



OKLAHOMA GEOLOGICAL SURVEY

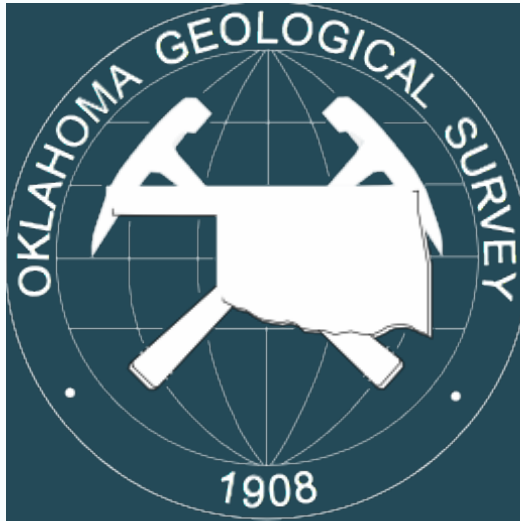
A State Agency For Research and Public Service

Oklahoma Earthquakes and Injection of Produced Water

Jeremy Boak, Director
Oklahoma Geological Survey

jboak@ou.edu

April 13, 2016



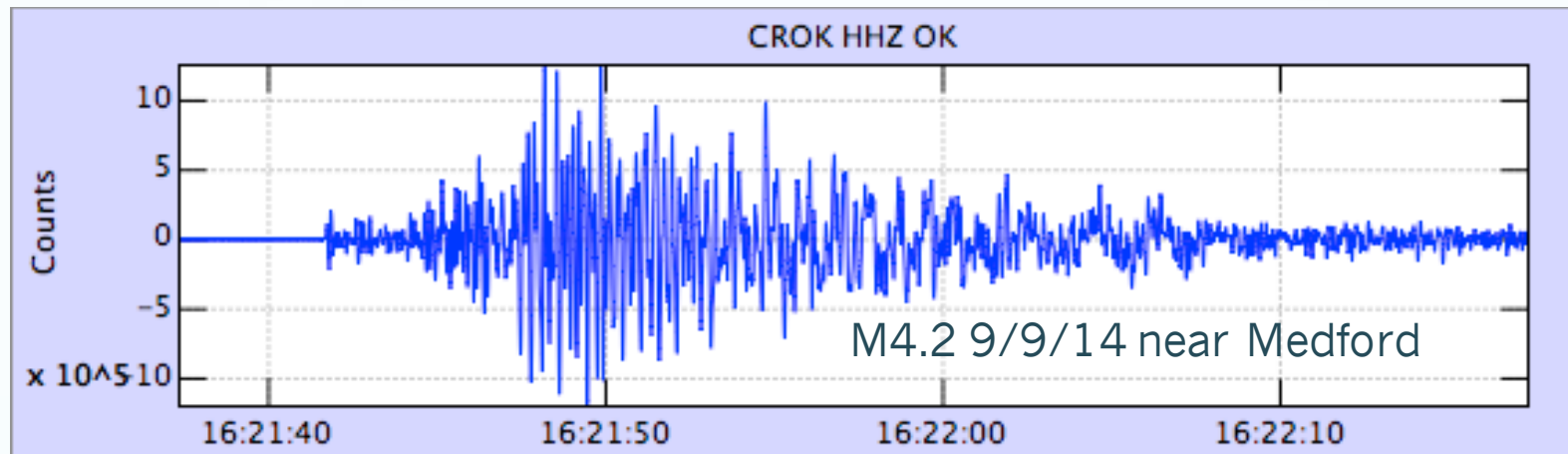
The Oklahoma Geological Survey is a state agency for research and public service located on the Norman Campus of the University of Oklahoma and affiliated with the OU College of Earth and Energy. The Survey is chartered in the Oklahoma Constitution and is charged with investigating the state's land,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

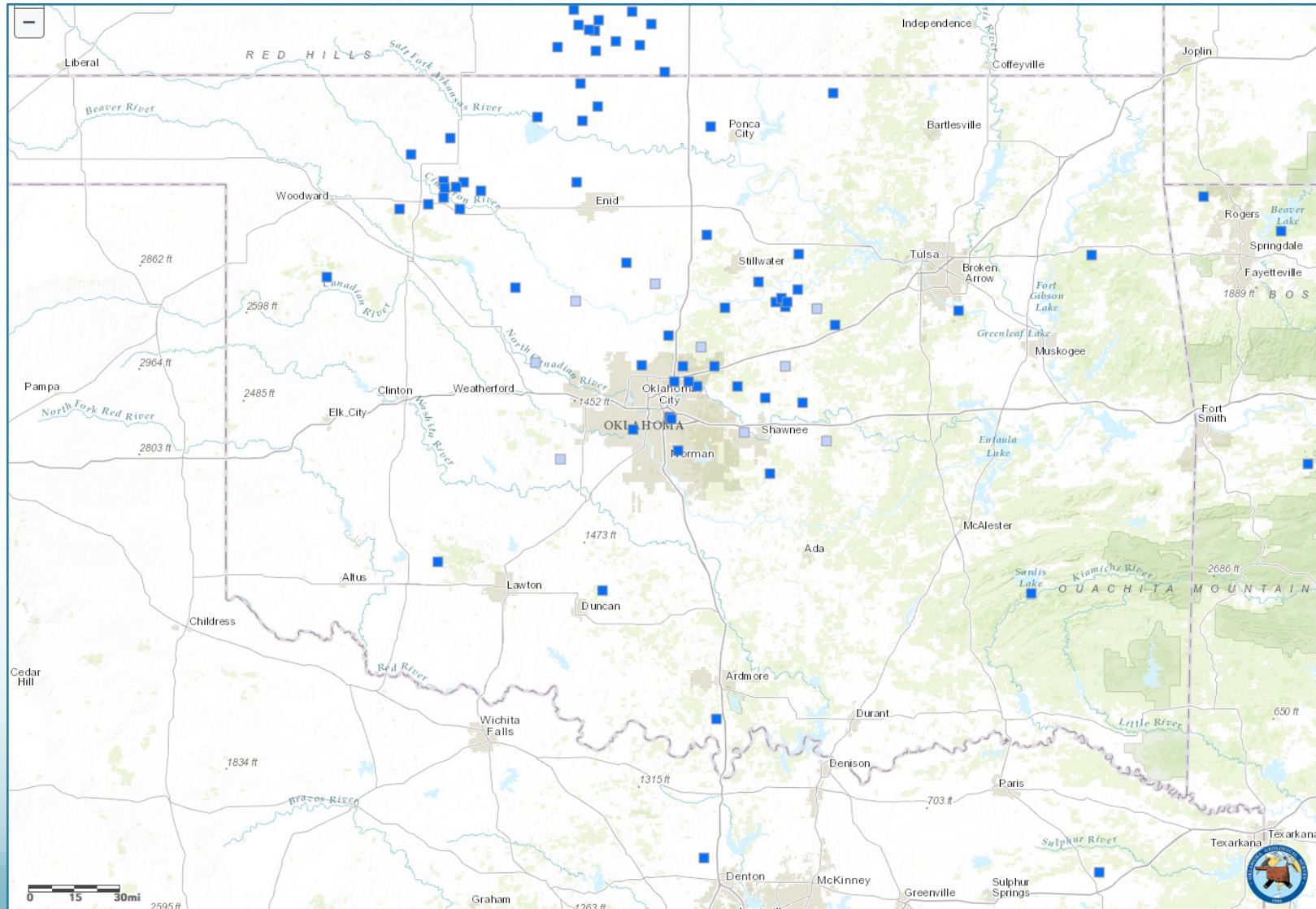
- **OGS Staff Engaged on the Seismicity Issue**
 - **Seismology:** Jefferson Chang, Fernando Ferrer, Noorulann Ghouse, Junjun Hu, Andrew Thiel, Isaac Woelfel
 - **Hydrogeology, Geology, Geophysics:** Kyle Murray, Richard Andrews, Kevin Crain, Steve Holloway, Jordan Williams
 - **Publications & Outreach:**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

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

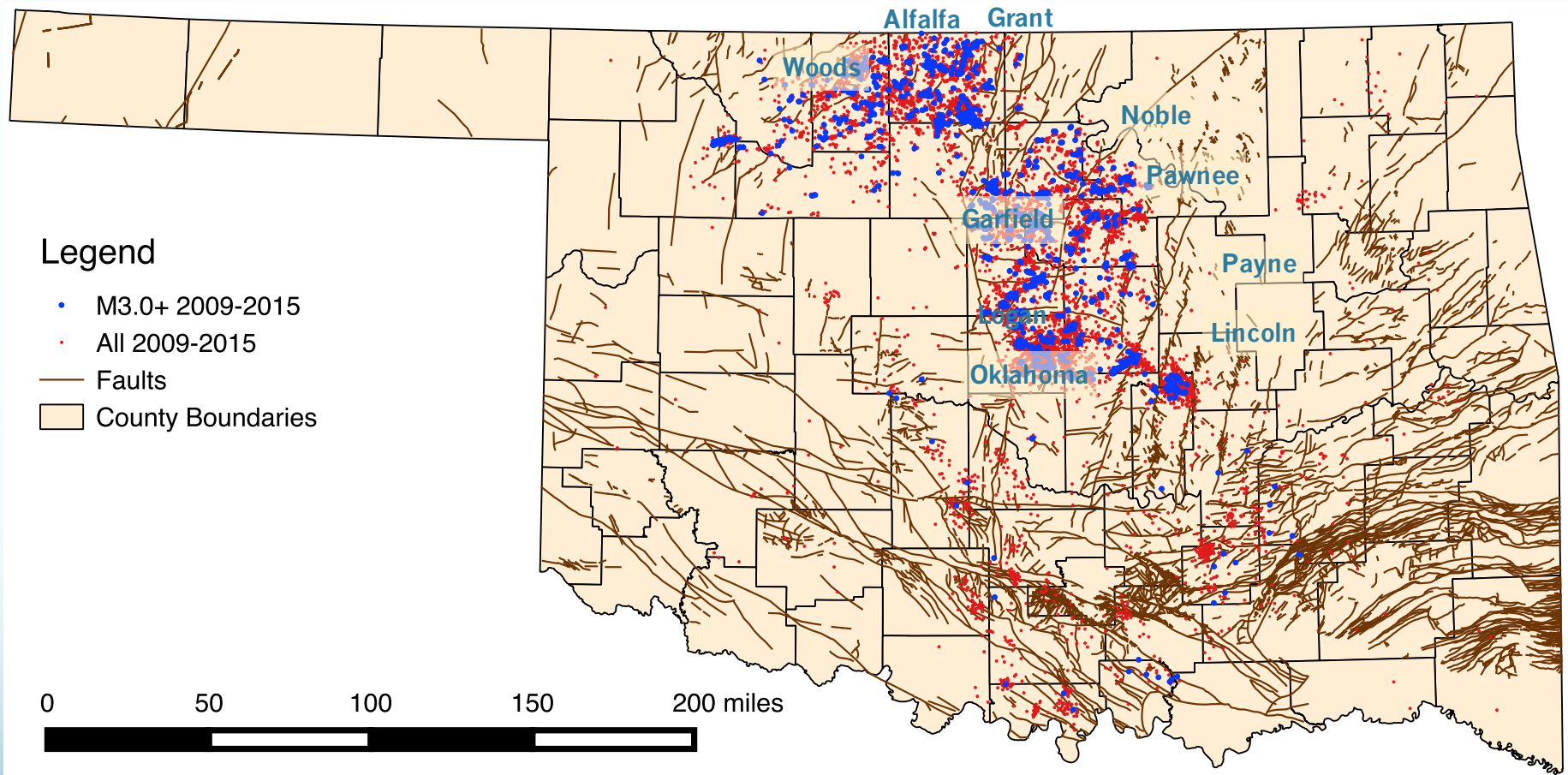
OGS Uses about 50 Stations to Locate Oklahoma Earthquakes



Measuring an Earthquake

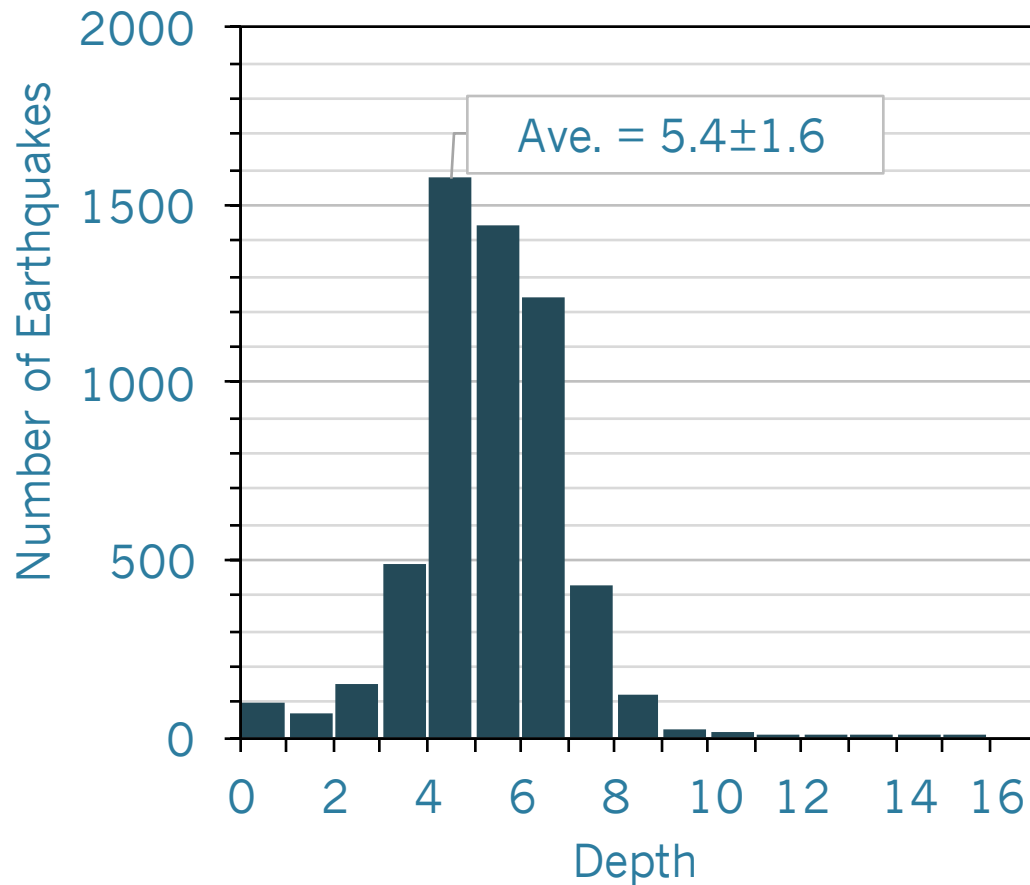
- Magnitude is a scaled estimate of energy released as seismic waves and is proportional to rupture area
- Magnitude measured multiple ways (M_L , m_b , M_w , M_o , M_s)
 - Magnitude estimates rarely the same between different methods
 - All magnitude measures are uncertain
 - Magnitude scales logarithmic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

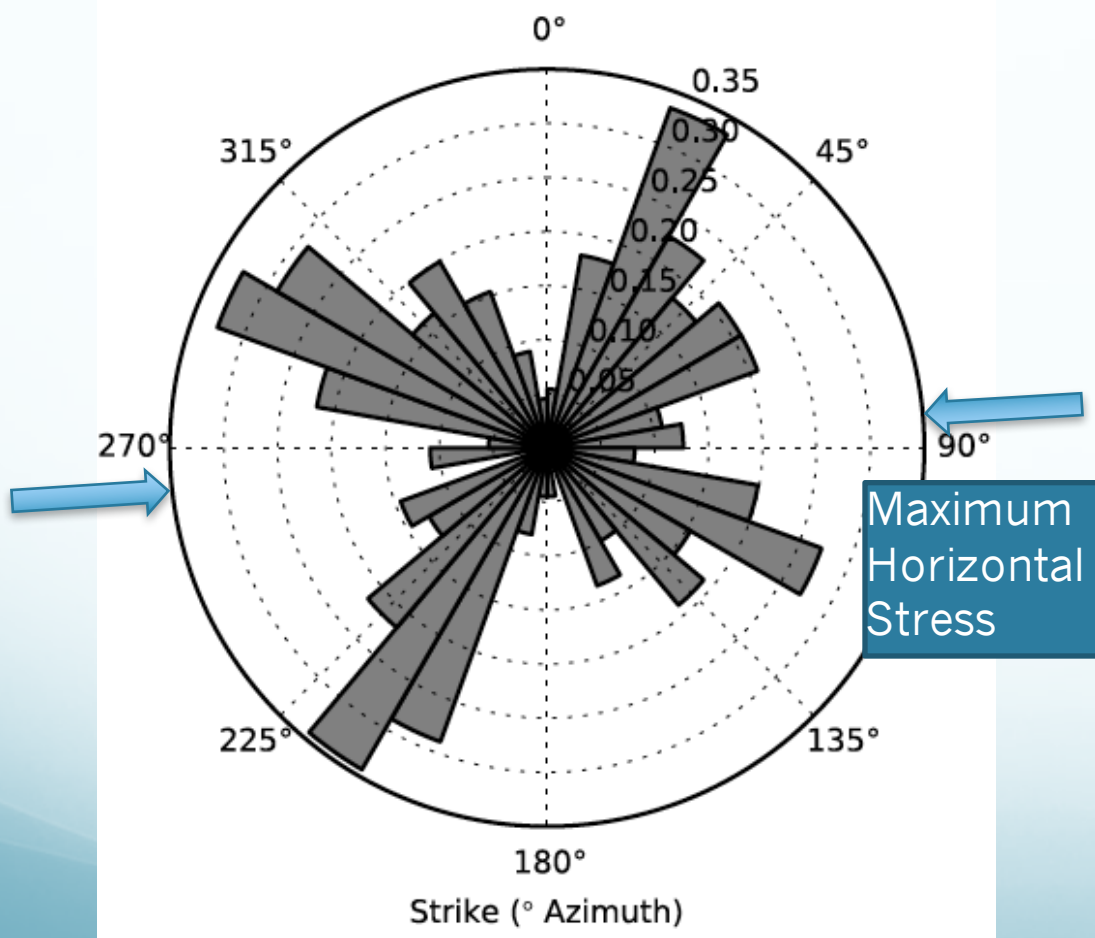
2015 Earthquakes



- 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

Earthquakes Occur on Faults Oriented in Preferred Directions

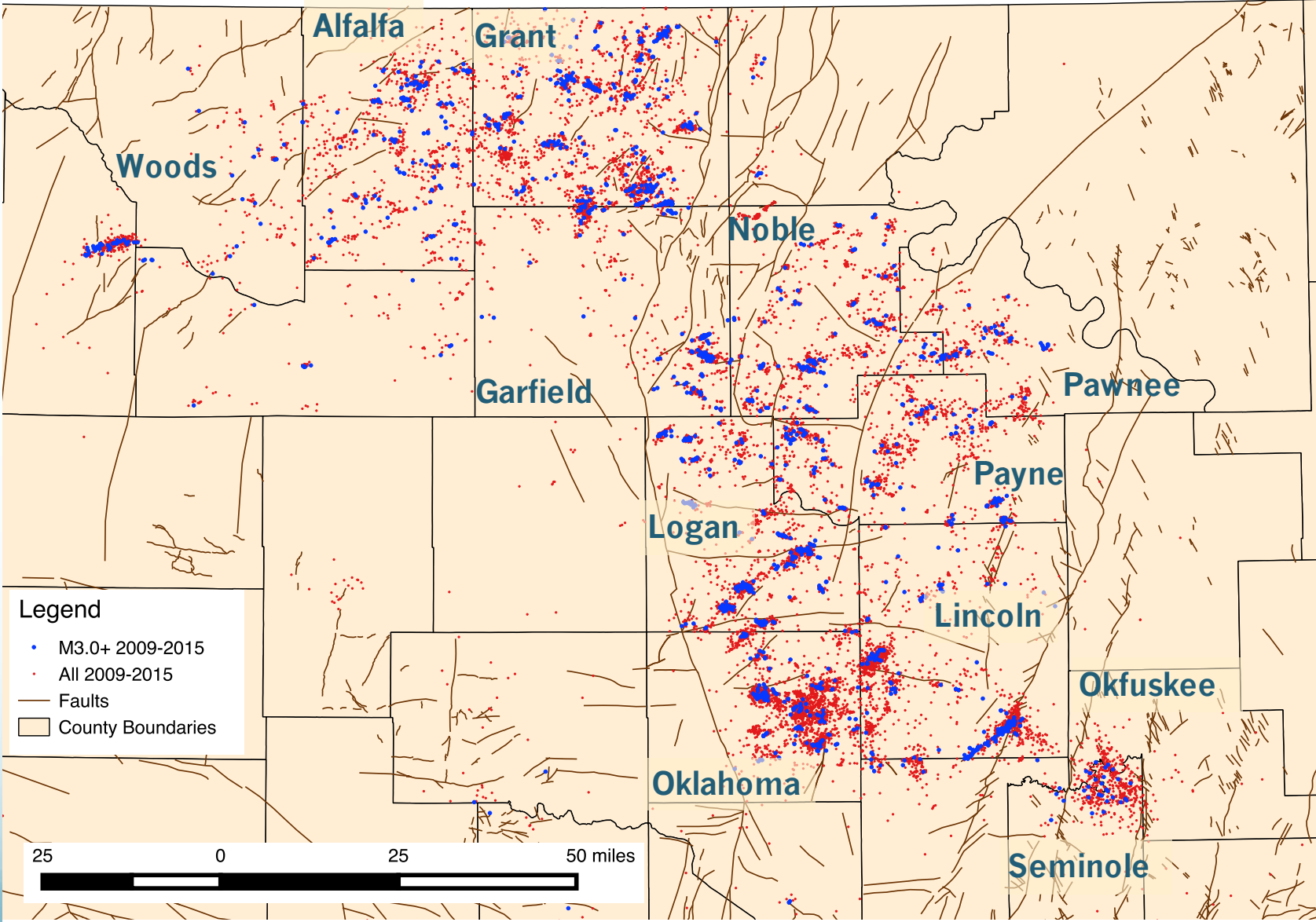
Active Fault Orientations 2014



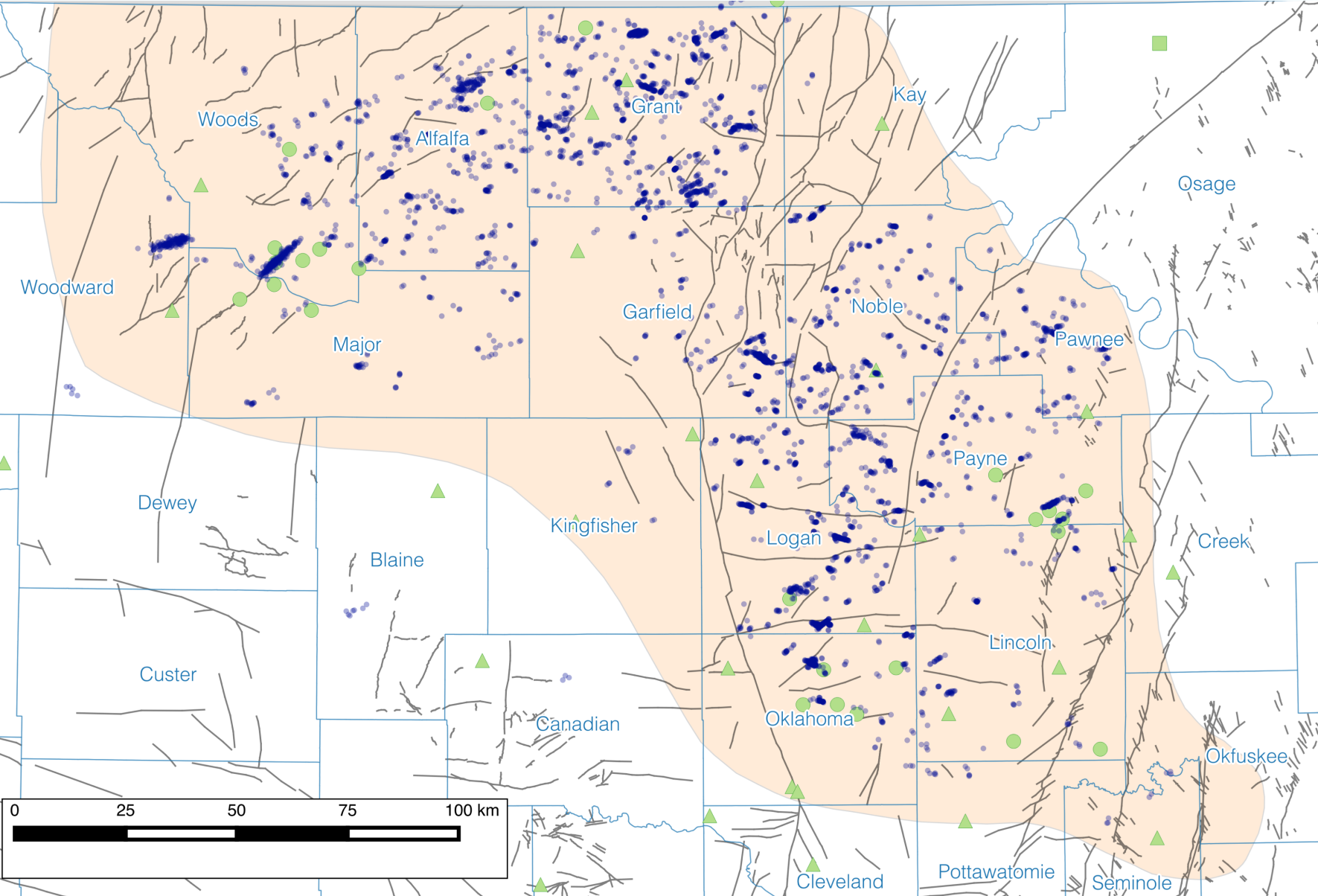
Natural Stresses and Earthquakes

- 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

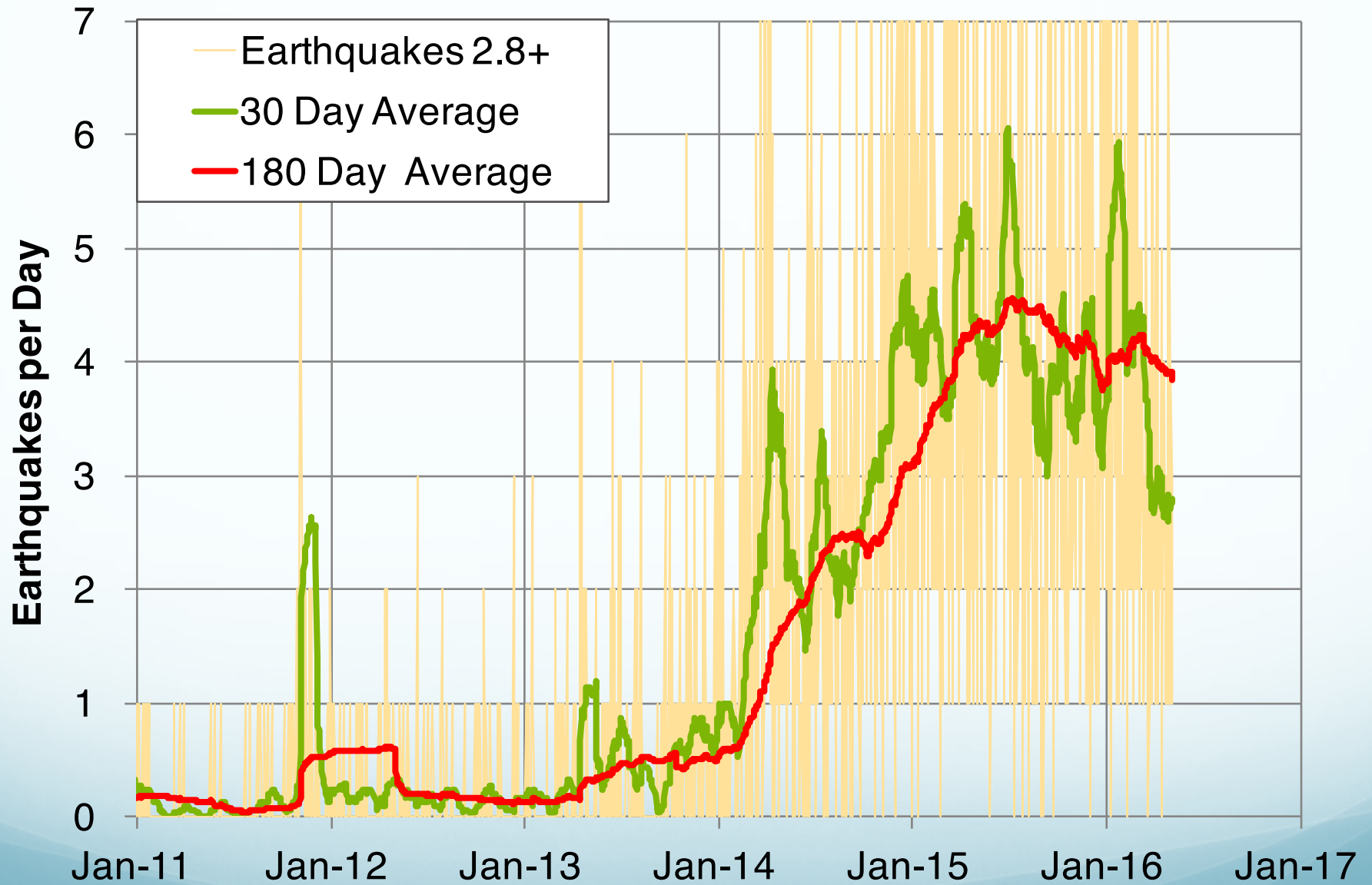
Earthquakes 2009-2015



Earthquakes 2015-2016

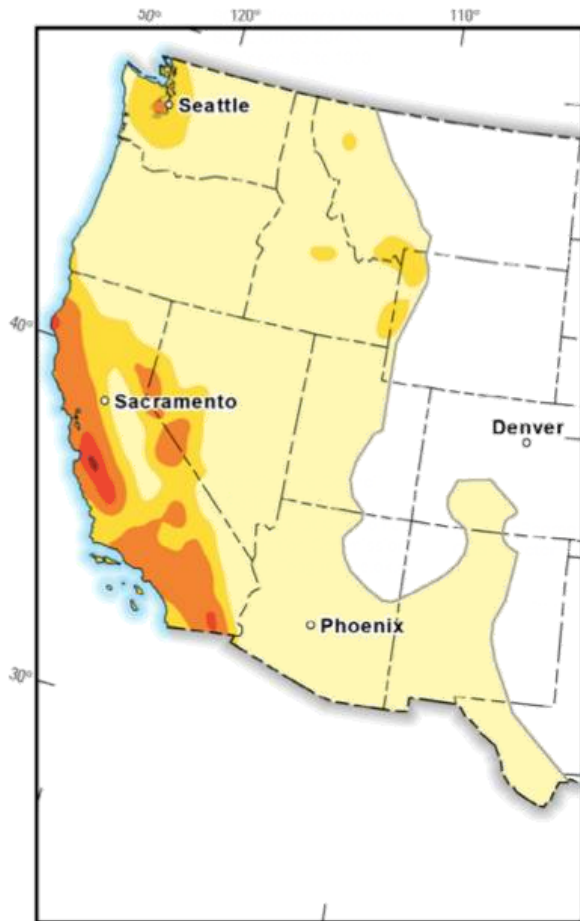


Oklahoma M2.8+ Earthquakes

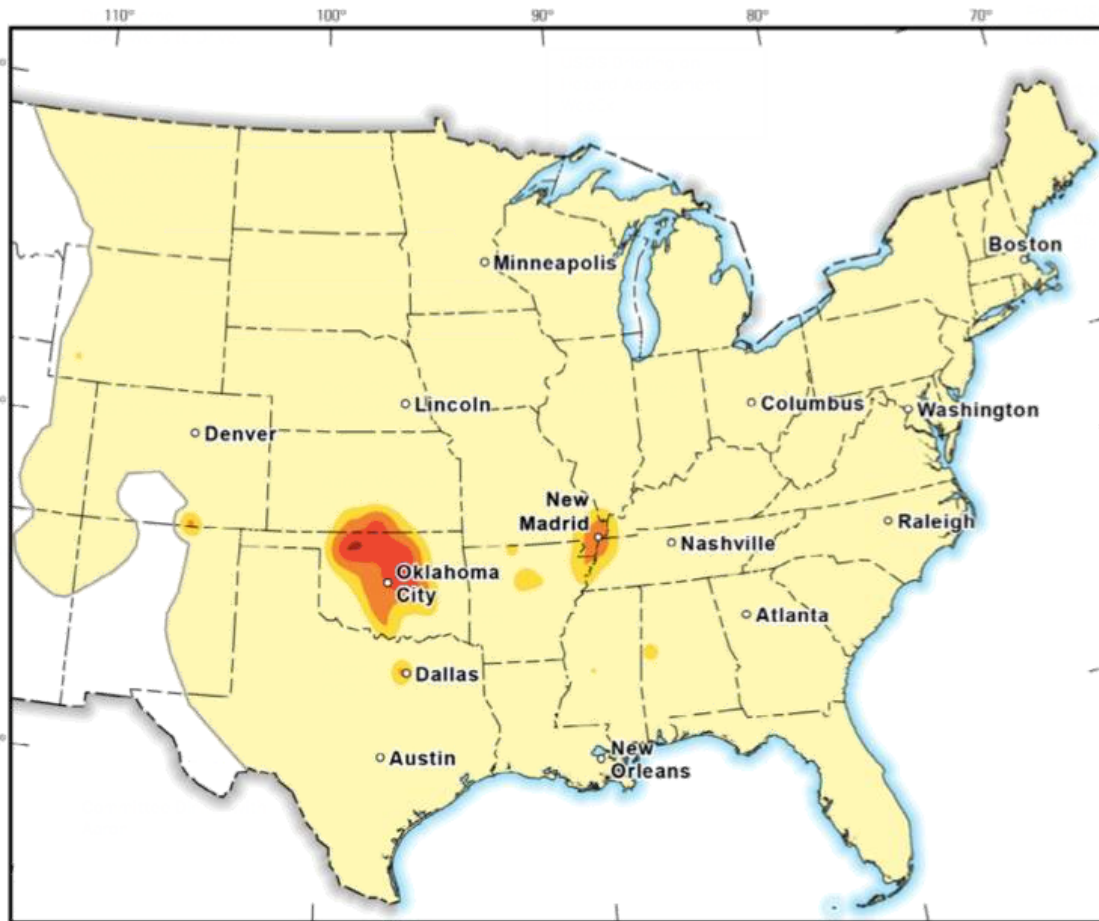


Comparison of Damage Probabilities

Damage defined as forecasted ground motions of MMI VI or greater ($\geq 0.12g$)



Based on results from the 2014
National Seismic Hazard Model

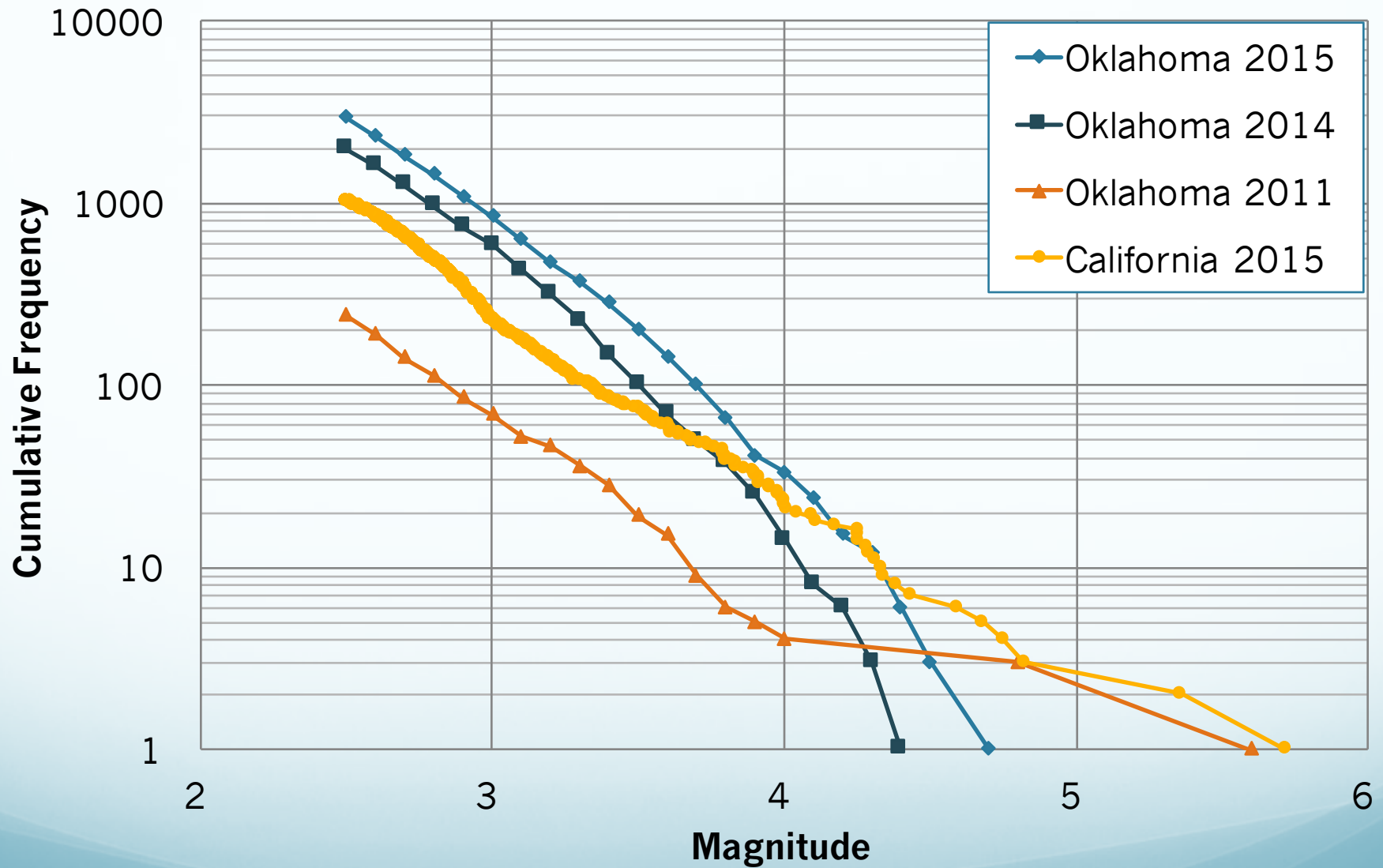


Based on results from this study

Chance of damage from an earthquake in 2016



Earthquake Capital of the U. S.?



Human Activity Can Induce Earthquakes

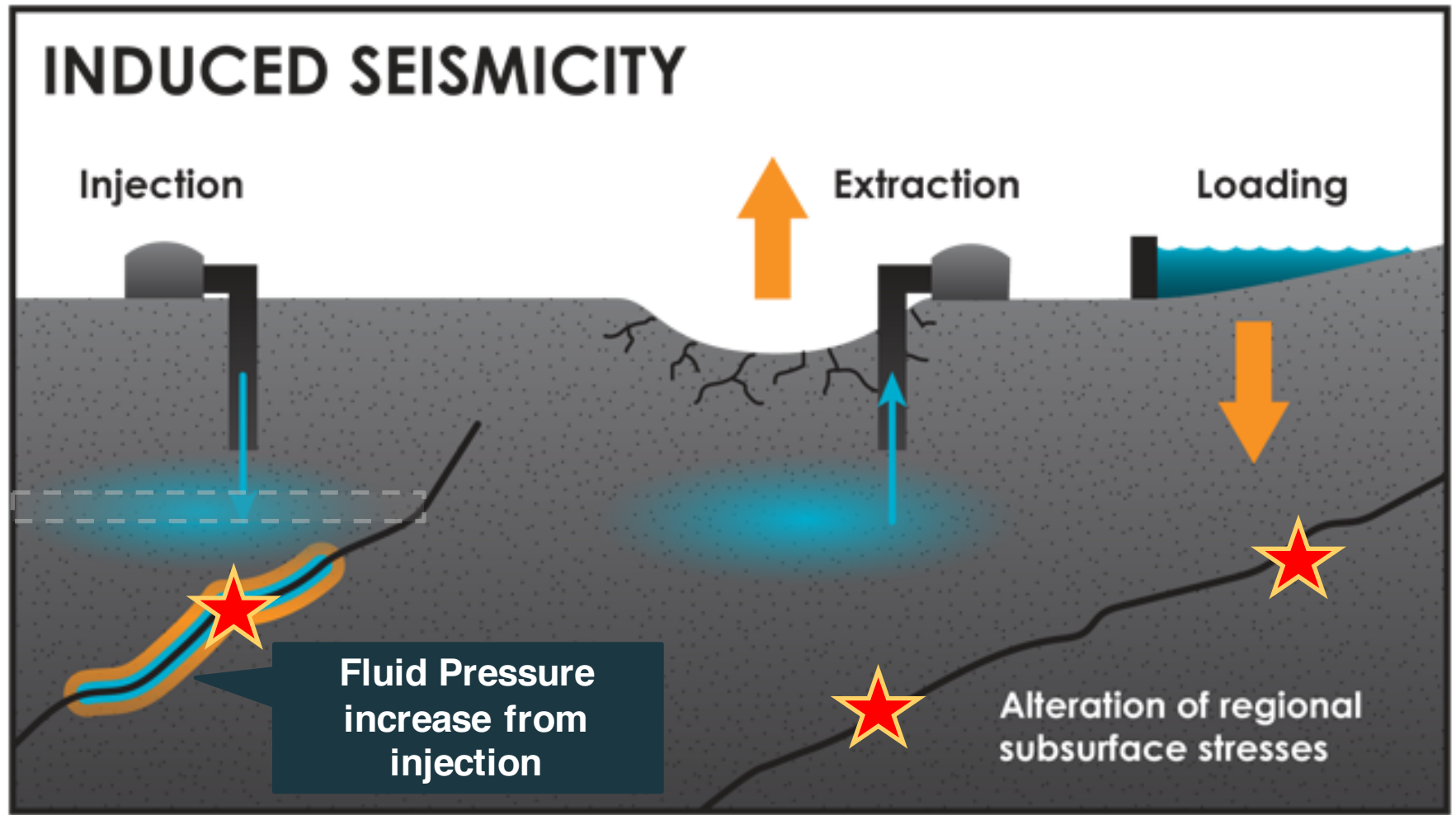
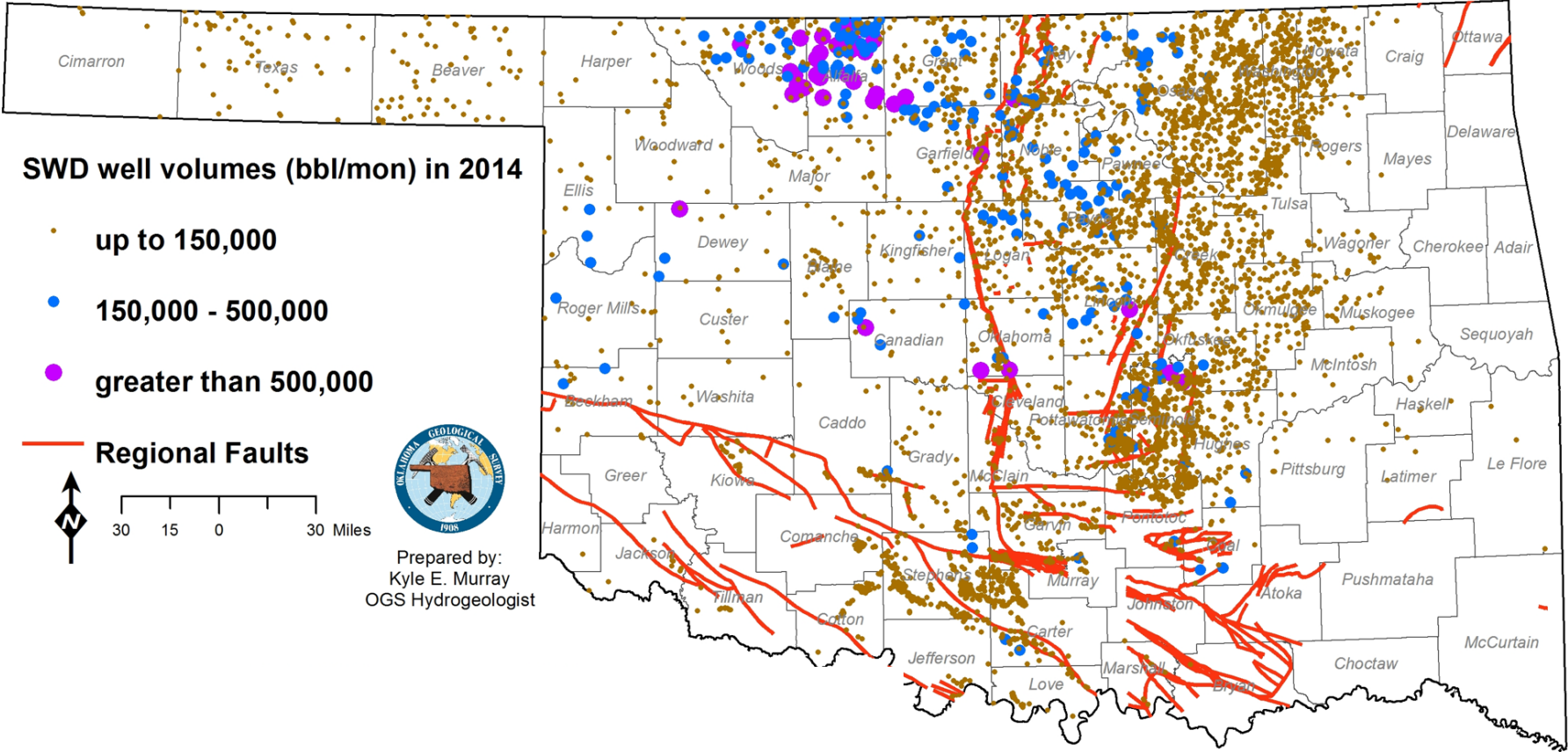


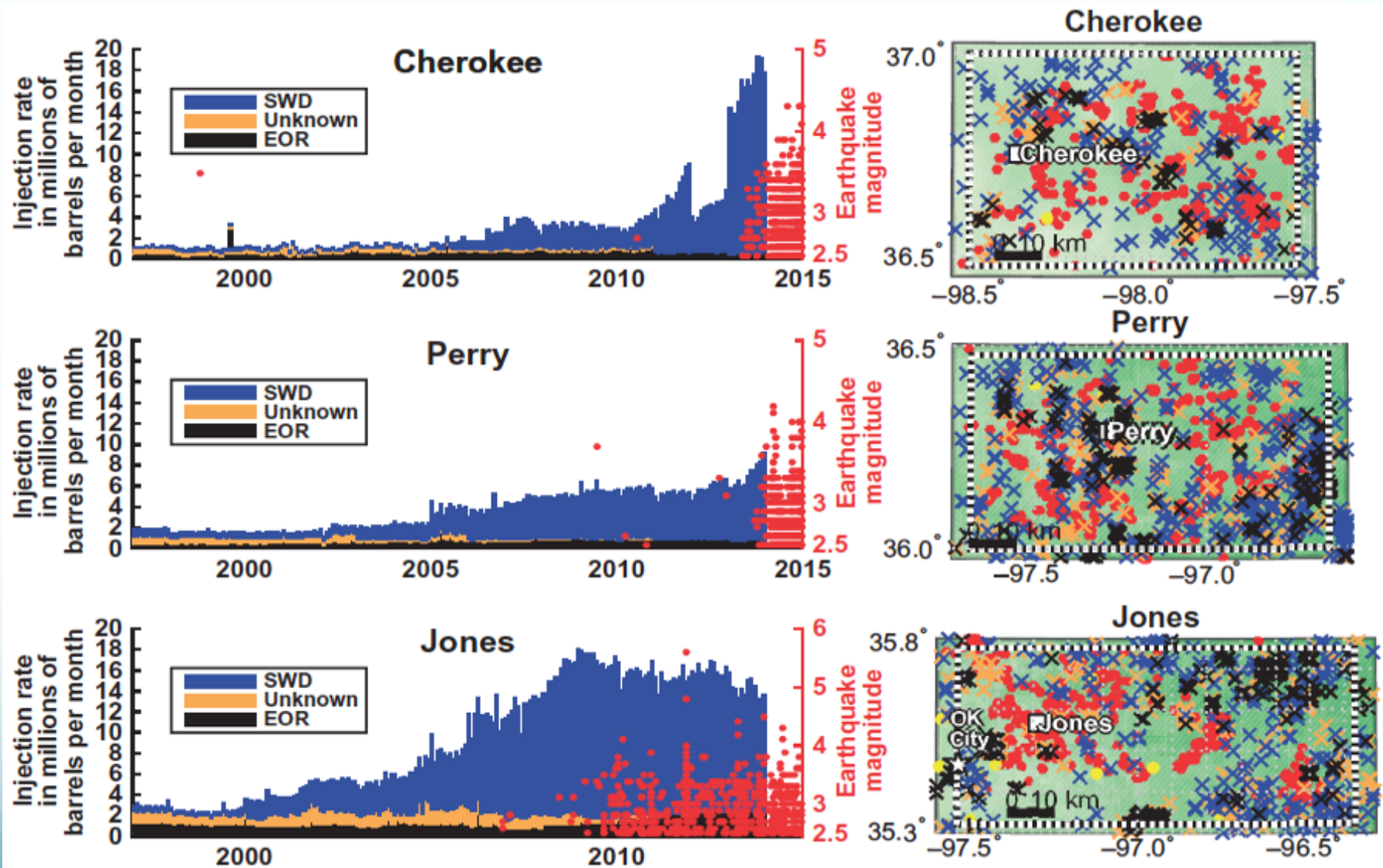
Figure modified from: <http://www.earthmagazine.org/article/ground-shaking-research-how-humans-trigger-earthquakes>

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



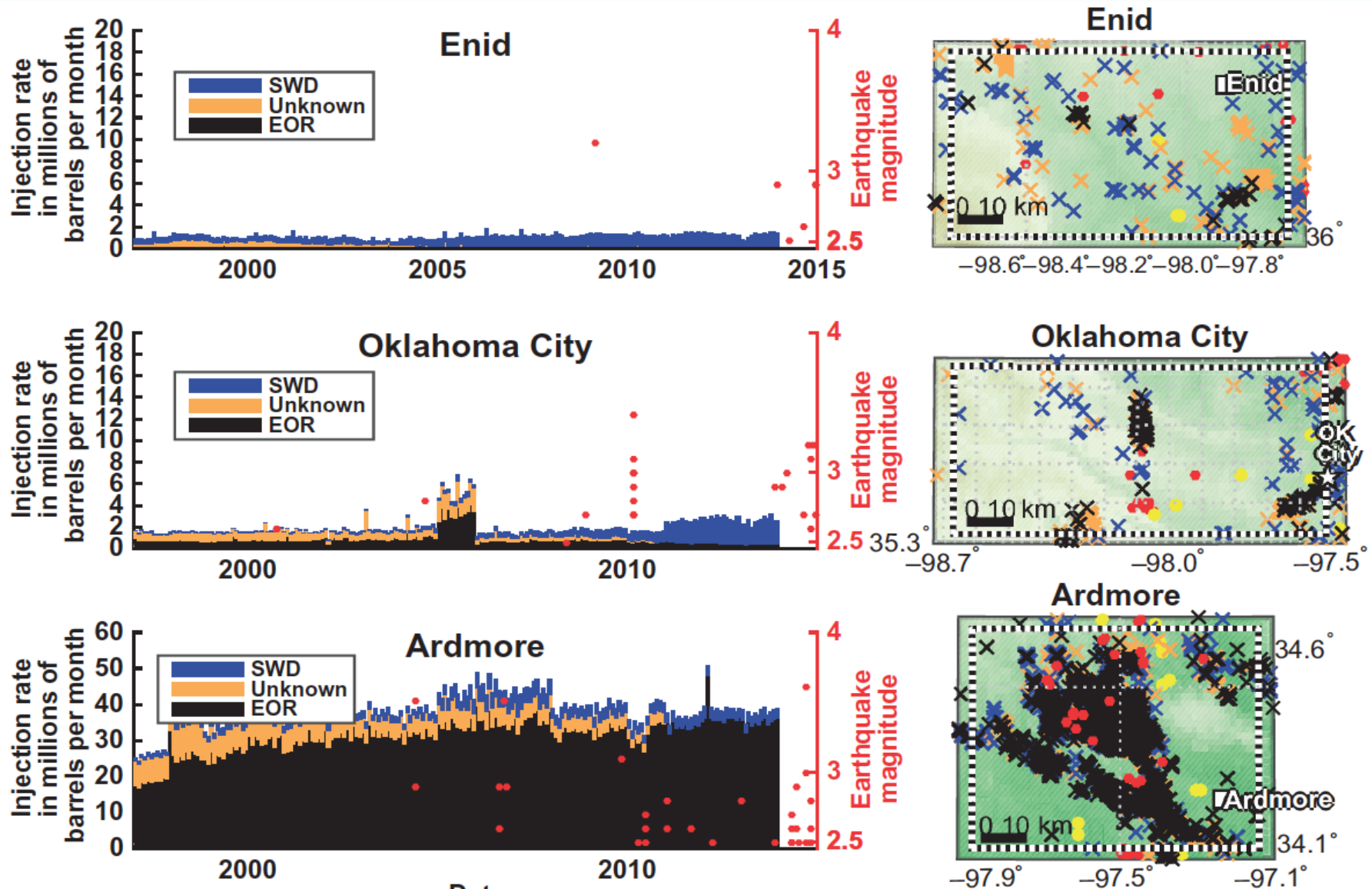
Murray 2014, OGS OF5-2015

Earthquake Activity Occurs Where Deep Injection Increases Substantially



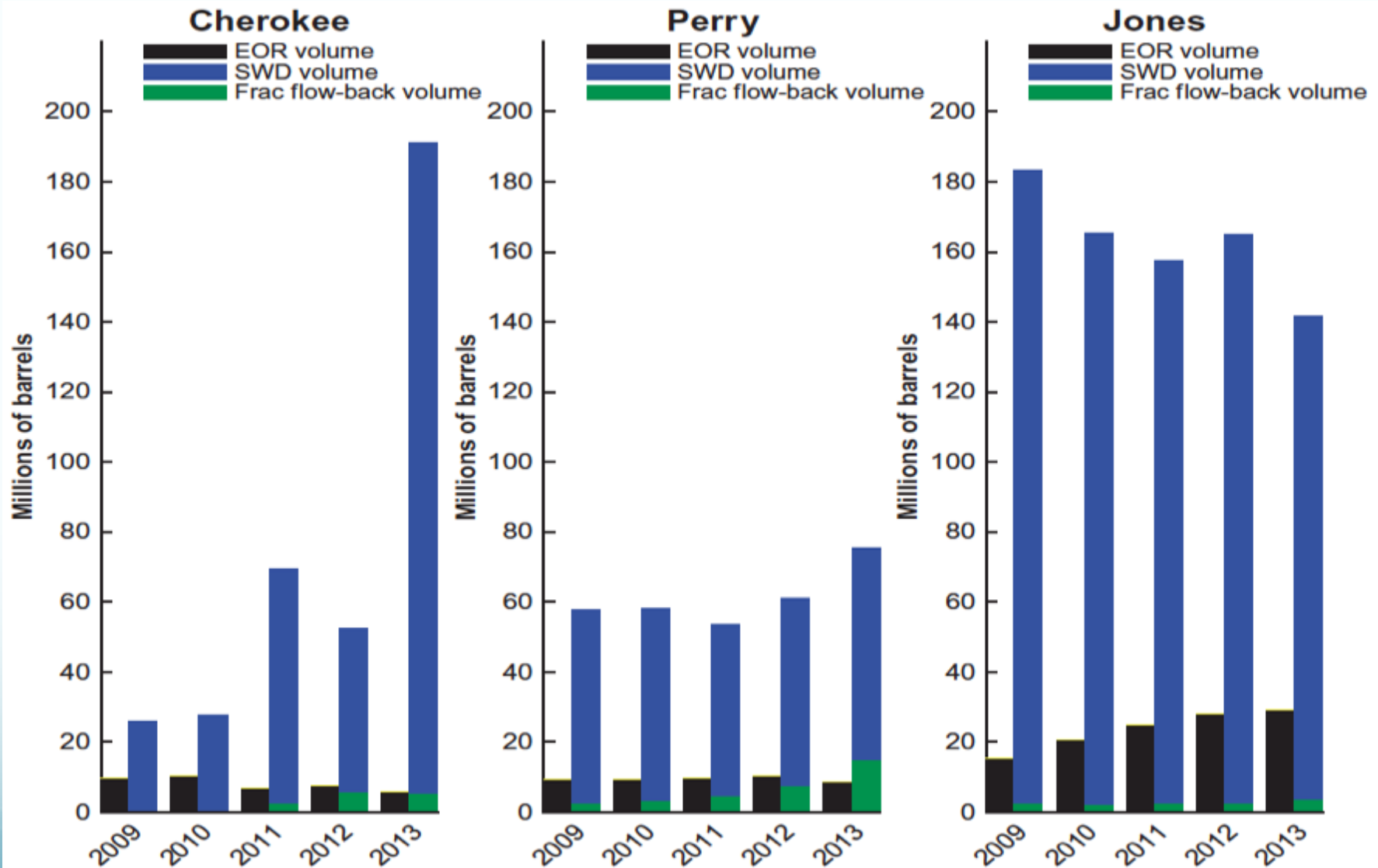
Source: Walsh, F. R., and Zoback, M. D. (2015) Oklahoma's recent earthquakes and saltwater disposal. *Sci. Adv.* 2015; 1:e1500195, 18 June 2015

Areas of Lower SWD Show Lower Earthquake Activity



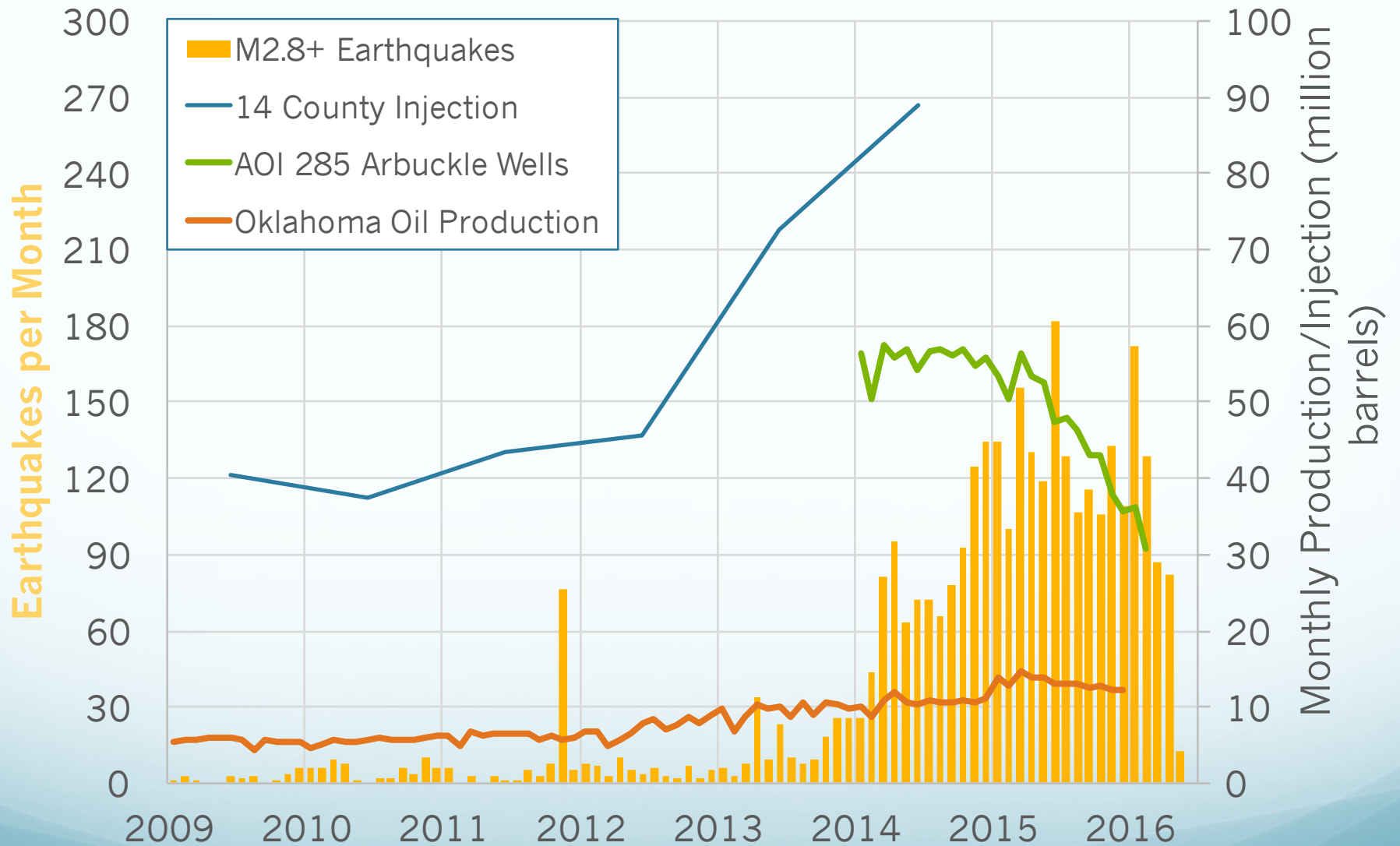
Source: Walsh, F. R., and Zoback, M. D. (2015) Oklahoma's recent earthquakes and saltwater disposal. *Sci. Adv.* 2015; 1:e1500195, 18 June 2015

SWD Includes Very Little Flowback Water from Hydraulic Fracturing

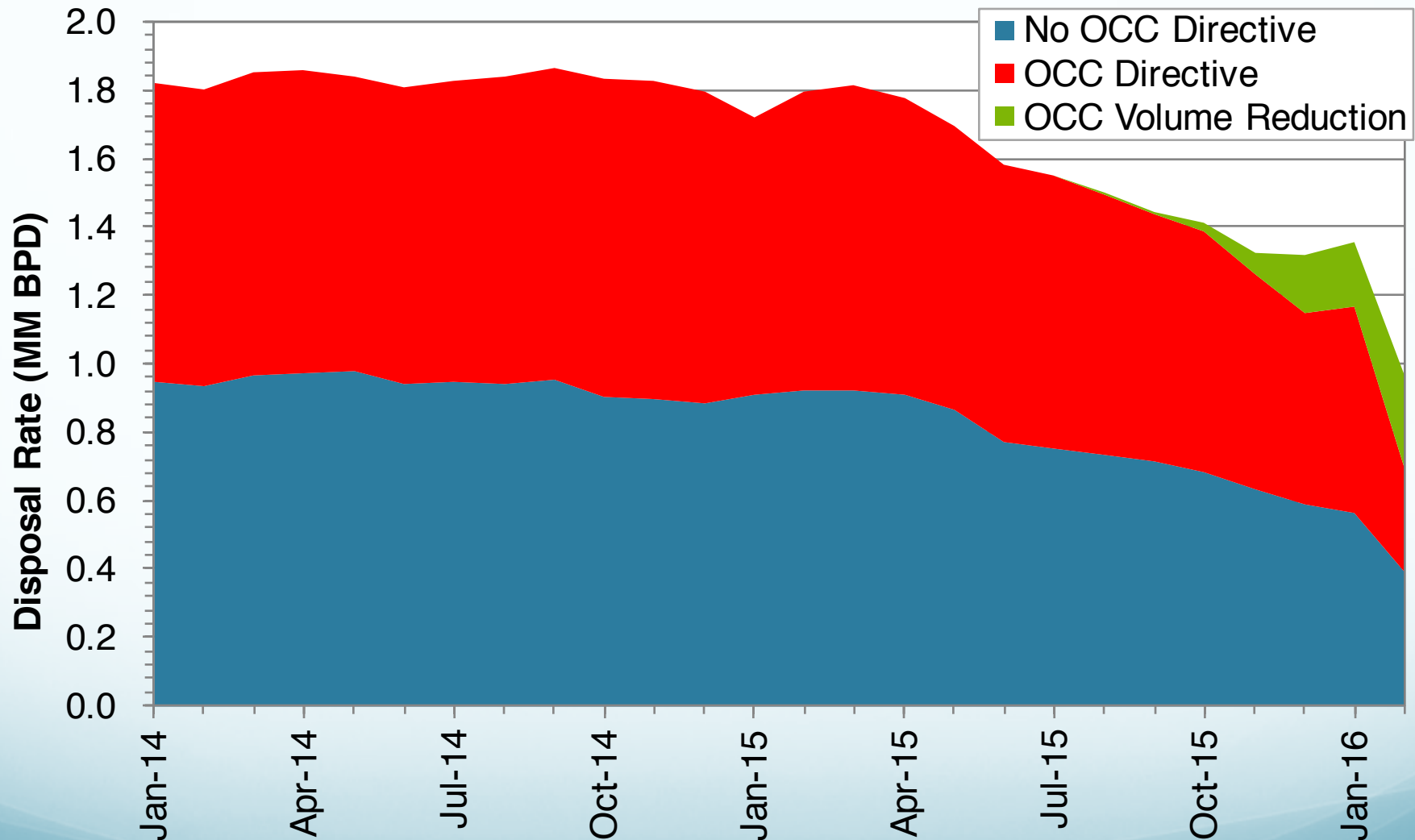


Source: Walsh, F. R., and Zoback, M. D. (2015) Oklahoma's recent earth-quakes and saltwater disposal. *Sci. Adv.* 2015; 1:e1500195, 18 June 2015

Earthquakes, Oil & Water

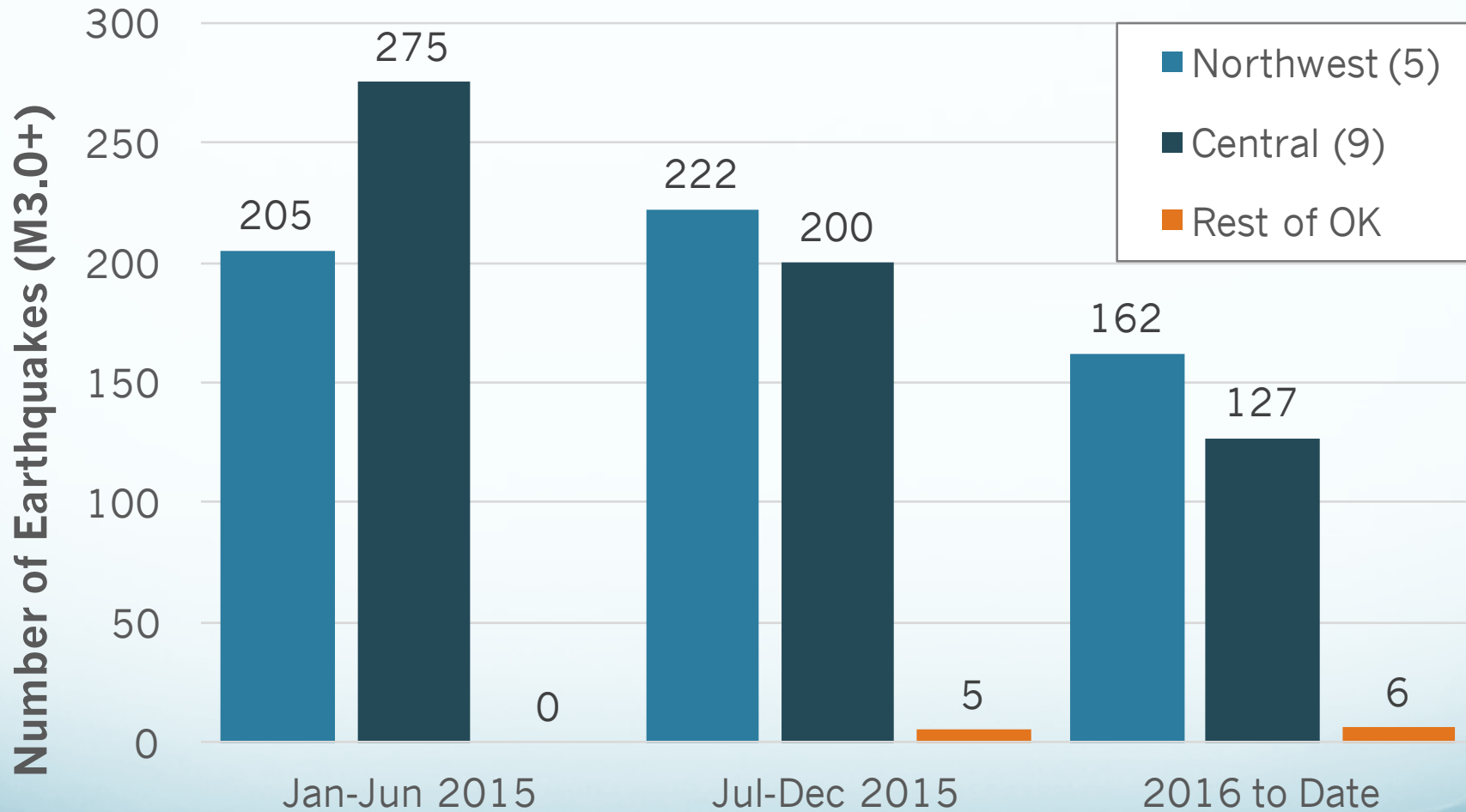


Injection rate decline in 285 Arbuckle SWD wells in seismic Area of Interest

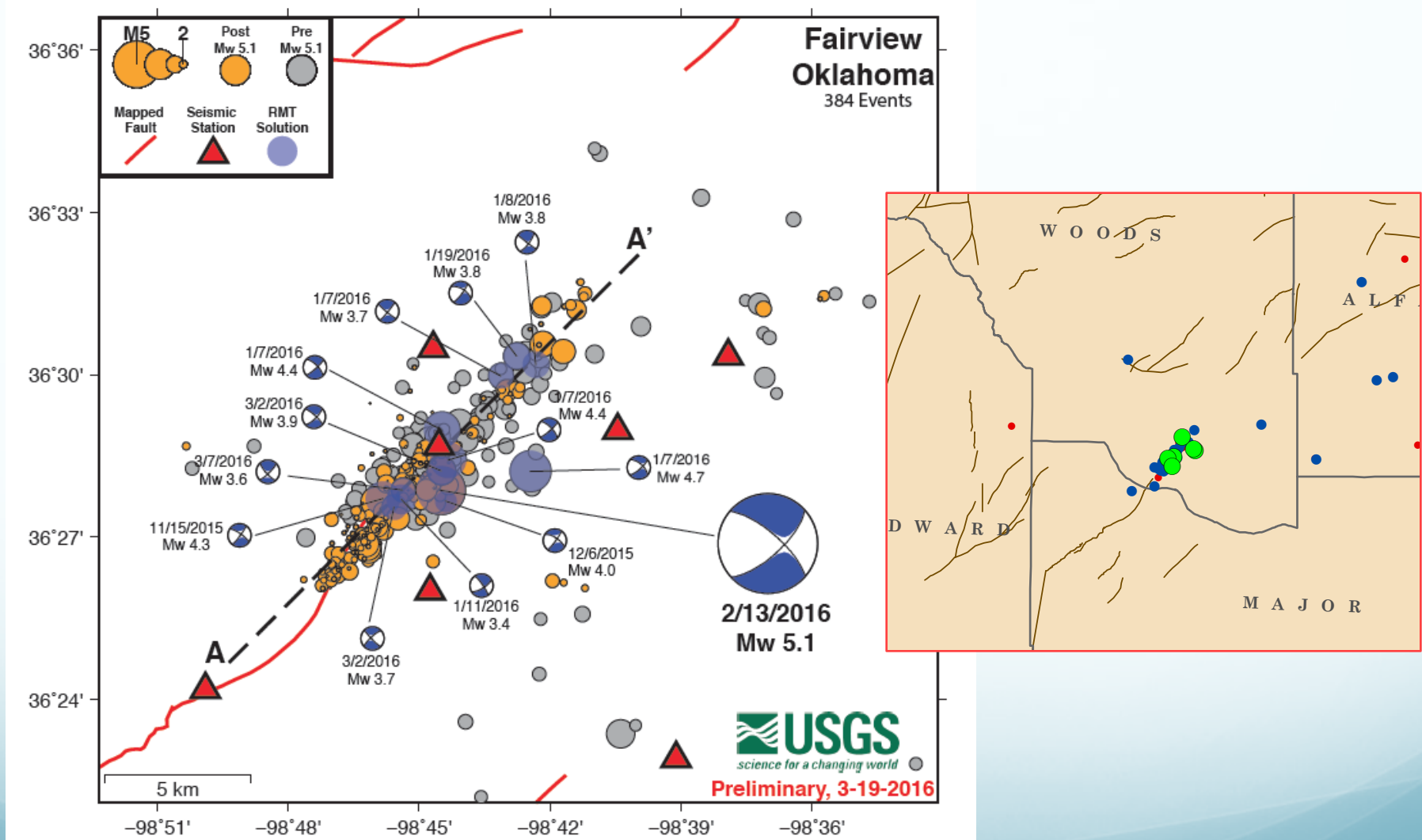


Focus of Seismic Activity Shifting to Northwest

2015-16 Earthquakes by Region

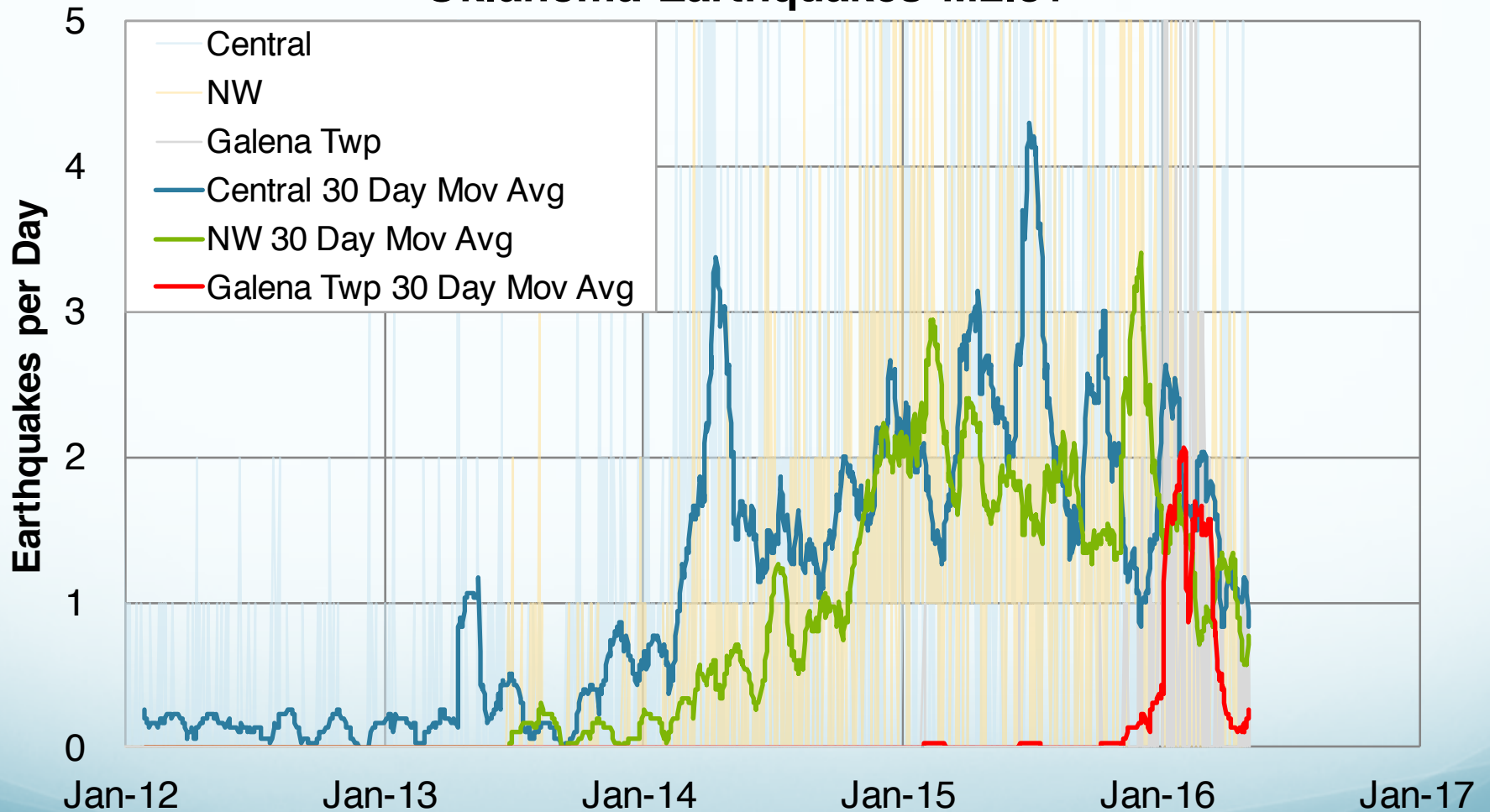


Recent Activity in Fairview/Waynoka Area



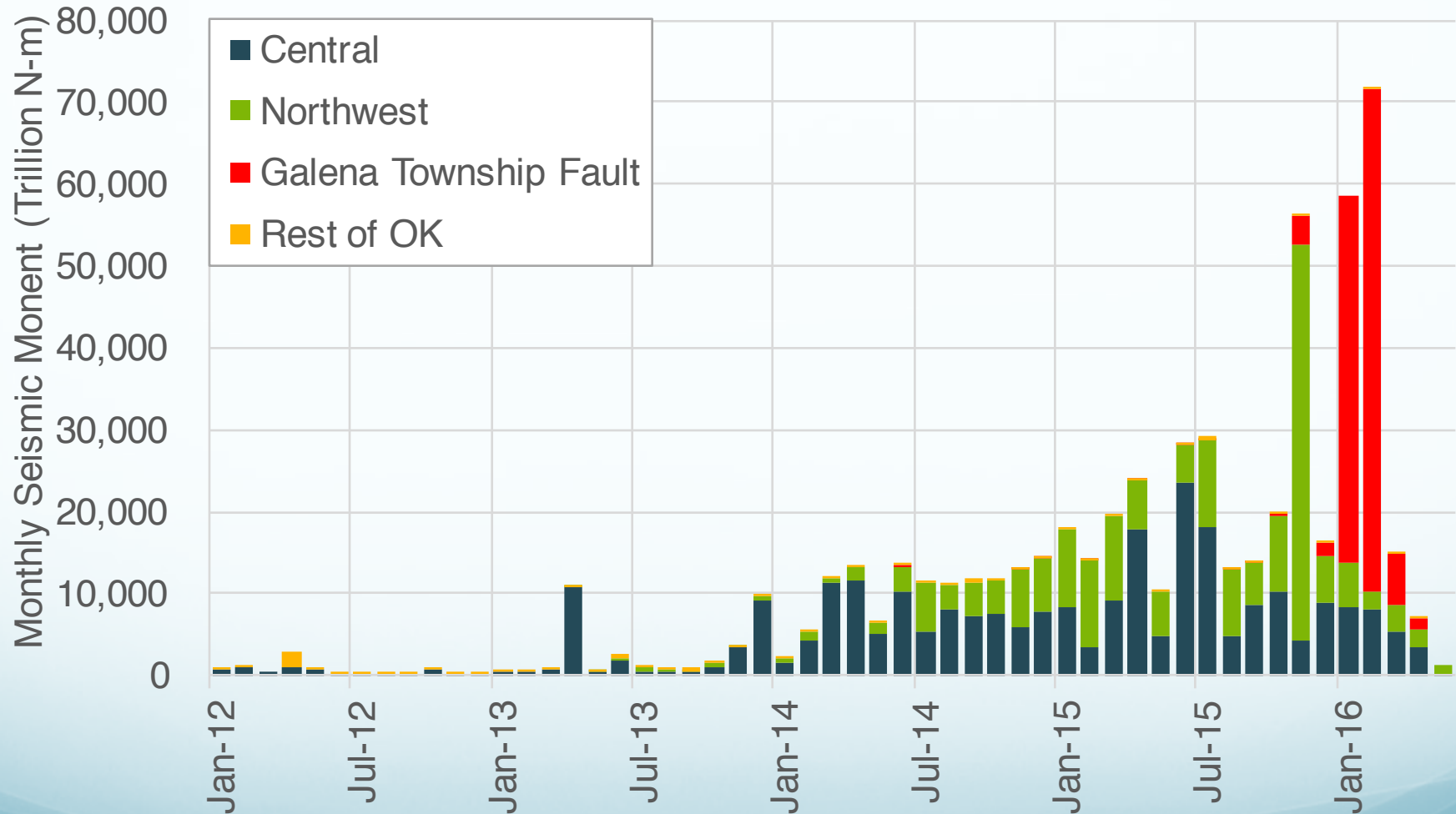
Galena Township Fault Activity is Major Element

Oklahoma Earthquakes M2.8+



Seismic Moment (Energy Release)

Seismic Moment by Region



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

Modified Mercalli Intensity Scale

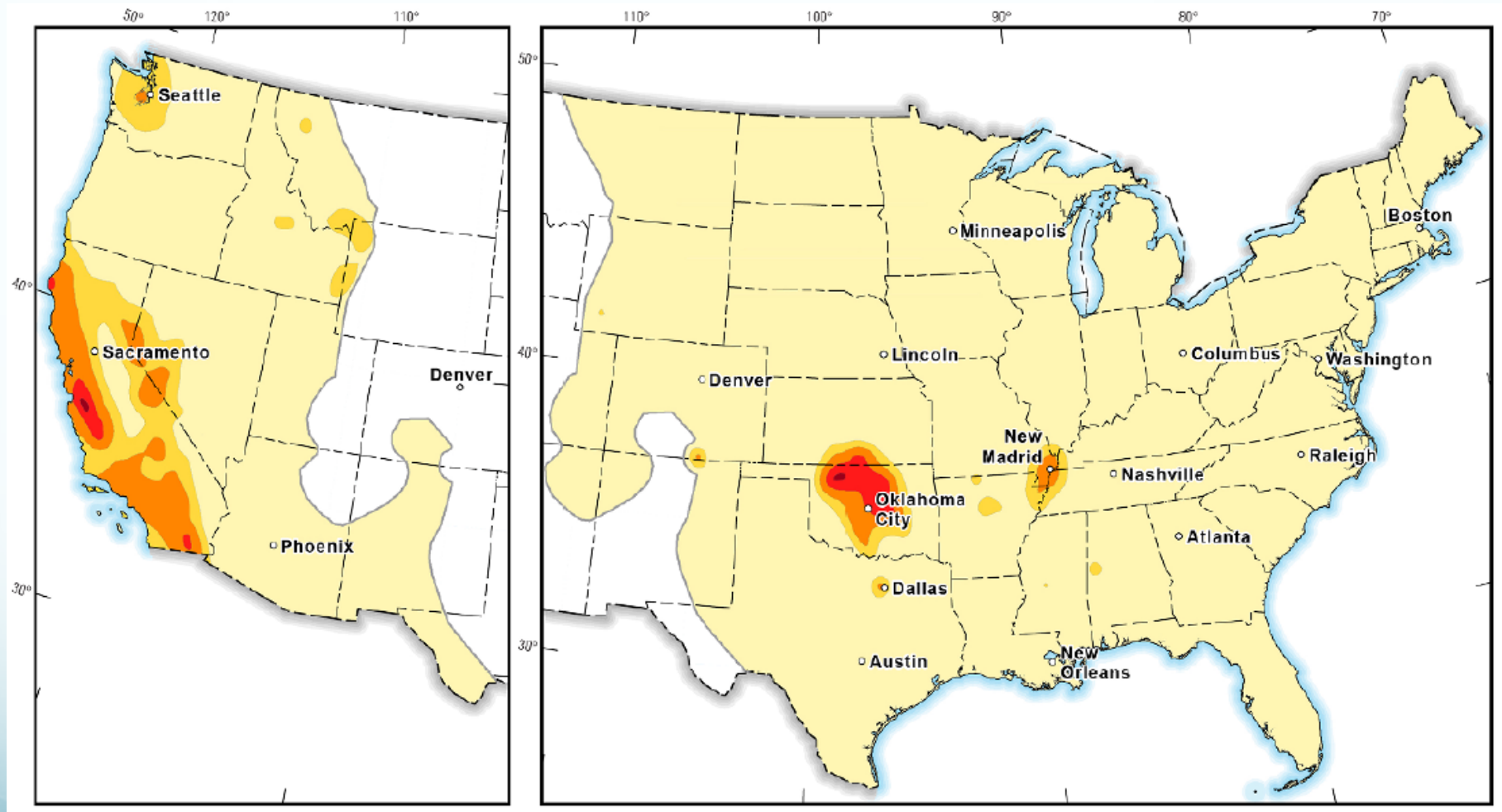
Intensity	Shaking	Description/Damage
I	Not felt	Not felt except by a very few under especially favorable conditions.
II	Weak	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Weak	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV	Light	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Moderate	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Strong	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	Very strong	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII	Severe	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	Violent	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Extreme	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

Intensity vs. Acceleration

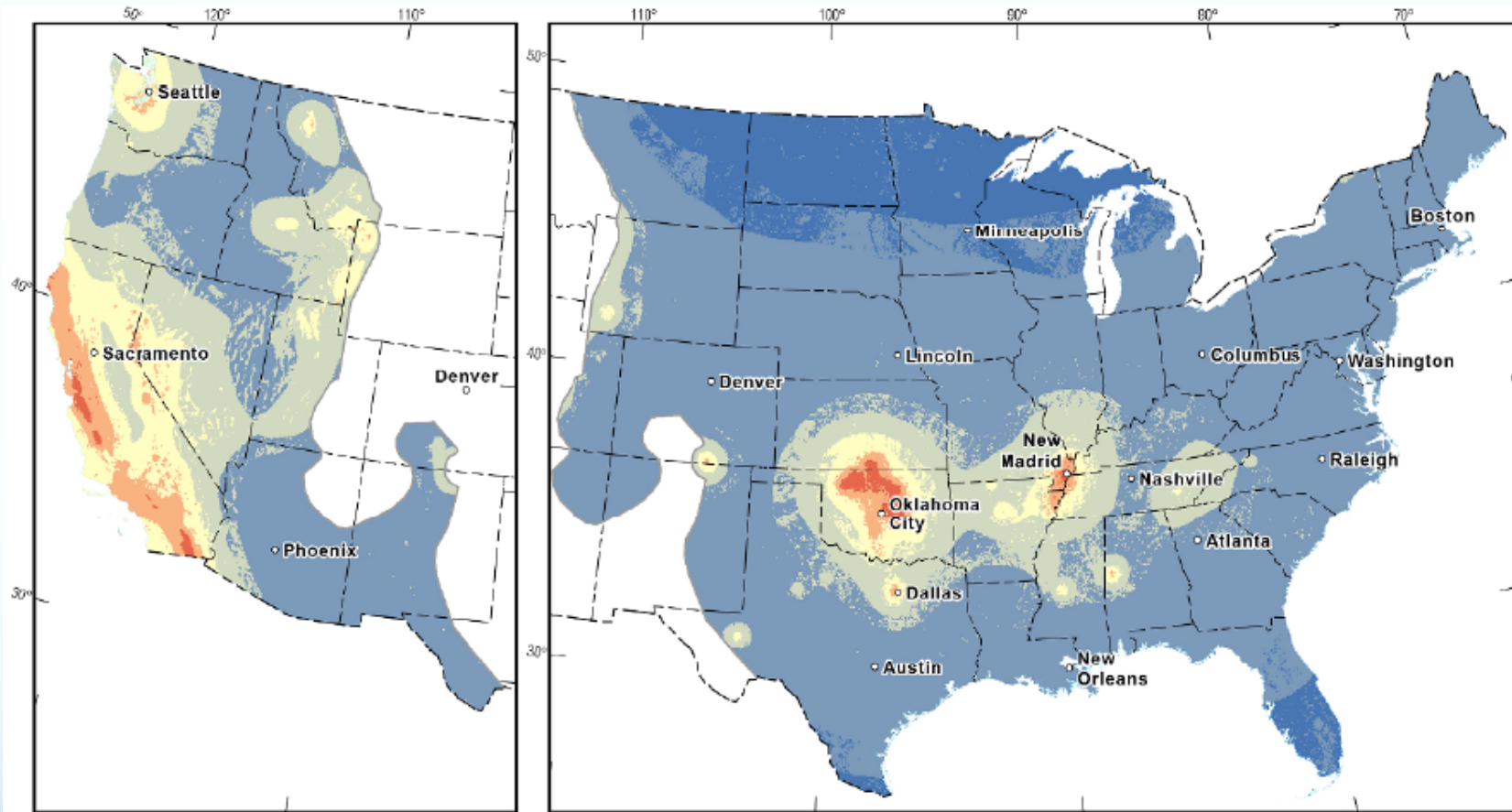
Instrumental Intensity	Acceleration (g)	Velocity (cm/s)	Perceived Shaking	Potential Damage
I	< 0.0017	< 0.1	Not felt	None
II-III	0.0017 - 0.014	0.1 - 1.1	Weak	None
IV	0.014 - 0.039	1.1 - 3.4	Light	None
V	0.039 - 0.092	3.4 - 8.1	Moderate	Very light
VI	0.092 - 0.18	8.1 - 16	Strong	Light
VII	0.18 - 0.34	16 - 31	Very strong	Moderate
VIII	0.34 - 0.65	31 - 60	Severe	Moderate to heavy
IX	0.65 - 1.24	60 - 116	Violent	Heavy
X+	> 1.24	> 116	Extreme	Very heavy

Source: <http://earthquake.usgs.gov/earthquakes/shakemap/background.php>

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+



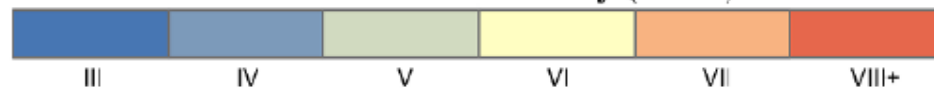
USGS 1% Hazard Map



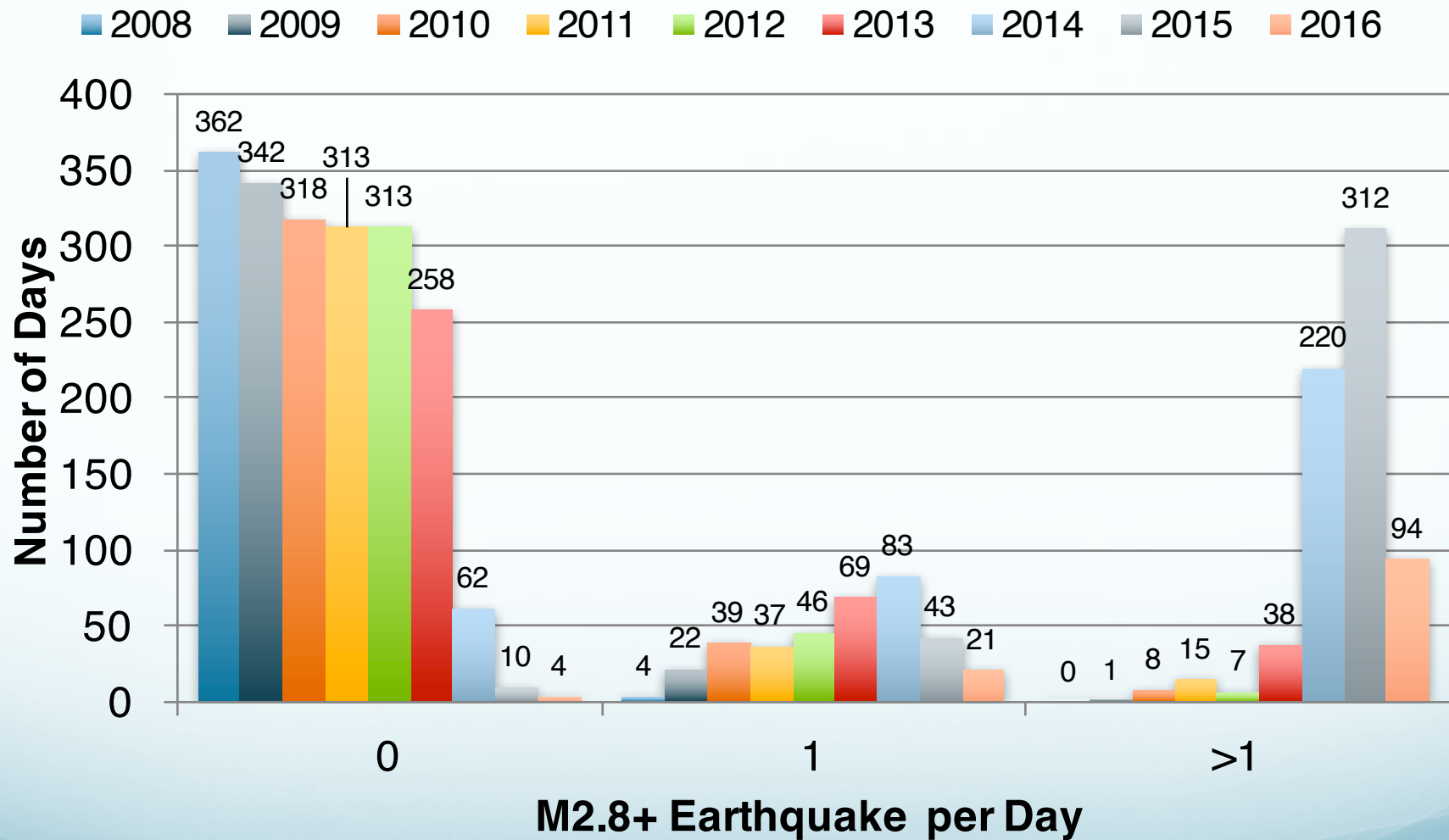
Based on results from the 2014
National Seismic Hazard Model

Based on results from this study

Modified Mercalli Intensity (MMI)



A Change in the Seismic Weather



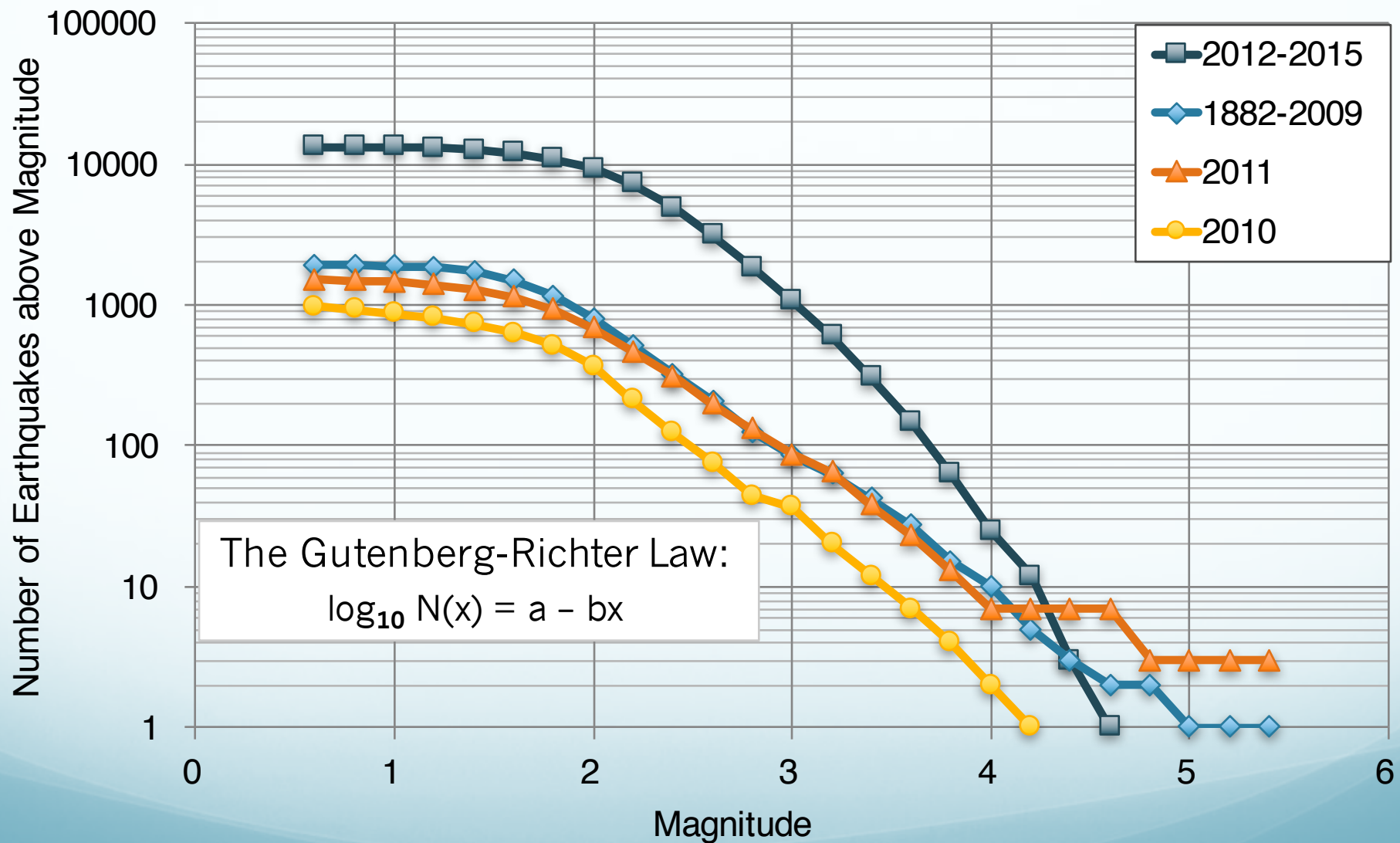
Earthquake Forecasting

- 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

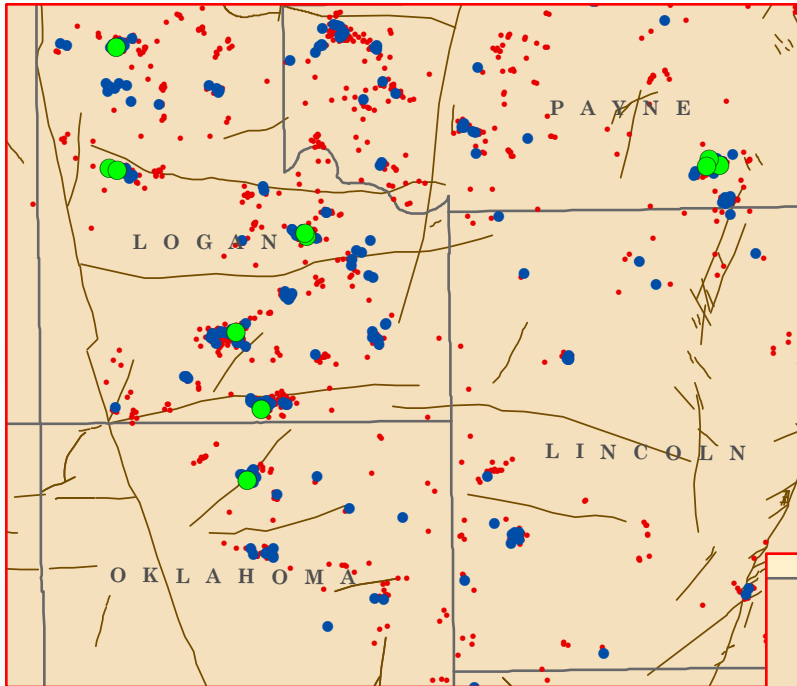
	Magnitude (M_L)					
Duration	3.0	4.0	4.5	5.0	5.5	6.0
4 Year	1.00	1.00	1.00	0.81	0.28	0.07
1 Year	1.00	1.00	1.00	0.71	0.24	0.06
6 months	1.00	1.00	0.98	0.63	0.21	0.06
30 days	1.00	0.87	0.39	0.11	0.02	0.007
10 days	1.00	0.74	0.31	0.09	0.03	0.007

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

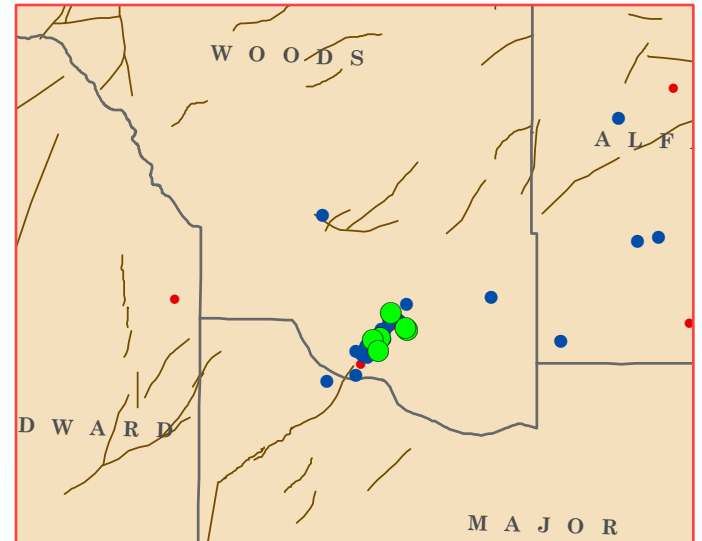
Gutenberg-Richter Relationships



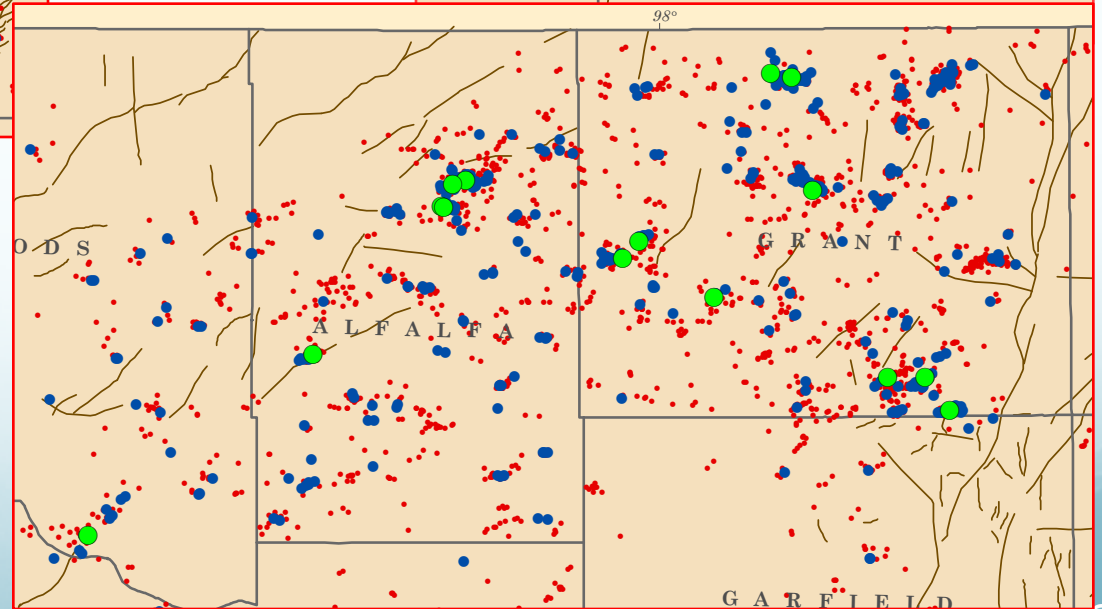
Recent Earthquake Activity



Fairview Area



Edmond and Cushing Areas

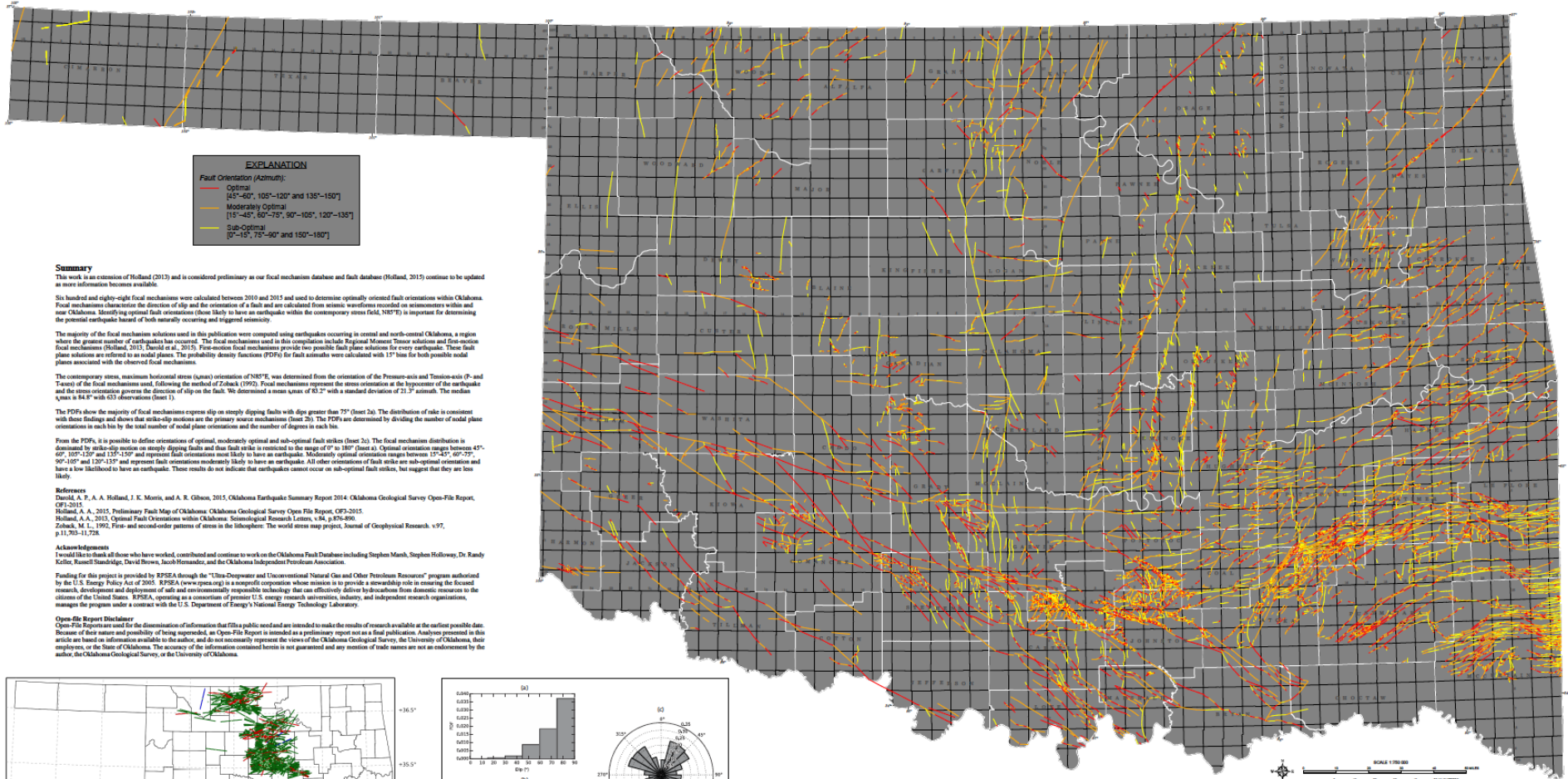


Grant, Alfalfa, Woods Counties

Optimally Oriented Faults in Oklahoma

OKLAHOMA GEOLOGICAL SURVEY
Dr. Zeev Berk, Director

OPEN-FILE REPORT OF 4-2015
Preliminary Oklahoma Optimal Fault Orientations



EXPLANATION

Fault Orientation (Azimuth):

- Optimal [45°-60°, 105°-120° and 135°-150°]
- Moderately Optimal [15°-45°, 80°-75°, 90°-105°, 120°-135°]
- Sub-Optimal [0°-15°, 75°-90° and 150°-180°]

Summary

This work is an extension of Holland (2013) and is considered preliminary as our focal mechanism database and fault database (Holland, 2015) 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, N₀T₀) 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., 2013). 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 N80°E, 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 83.2 with a standard deviation of 21.3° azimuth. The median σ_{max} is 84.8° with 633 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 strike 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 thus fault strike is restricted to the range of 0° to 180° (Inset 4). 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 orientations 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, OF-1-2015.
- Holland, A. A., 2015, Preliminary Fault Map of Oklahoma: Oklahoma Geological Survey Open File Report, OF-3-2015.
- 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.

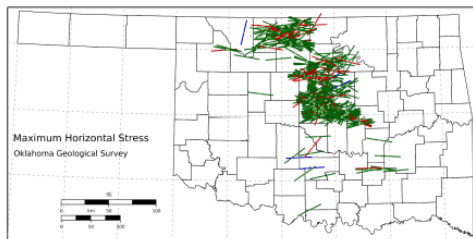
Acknowledgments

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 Keller, Russell Sandridge, David Brown, Jacob Rosenzweig, and the Oklahoma Independent Petroleum Association.

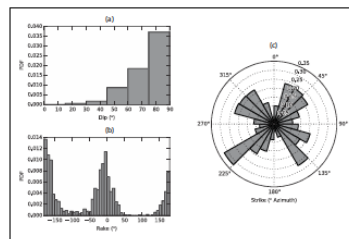
Funding for this project is provided by BPSEA through the "Ultra-Deepwater and Unconventional Natural Gas and Other Petroleum Resources" program authorized by the U.S. Energy Policy Act of 2005. BPSEA (www.bpsea.org) is a nonprofit corporation whose mission is to provide a stewardship role in ensuring 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. BPSEA, 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.

Open-File Report Disclaimer

Open-File Reports are used for the dissemination of information that the public needs and are intended to make the results of research available at the earliest possible date. Because of their nature and possibility of being superseded, an Open-File Report is intended as a preliminary report and is not a final publication. Analyses presented in this article are based on information available to the author, and do not necessarily represent the views of the Oklahoma Geological Survey, the University of Oklahoma, their employees, or the State of Oklahoma. The accuracy of the information contained herein is not guaranteed and any mention of trade names are not an endorsement by the author, the Oklahoma Geological Survey, or the University of Oklahoma.



Inset 1: Maximum horizontal stress orientation of P- and T-axis of 633 focal mechanisms, following the convention of Zoback (1992); red, normal faulting; green, strike-slip faulting; blue, thrust faulting.

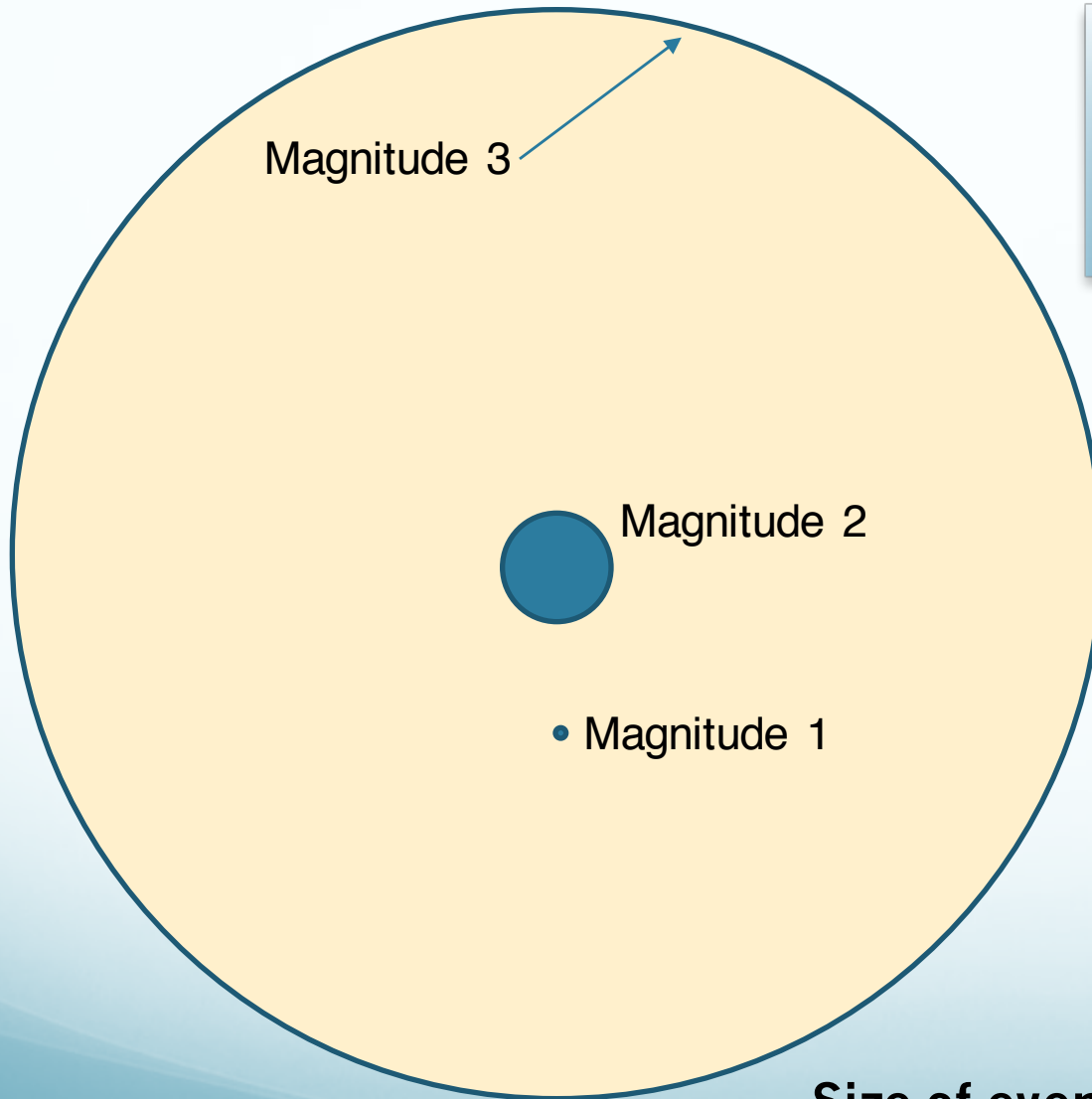


Inset 2: Probability density functions for fault orientations for 688 focal mechanisms within Oklahoma with 15° bin intervals and a total of 1,376 nodal planes; (a) PDF of fault dip, (b) PDF of fault strike, (c) PDF of fault strike.

PRELIMINARY OKLAHOMA OPTIMAL FAULT ORIENTATIONS

By
Amberlee P. Darold and Austin A. Holland
2015

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**

Improved Earthquake Locations

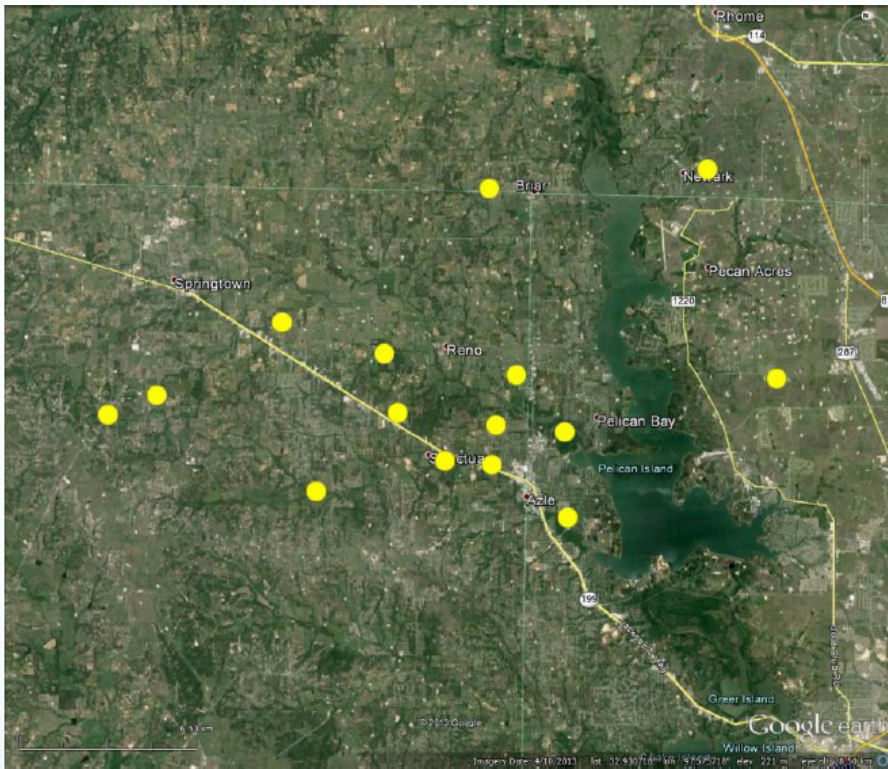


Figure 1. Earthquake epicenters determined by USGS-NEIC, November 1-26, 2013.

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

