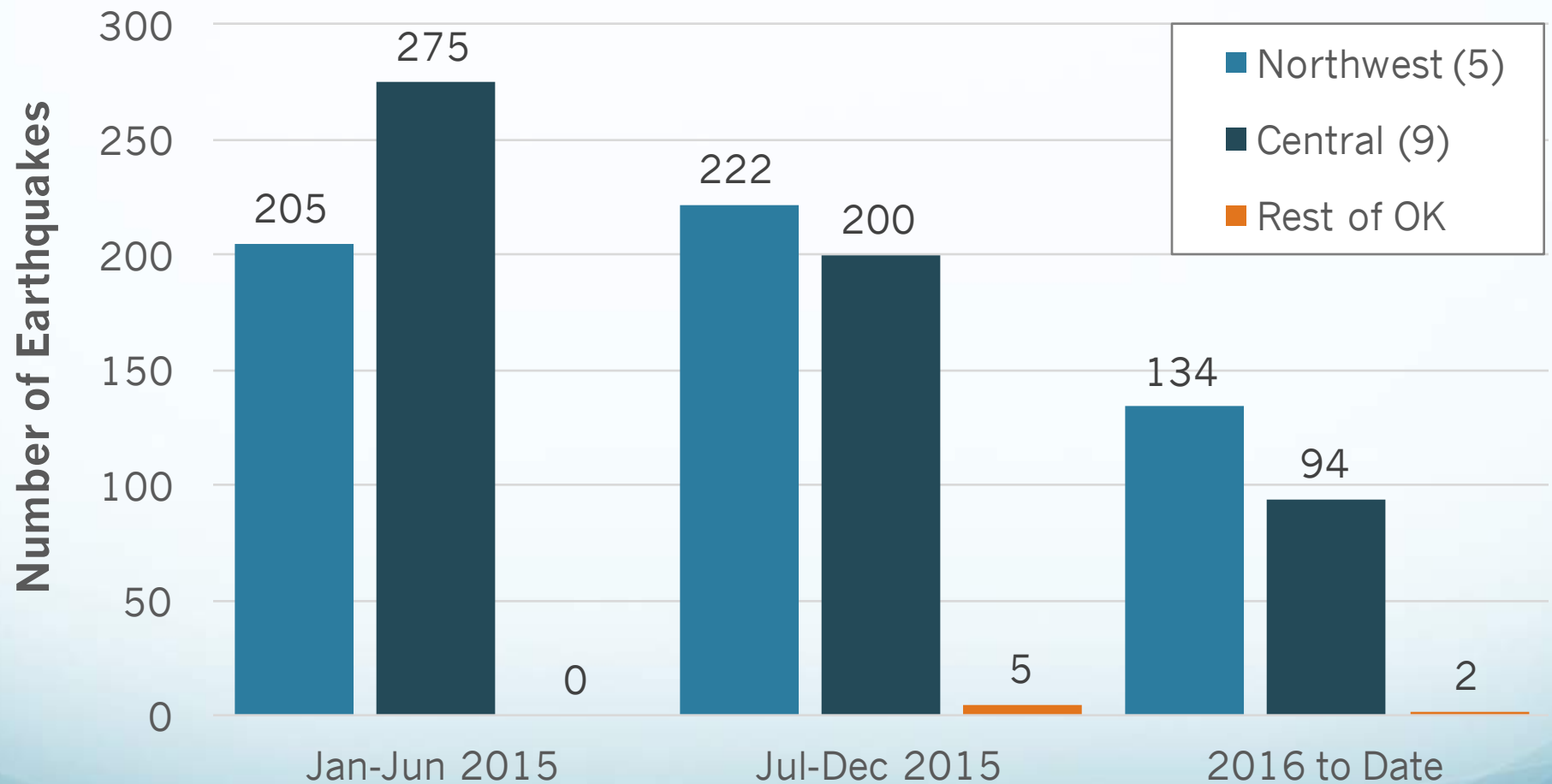


Injection Rate Decline in 285 Arbuckle SWD Wells in Seismic Area of Interest

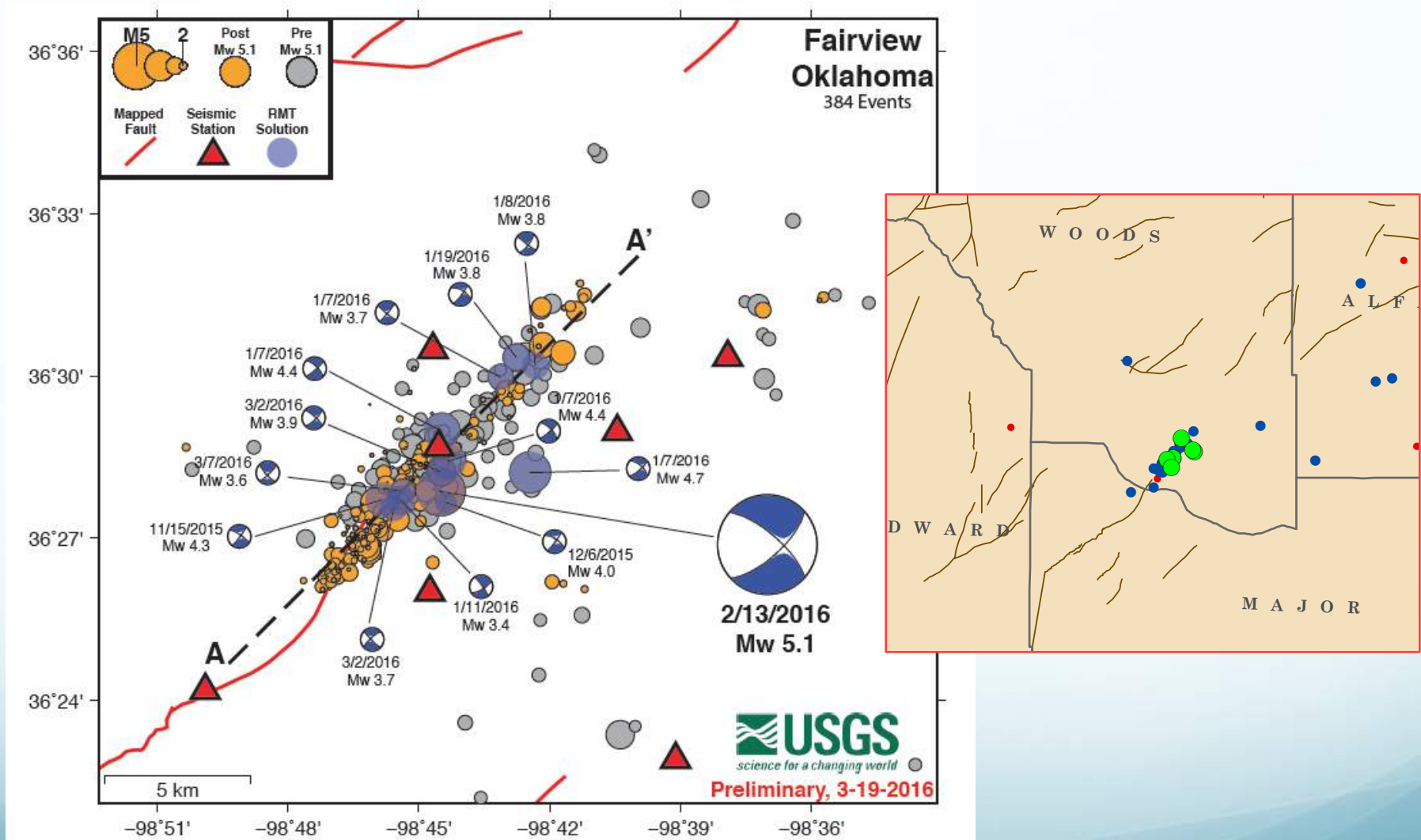


Focus of Seismic Activity Shifting to Northwest

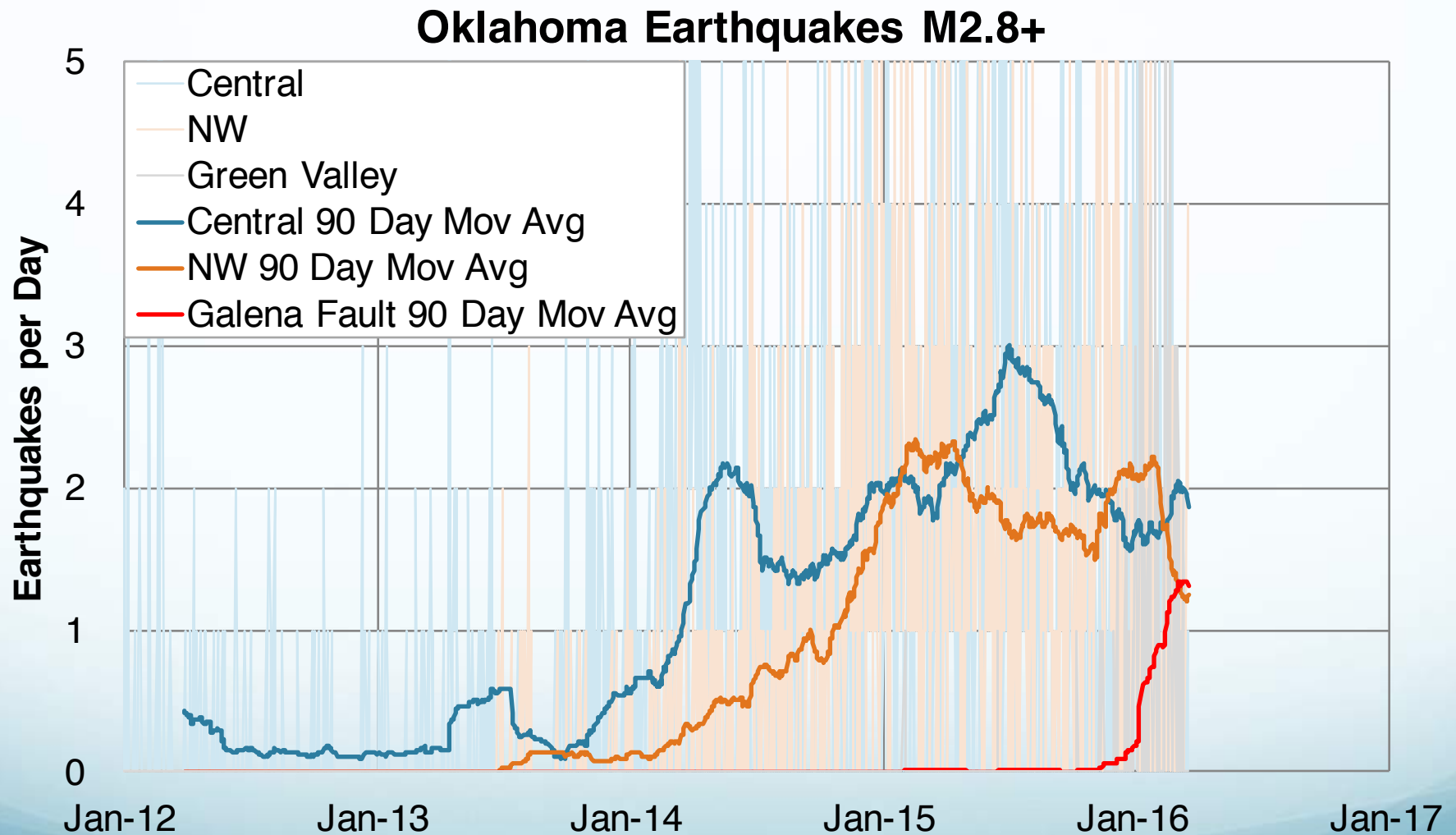
2015-16 Earthquakes by Region



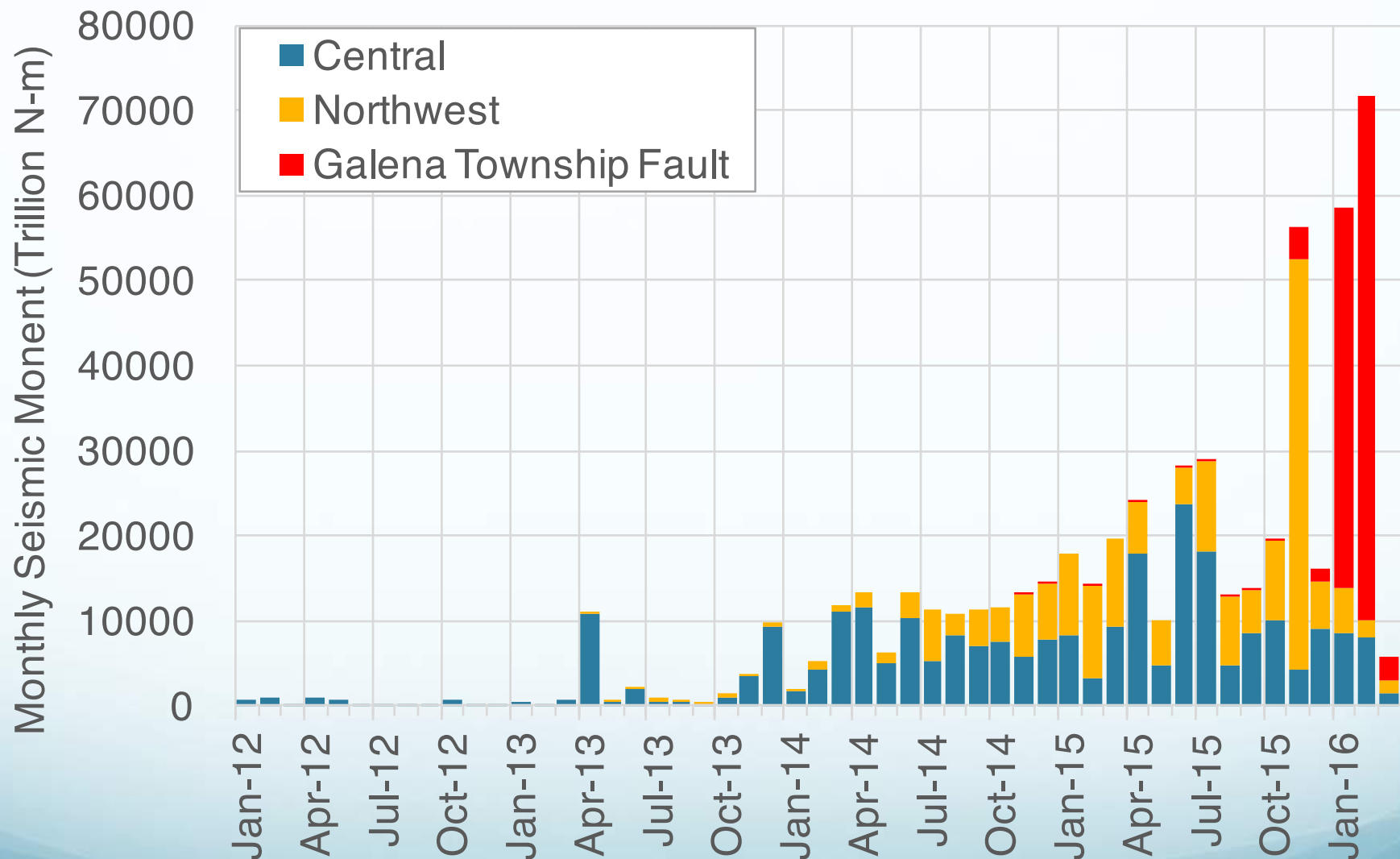
Recent Activity in Fairview/Waynoka Area



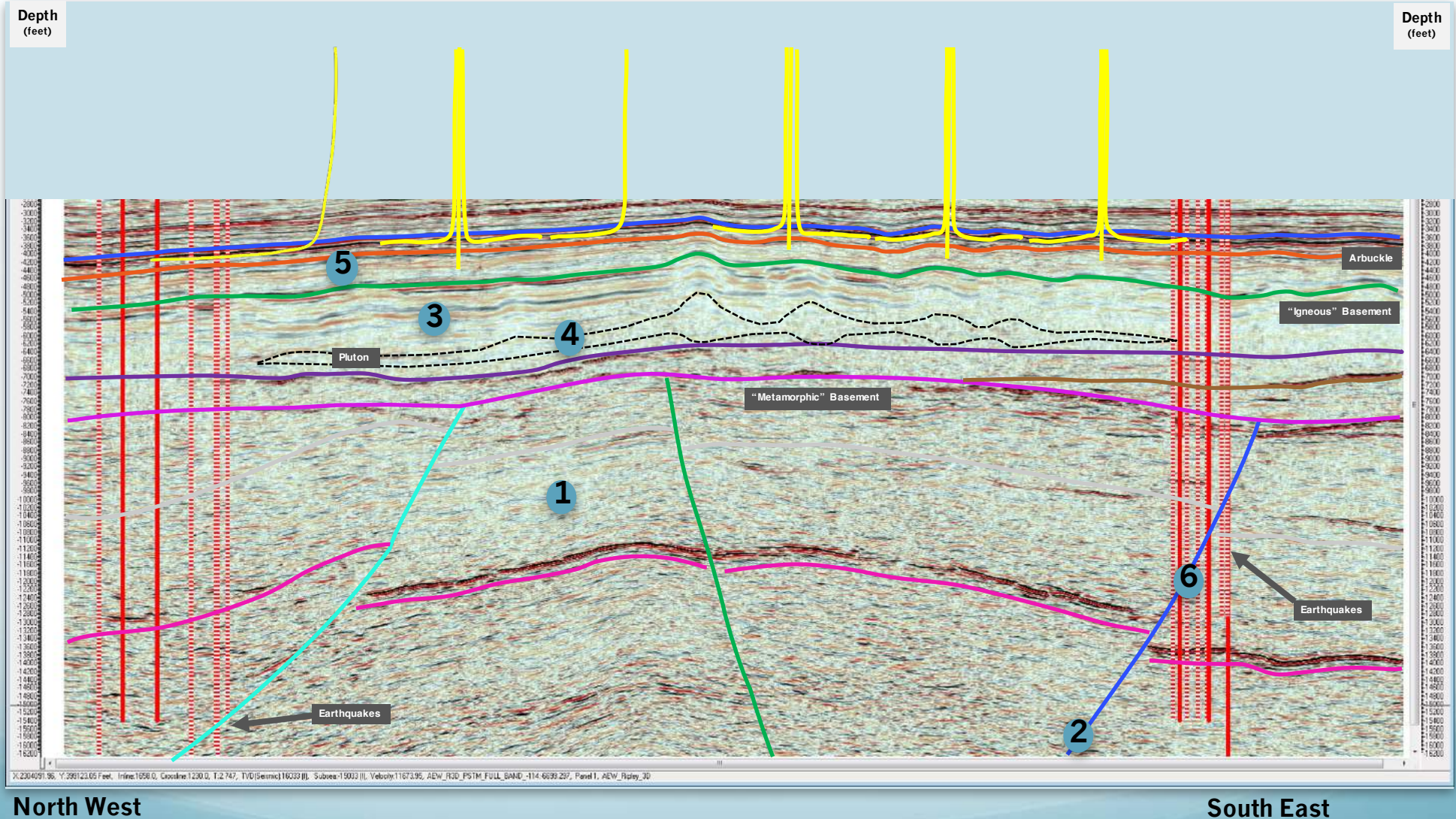
Galena Township Fault Activity is Major Element



Seismic Moment by Region



Industry Collaboration Addresses Important Issues



Summary: Induced Seismicity in Oklahoma

- No documented case of induced seismicity comes close to the current earthquake rates or the area over which the earthquakes are occurring in Oklahoma
- The OGS considers it very likely that the majority of recent earthquakes, particularly those in central and north-central Oklahoma, are triggered by the injection of produced water in SWD wells.
- Hydraulic fracturing flowback water only contributes a small amount to the SWD apparently responsible for the observed rate of earthquakes

Questions or Comments?



- OGS website : <http://www.ou.edu/ogs>

- Report Feeling an Earthquake

- ✓ Quicklink on homepage

- Earthquake FAQ

- Recent Earthquakes

- Current Publications

- Earthquake Preparedness

- <http://www.earthquakes.ok.gov>

- <http://www.ok.goc/reddirtready/>

- <http://www.ready.gov/earthquakes>

- <http://www.dropcoverholdon.org/>

- <http://www.earthquakecountry.info/roots/index.php>



@OKearthquakes



Oklahoma Geological Survey –
Earthquake Notices



okgeosurvey



Oklahoma Geological Survey



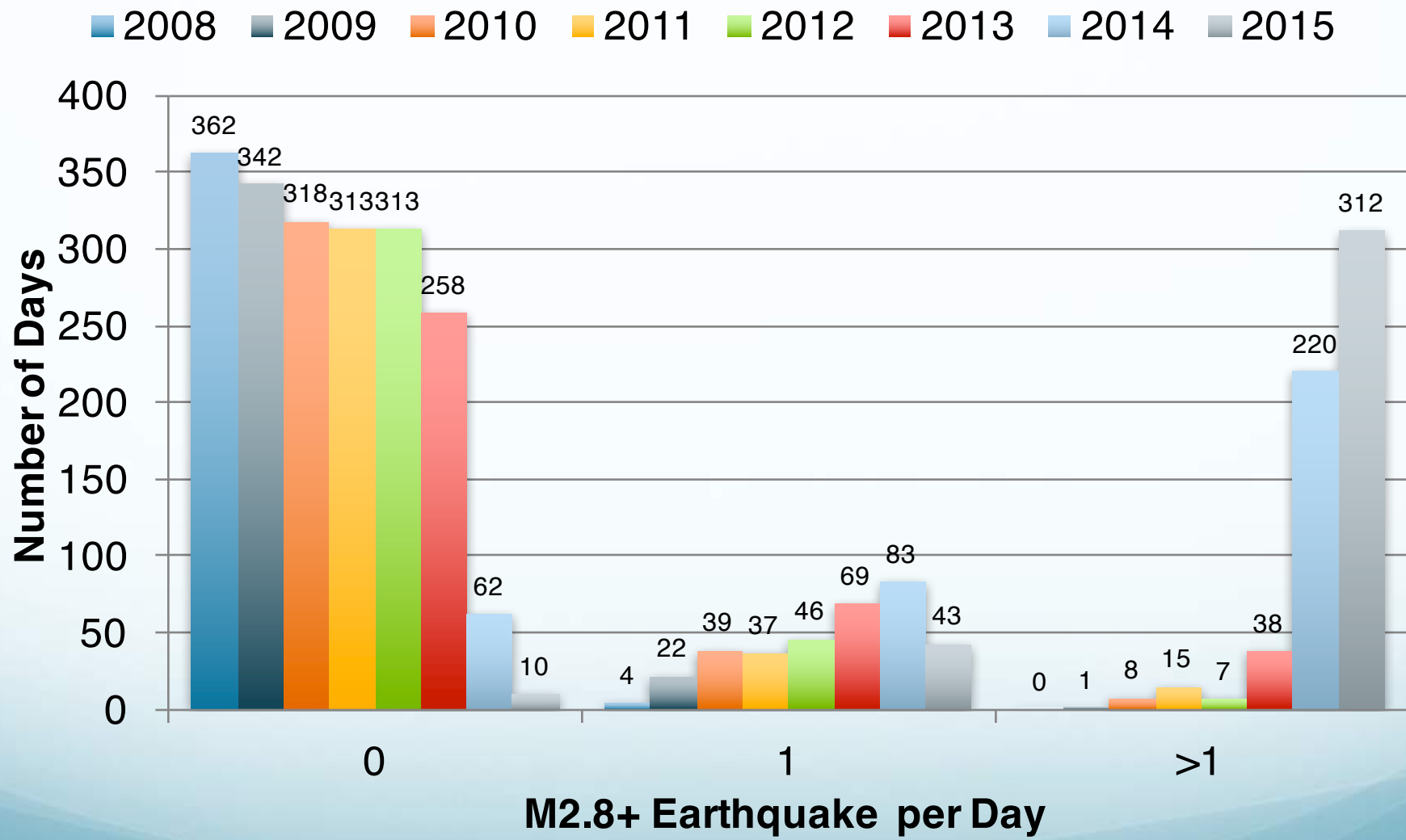
OKgeosurvey



ogs.ou.edu

Backup Material

A Change in the Seismic Weather



Earthquake Forecasting

- Probability of one or more earthquakes of magnitude (m) over the specified time
- Not a prediction, but a forecast
- Shorter the period, the more uncertain the estimate

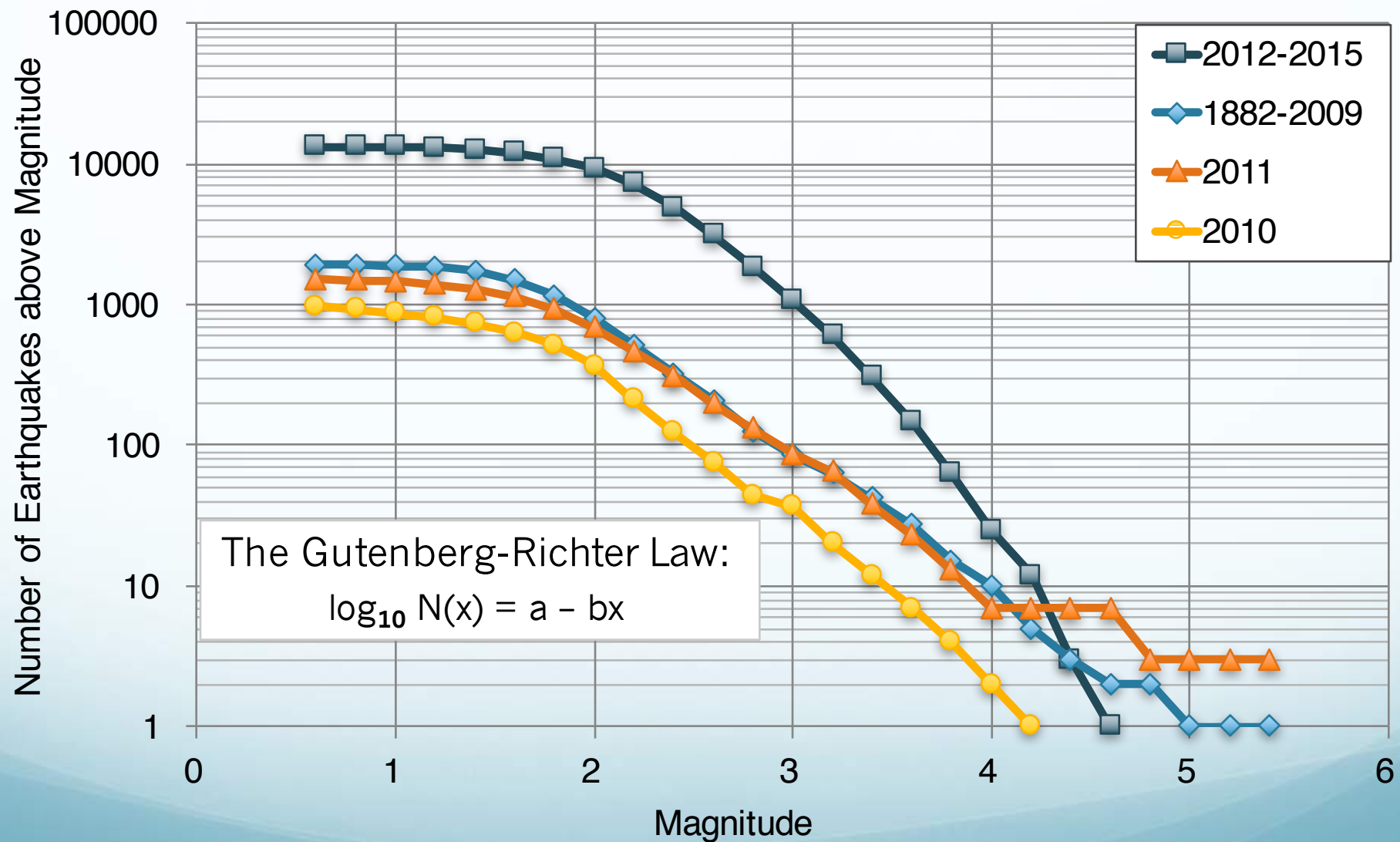
	Magnitude (M_L)					
Duration	3.0	4.0	4.5	5.0	5.5	6.0
4 Year	1.00	1.00	1.00	0.80	0.28	0.06
1 Year	1.00	1.00	1.00	0.72	0.24	0.06
6 months	1.00	1.00	0.98	0.63	0.21	0.05
30 days	1.00	0.93	0.48	0.15	0.04	0.01
10 days	1.00	0.28	0.06	0.01	0.003	0.0006

Probabilities are expressed as values from 0 to 1. To transform probabilities to percent, multiply by 100.

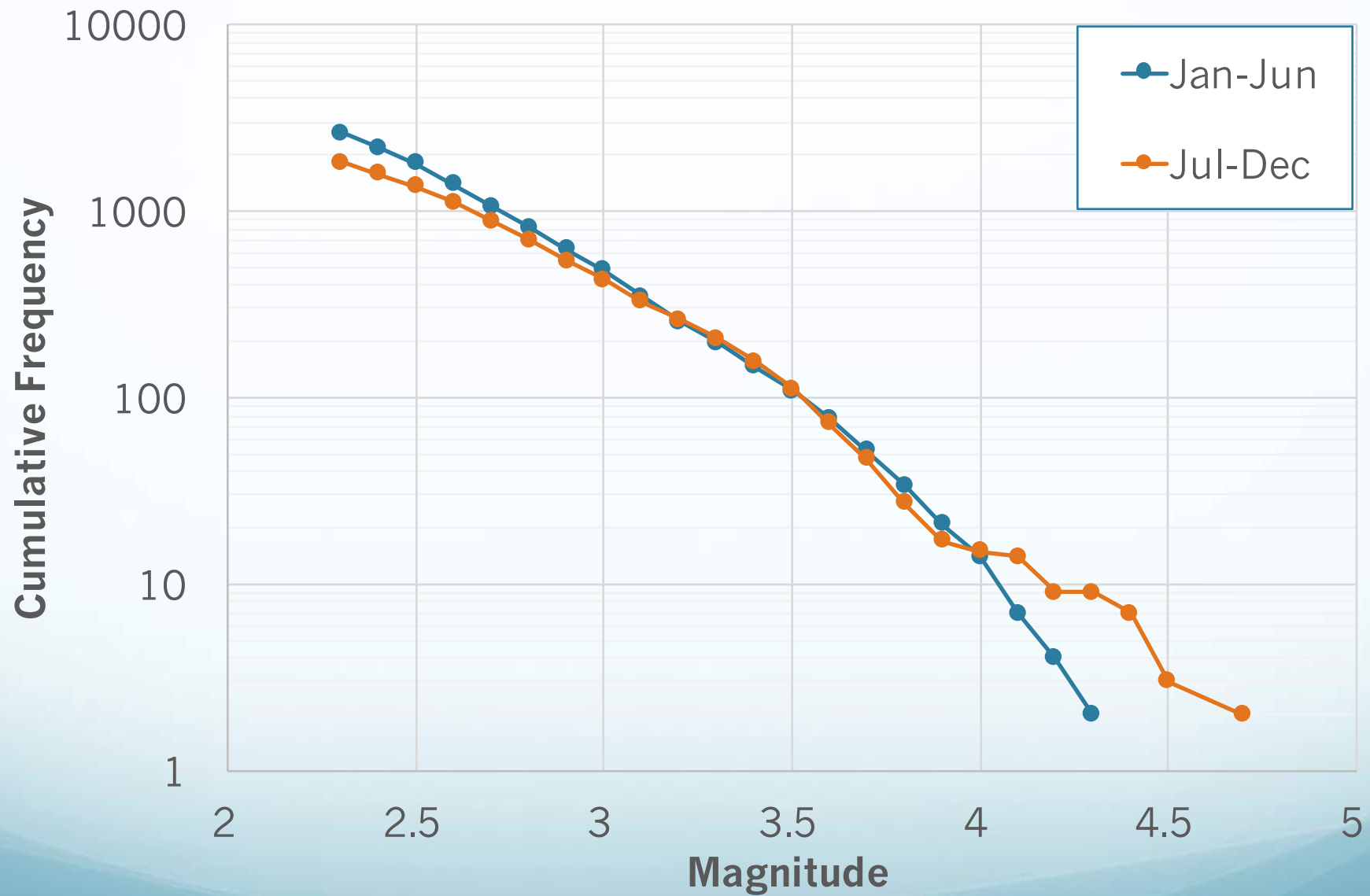
Strategic Direction for the OGS

- Continue and expand collaborations on understanding induced and intraplate seismicity
- Integrate OGS data and collections through a geographically referenced database
- Fund creation of a new facility for the Oklahoma Petroleum Information Center (OPIC)
- Rejuvenate the publications (hard copy and electronic) and outreach of the OGS
- Prepare for the next geologic headline – water?

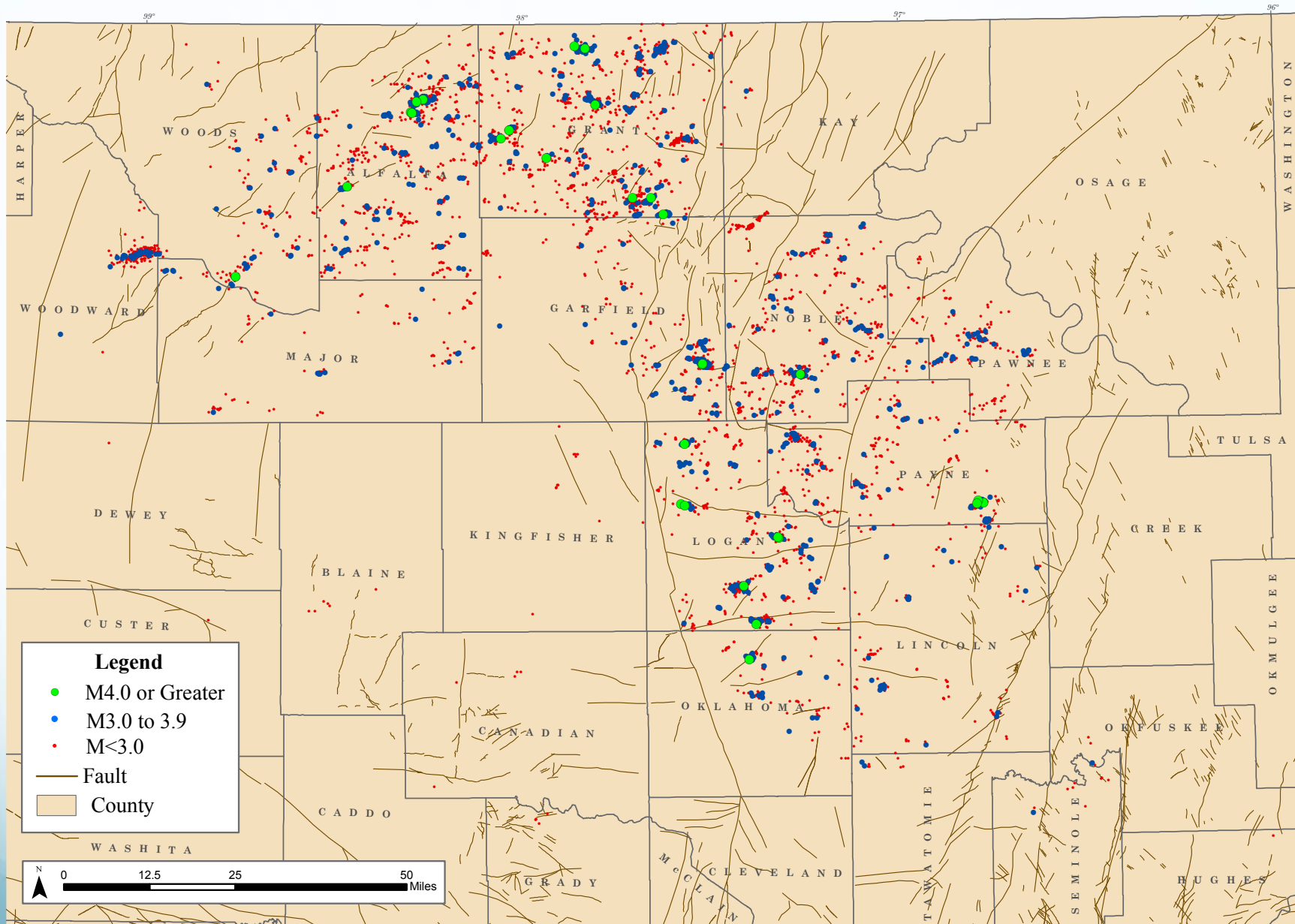
Gutenberg-Richter Relationships



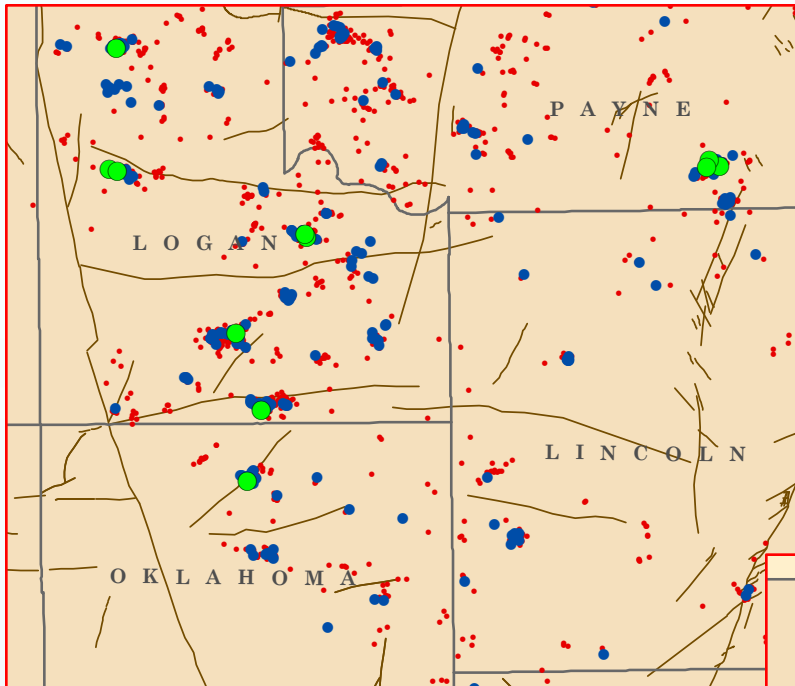
2015 Earthquake Frequency



Earthquakes 2015

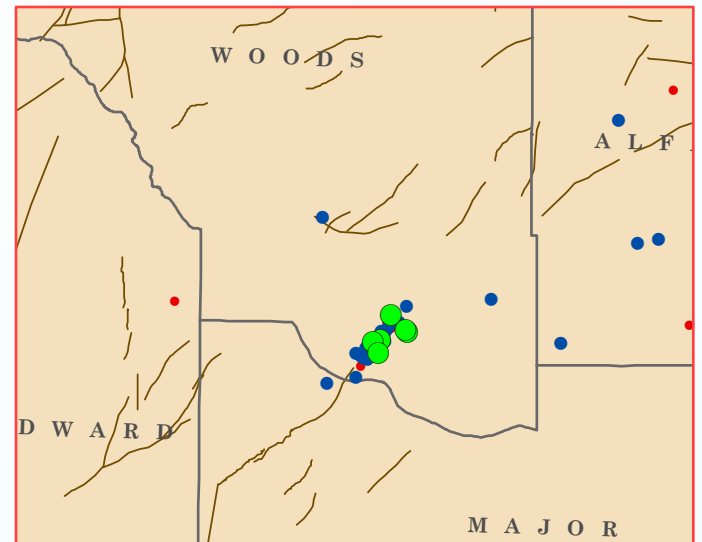


Recent Earthquake Activity

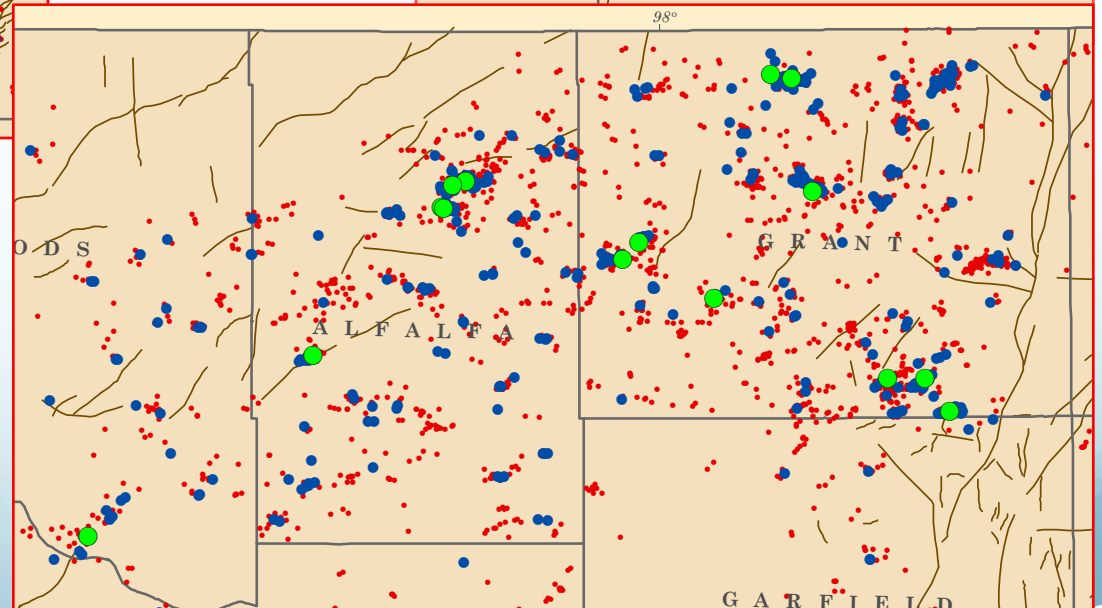


Edmond and Cushing Areas

Fairview Area



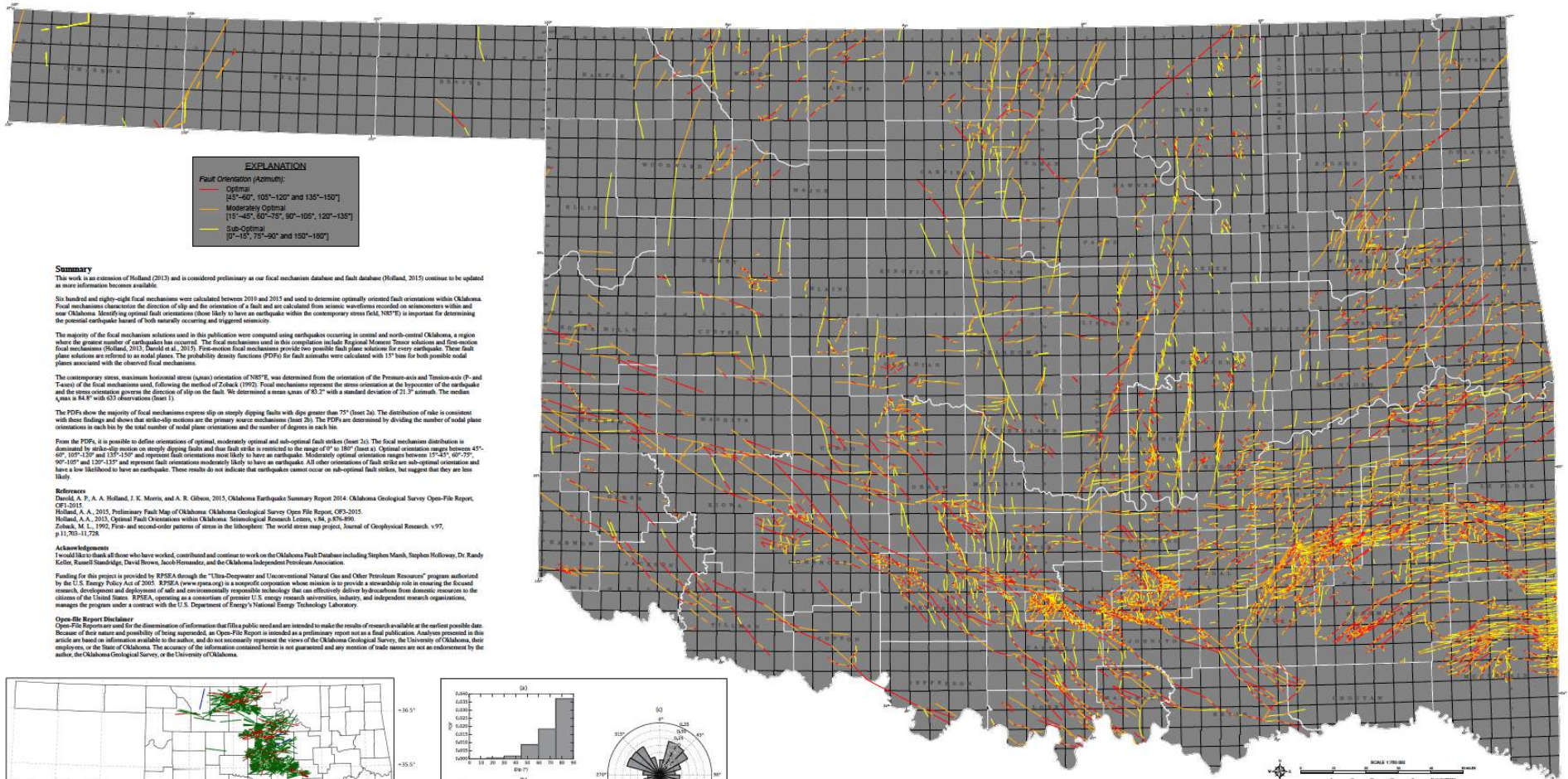
Grant, Alfalfa, Woods Counties



Optimally Oriented Faults in Oklahoma

OKLAHOMA GEOLOGICAL SURVEY
Dr. Jeremy Hook, Director

OPEN-FILE REPORT OF 2015
Preliminary Oklahoma Optimal Fault Orientations



Summary

This work is an extension of Holland (2013) and is considered preliminary as our focal mechanism database and fault database (Holland, 2013) continue to be updated as more information becomes available.

Six hundred and eighty-eight focal mechanisms were calculated between 2010 and 2015 and used to determine optimally oriented fault orientations within Oklahoma. Focal mechanisms characterize the direction of slip and the orientation of a fault and are calculated from seismic waveforms recorded on seismometers within and near Oklahoma. Identifying optimal fault orientations (those likely to have an earthquake within the contemporary stress field, NDE) is important for determining the potential earthquake hazard of both naturally occurring and triggered seismicity.

The majority of the focal mechanism solutions used in this publication were computed using earthquakes occurring in central and north-central Oklahoma, a region where the greatest number of earthquakes has occurred. The focal mechanisms used in this compilation include Regional Moment Tensor solutions and first-motion focal mechanisms (Holland, 2013; David et al., 2015). First-motion focal mechanisms provide two possible fault plane solutions for every earthquake. These fault plane solutions are referred to as nodal planes. The probability density functions (PDFs) for fault azimuths were calculated with 15° bins for both possible nodal planes associated with the observed focal mechanisms.

The contemporary stress, maximum horizontal stress (azimuth) orientation of NDE, was determined from the orientation of the Pressure-axis and Tension-axis (P- and T-axis) of the focal mechanisms used, following the method of Zoback (1992). Focal mechanisms represent the stress orientation at the hypocenter of the earthquake and the stress orientation governs the direction of slip on the fault. We determined a mean stress of 65.2° with a standard deviation of 21.3°. The median σ_{max} is 84.8° with 623 observations (Inset 1).

The PDFs show the majority of focal mechanisms express slip on steeply dipping faults with dips greater than 75° (Inset 2a). The distribution of rake is consistent with these findings and shows that strike-slip motions are the primary source mechanisms (Inset 2b). The PDFs are determined by dividing the number of nodal plane orientations in each bin by the total number of nodal plane orientations and the number of degrees in each bin.

From the PDFs, it is possible to define orientations of optimal, moderately optimal and sub-optimal fault strikes (Inset 2c). The focal mechanism distribution is dominated by strike-slip motion on steeply dipping faults and that fault strike is restricted to the range of 0° to 180° (Inset 2c). Optimal orientation ranges between 45°-60°, 105°-120° and 135°-150° and represent fault orientations most likely to have an earthquake. Moderately optimal orientation ranges between 15°-45°, 60°-75°, 90°-105° and 120°-135° and represent fault orientations moderately likely to have an earthquake. All other orientations of fault strike are sub-optimal orientation and have a low likelihood to have an earthquake. These results do not indicate that earthquakes cannot occur on sub-optimal fault strikes, but suggest that they are less likely.

References

- David, A. P., A. A. Holland, J. E. Morris, and A. R. Gibson, 2015, Oklahoma Earthquake Summary Report 2014: Oklahoma Geological Survey Open-File Report, OF1-2015.
- Holland, A. A., 2015, Preliminary Fault Map of Oklahoma: Oklahoma Geological Survey Open File Report, OF3-2015.
- Holland, A. A., 2013, Optimal Fault Orientations within Oklahoma: Seismological Research Letters, v.84, p.876-890.
- Zoback, M. L., 1992, First- and second-order patterns of stress in the lithosphere: The world stress map project, *Journal of Geophysical Research*, v.97, p.11,703-11,728.

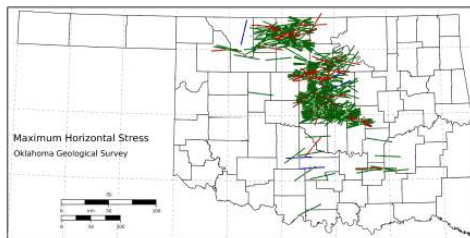
Acknowledgments

I would like to thank all those who have worked, contributed and continue to work on the Oklahoma Fault Database including Stephen Marsh, Stephen Holloway, Dr. Randy Kiefer, Russell Sandridge, David Brown, Jacob Hernandez, and the Oklahoma Independent Petroleum Association.

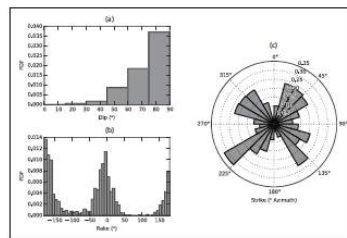
Funding for this project is provided by RPSEA through the "Ultra-Deepwater and Unconventional Natural Gas and Other Petroleum Resources" program authorized by the U.S. Energy Policy Act of 2005. RPSEA (www.rpseainc.org) is a nonprofit corporation whose mission is to provide a stewardship role in ensuring the focused research, development and deployment of safe and environmentally responsible technology that can effectively deliver hydrocarbons from domestic resources to the citizens of the United States. RPSEA, operating as a consortium of premier U.S. energy research universities, industry, and independent research organizations, manages the program under a contract with the U.S. Department of Energy's National Energy Technology Laboratory.

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Inset 1: Maximum horizontal stress orientation of P- and T-axis of 623 focal mechanisms, following the convention of Zoback (1992); red, normal faulting; green, strike-slip faulting; blue, thrust faulting.



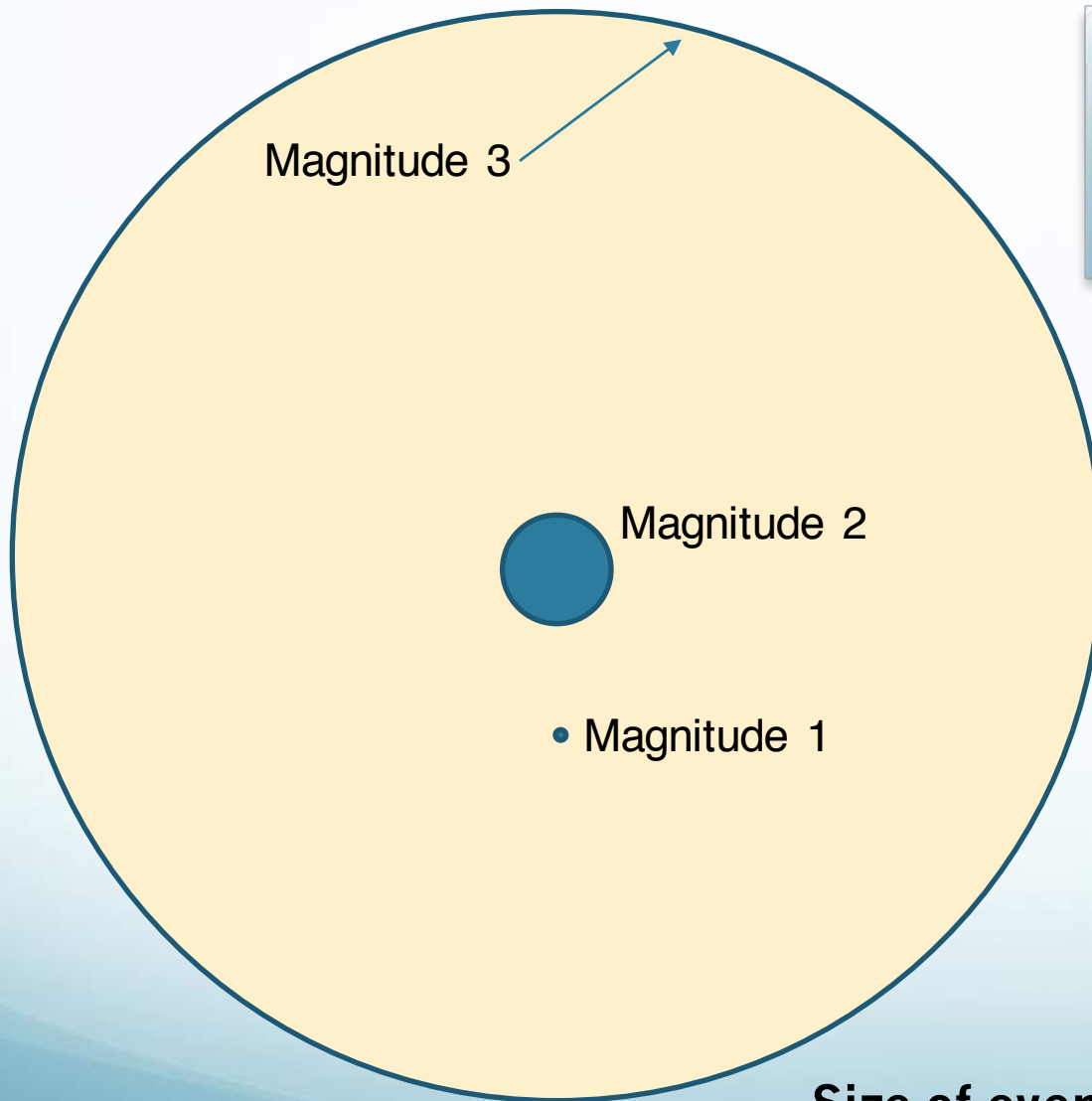
Inset 2: Probability density functions for fault orientations for 688 focal mechanisms within Oklahoma with 15° bin intervals and a total of 1,376 nodal planes; (a) PDF of fault dip, (b) PDF of fault rake, (c) PDF of fault strike.

PRELIMINARY OKLAHOMA OPTIMAL FAULT ORIENTATIONS

By
Amberlee P. Darold and Austin A. Holland
2015

OGS OF4-2015 Preliminary Oklahoma Optimal Fault Orientations
Sources: Literature & OIPA

Magnitude scale is logarithmic



Magnitude Kinetic Energy

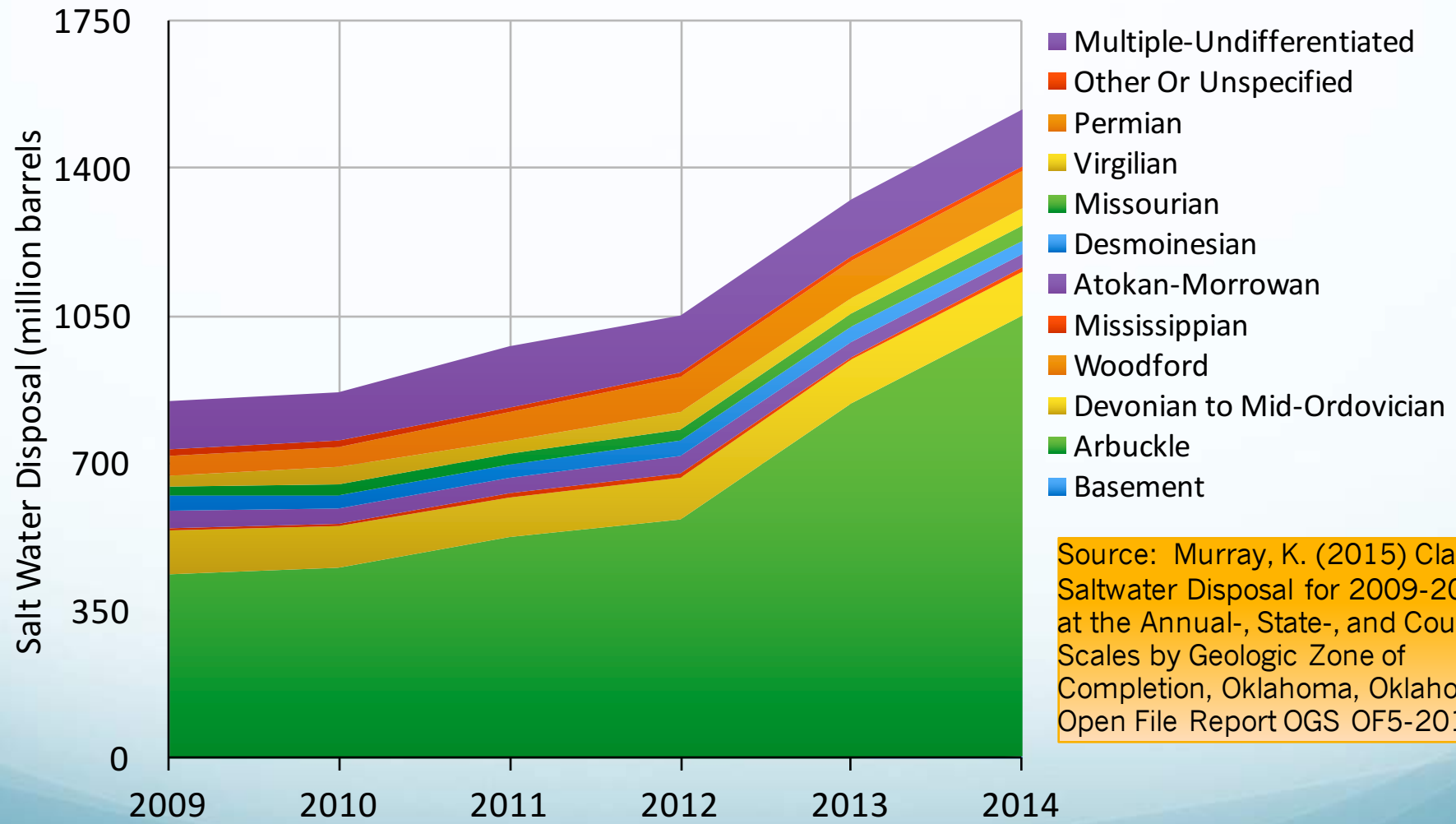
3	29 tons TNT
2	Large Quarry or Mine Blast
1	1 Stick Dynamite

Source: Alabama Quake.com

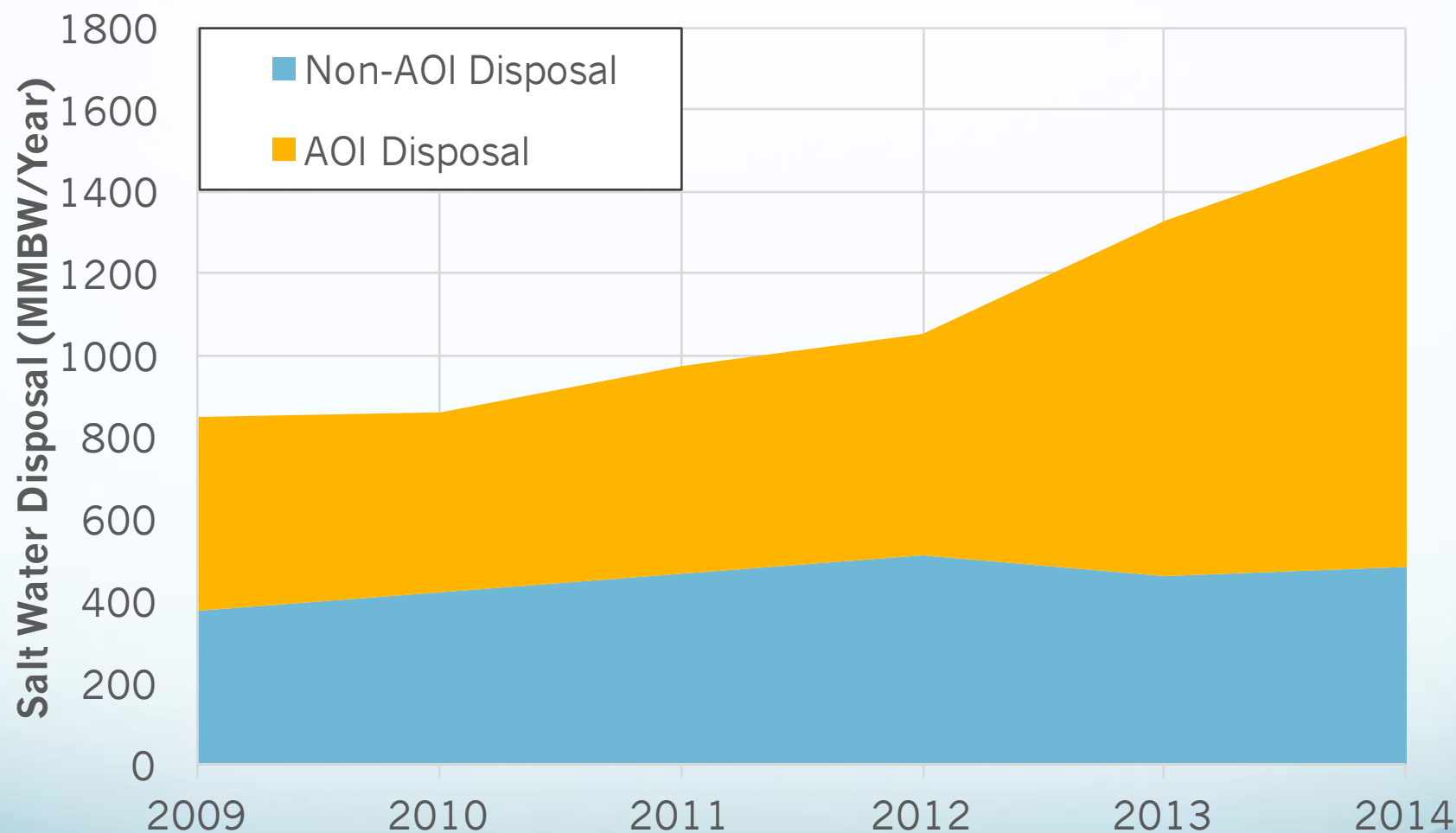
- Magnitude - a scaled estimate of energy released as seismic waves
 - proportional to rupture area
- Magnitude measured multiple ways (M_L , m_b , M_w , M_o , M_s)
- Magnitude estimates rarely the same between different methods and all are uncertain

**Size of event 10x larger per magnitude level
32x more energy per magnitude level**

Most SWD occurs in Arbuckle Group



SWD greater inside than outside seismically active Area of Interest



Source: Murray, K. (2015) Class II Saltwater Disposal for 2009-2014 at the Annual-, State-, and County-Scales by Geologic Zone of Completion, Oklahoma, Oklahoma Open File Report OGS OF5-2015

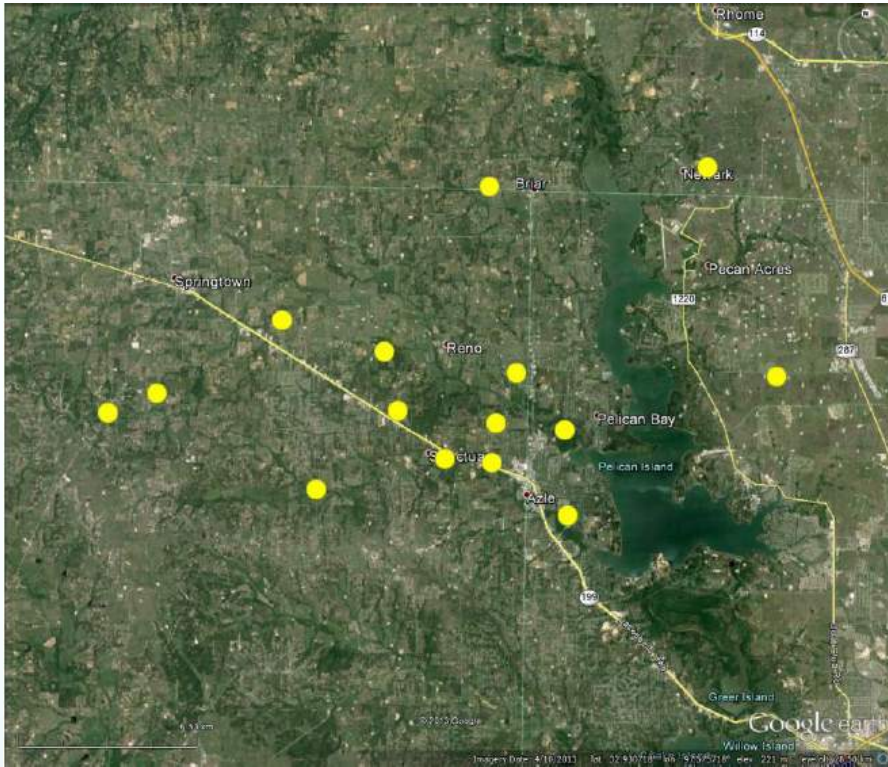
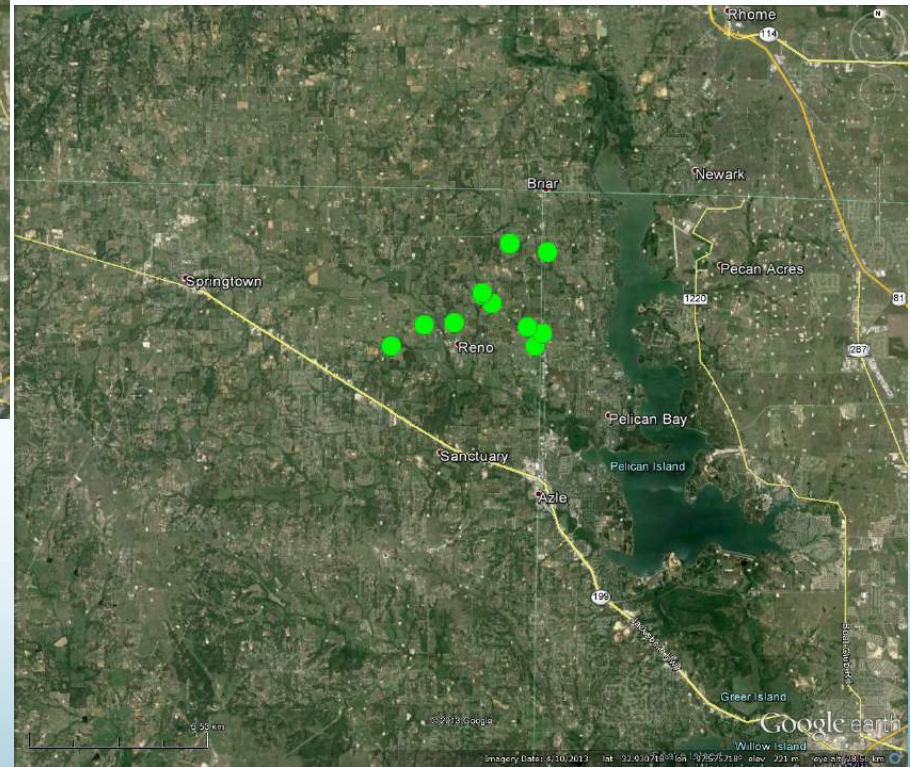


Figure 1. Earthquake epicenters determined by USGS-NEIC, November 1-26, 2013.

Figure 2. Center of shaking for earthquakes, November 6-26, 2013.



Summary for induced seismicity in Oklahoma

- 2013 seismicity 70 times background prior to 2008
 - Unlikely to be explained by variations in earthquake rate from naturally occurring sequences
- 2015 seismicity 600 times background
 - Extremely unlikely result of a natural process
- Most earthquakes in central/north-central Oklahoma occur as earthquake swarms
 - Not foreshock-mainshock-aftershock pattern characteristic of natural earthquake sequences
 - Natural earthquake sequences have occurred in the region
- Earthquakes occur deeper than most oil and gas operations
- Reactivation of deeper basement faults from water injection at shallower depths common in cases of induced seismicity

Scientific Challenges & Knowledge Gaps

- Uncharacteristically large number of earthquakes **challenge to monitoring and reporting, and seismic station maintenance**
- Long history of oil and gas activity and large number of wells
 - Density of injection wells, Arbuckle permeability makes **well-to-earthquake link difficult**
 - Standard methods to identify potentially induced seismicity have produced small numbers of identified cases
 - **Research required to understand induced seismicity to mitigate future occurrences**
- We can identify regions of induced/triggered seismicity, but questions remain
 - What controls timing and greater seismic response to injection?
 - What geologic or injection characteristics cause the seismic response?
 - What are the appropriate approaches to mitigation?