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

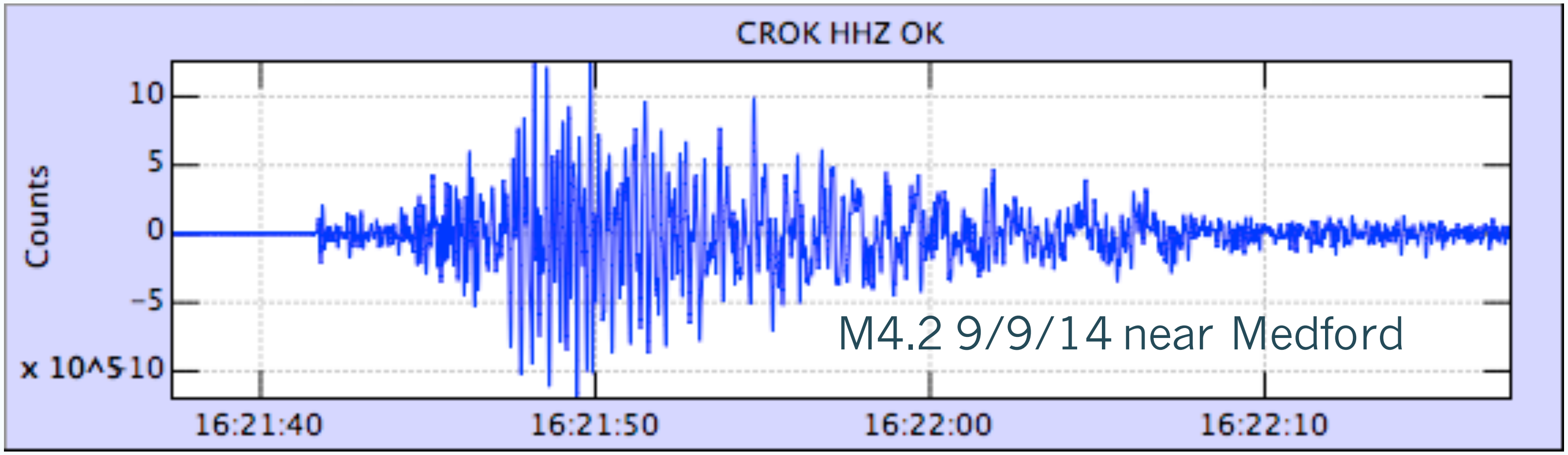
The Oklahoma Geological Survey is a state agency for research and public service located on the Norman Campus of the University of Oklahoma and affiliated with the OU College of Earth and Energy. The Survey is chartered in the Oklahoma Constitution and is charged with investigating the state's land,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

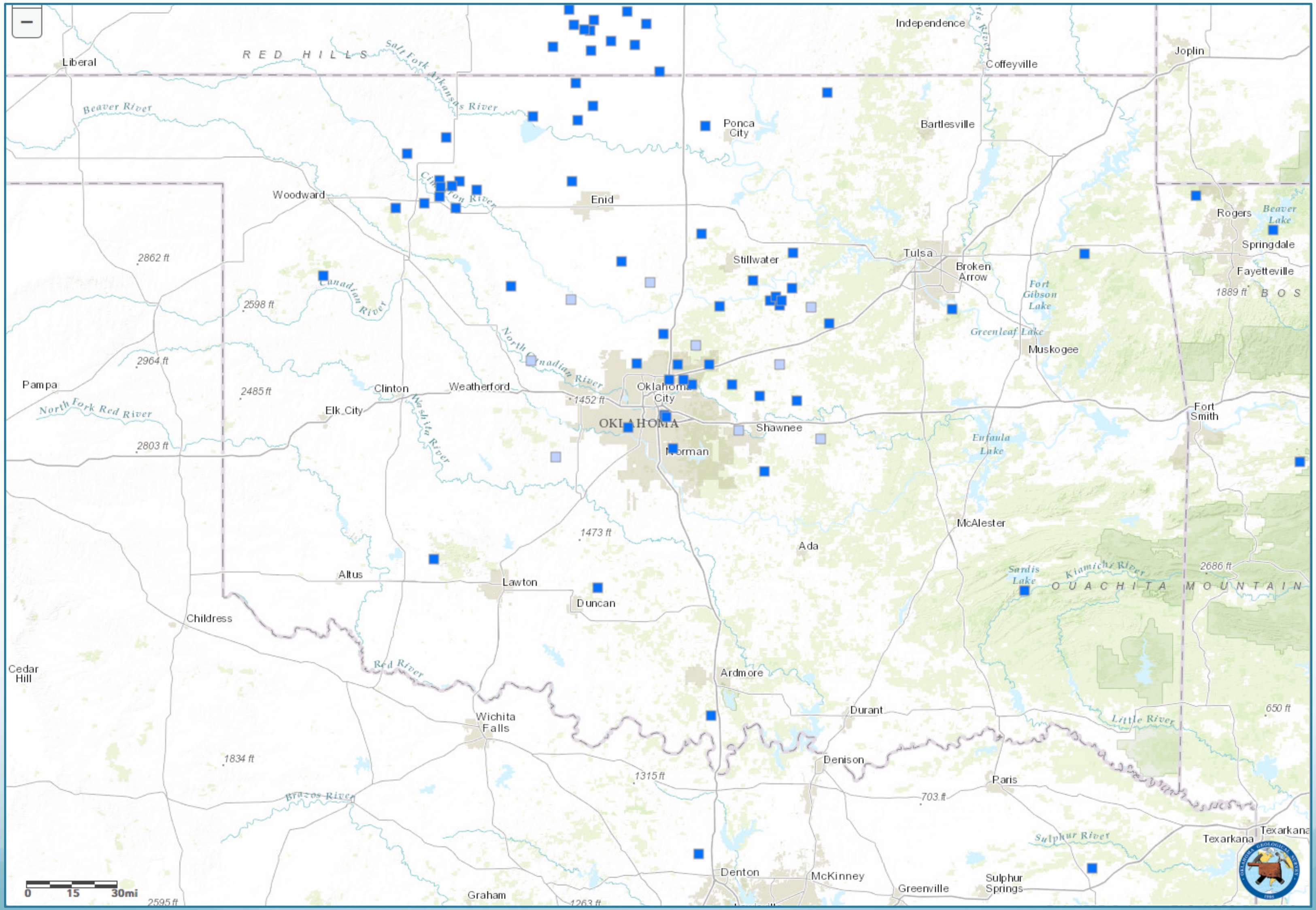
- **OGS Staff Engaged on the Seismicity Issue**
  - **Seismology**: Jefferson Chang, Fernando Ferrer, Noorulann Ghouse, Junjun Hu, Andrew Thiel, Isaac Woelfel
  - **Hydrogeology, Geology, Geophysics**: Kyle Murray, Richard Andrews, Kevin Crain, Steve Holloway, Jordan Williams
  - **Publications & Outreach**: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

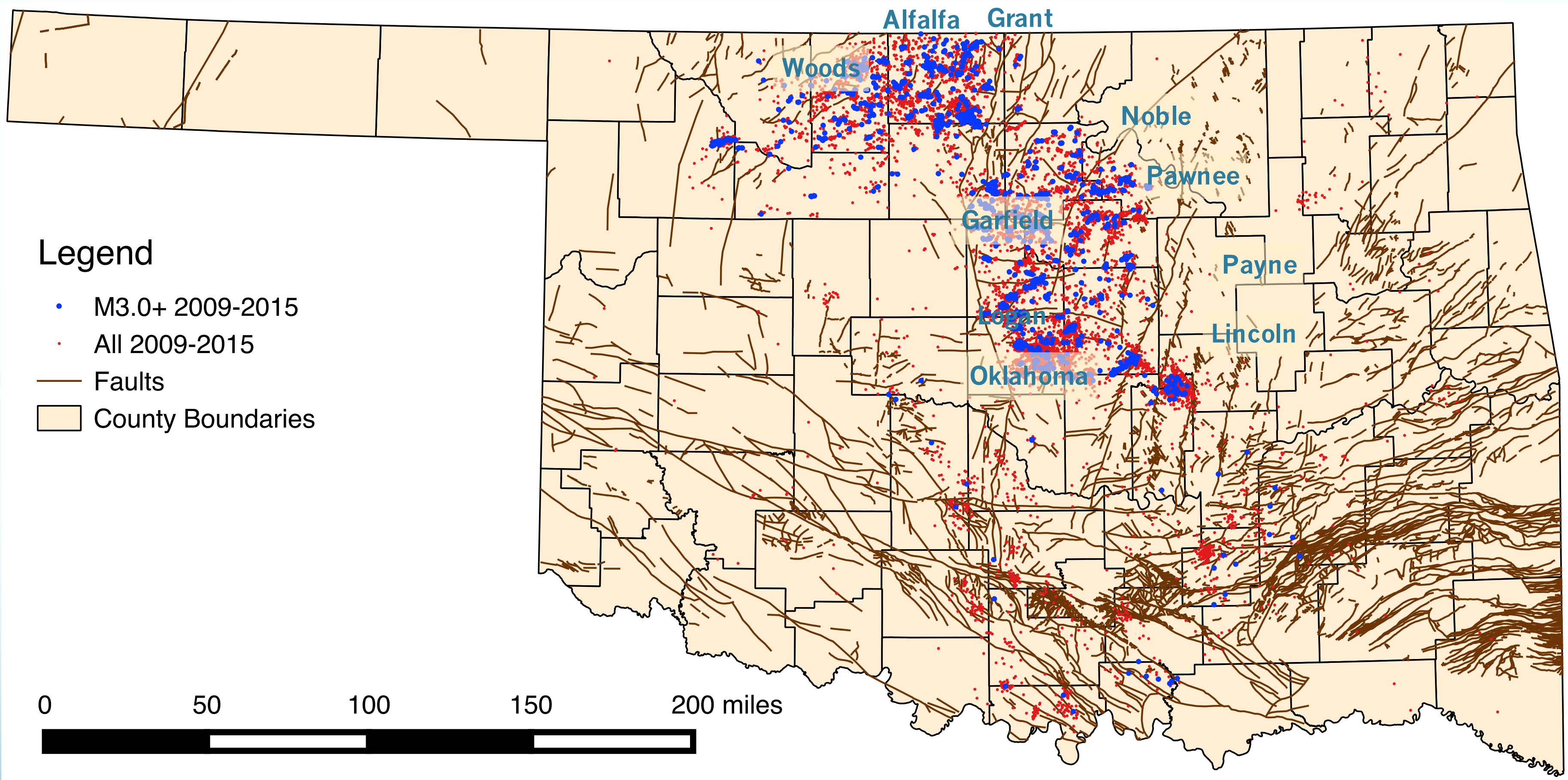
OGS Uses about 50 Stations to Locate Oklahoma Earthquakes



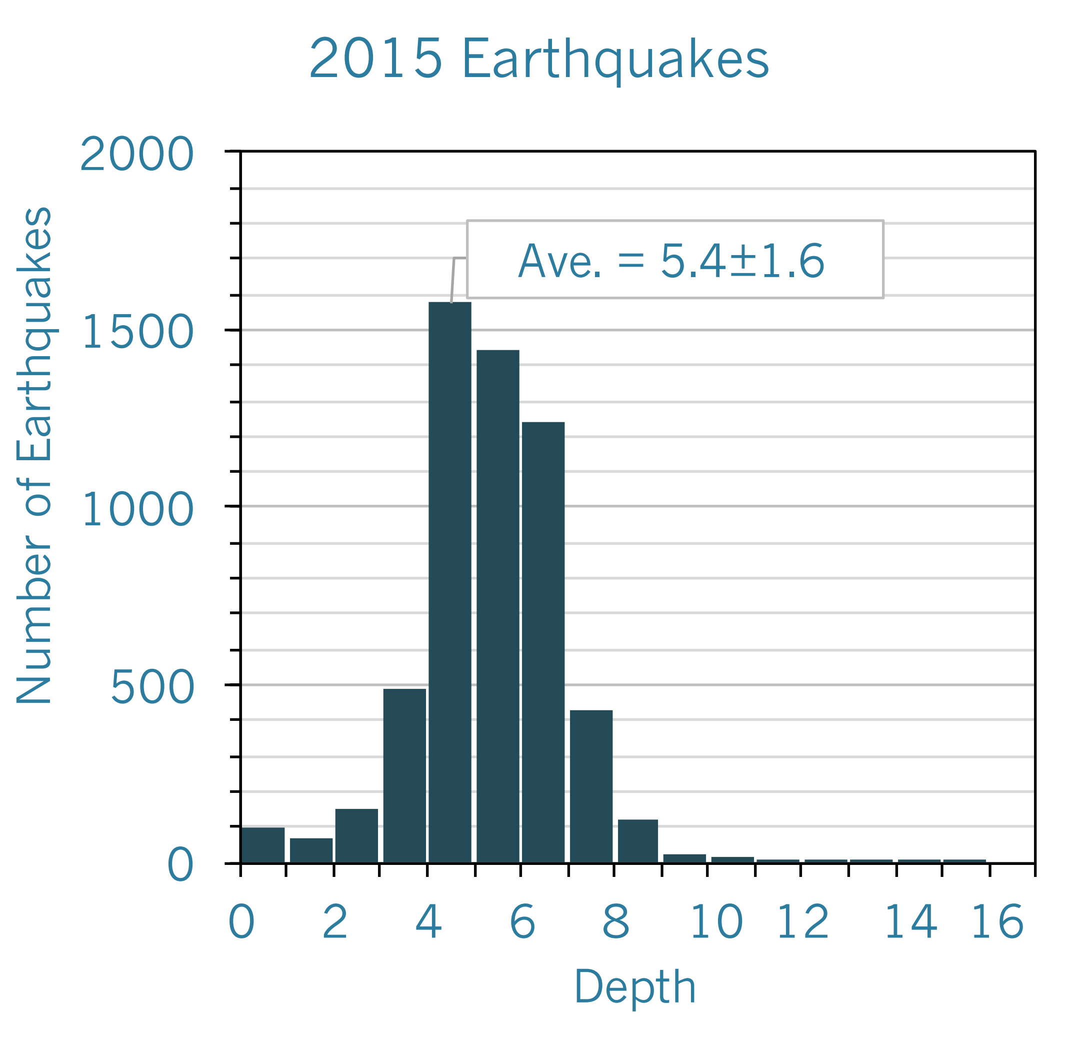
Measuring an Earthquake

- 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



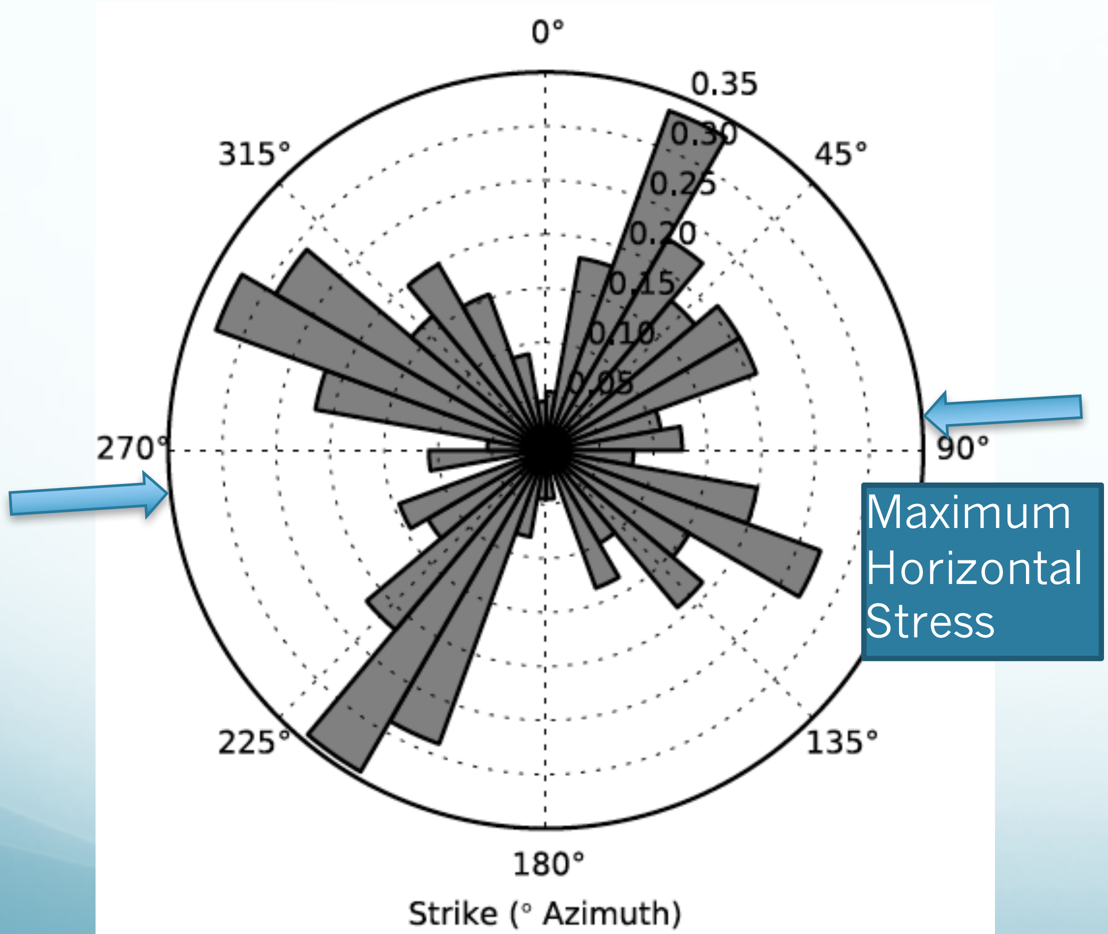
Earthquakes Occur in the Basement below Oil and Gas Activity



- 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

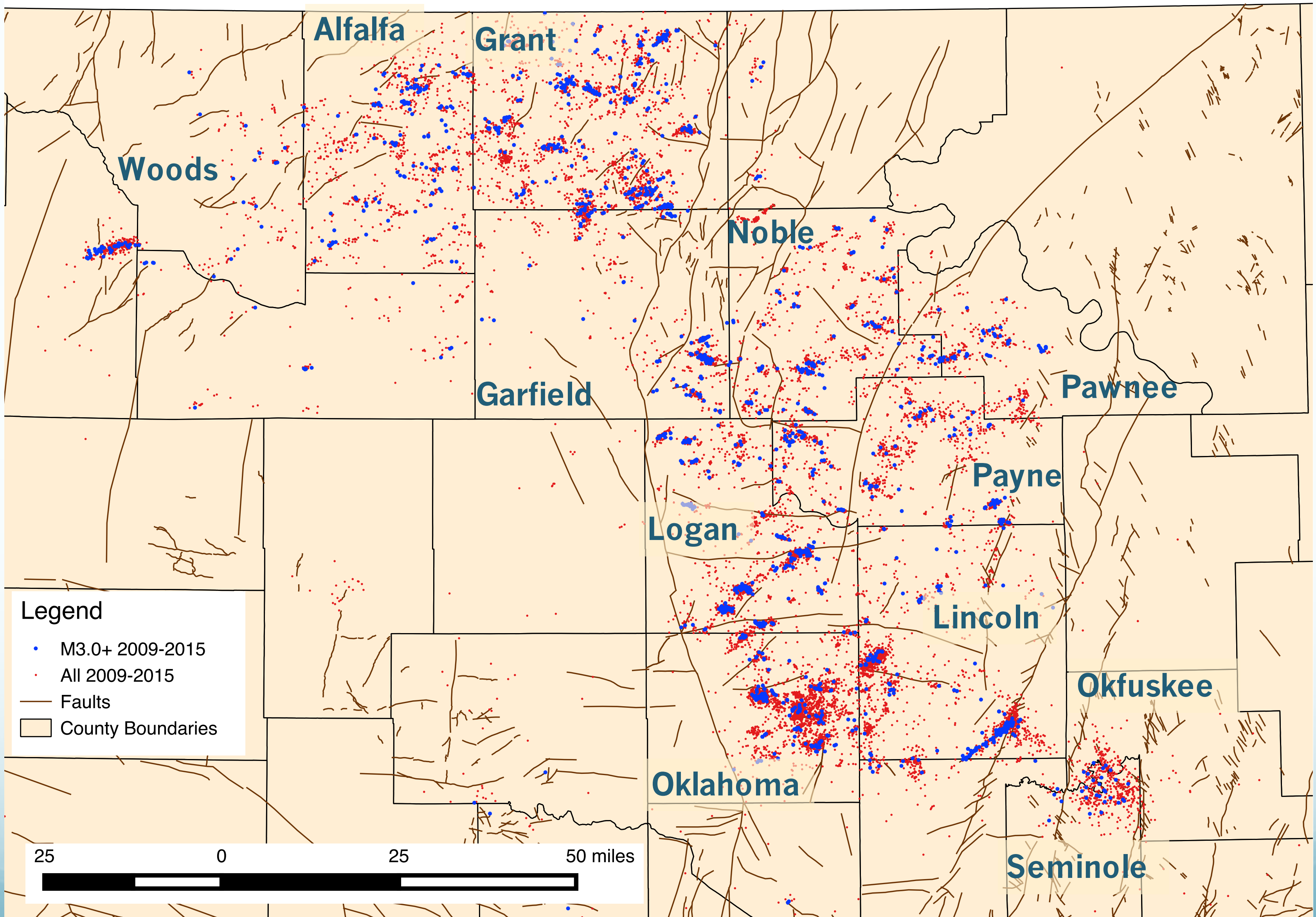
Active Fault Orientations 2014



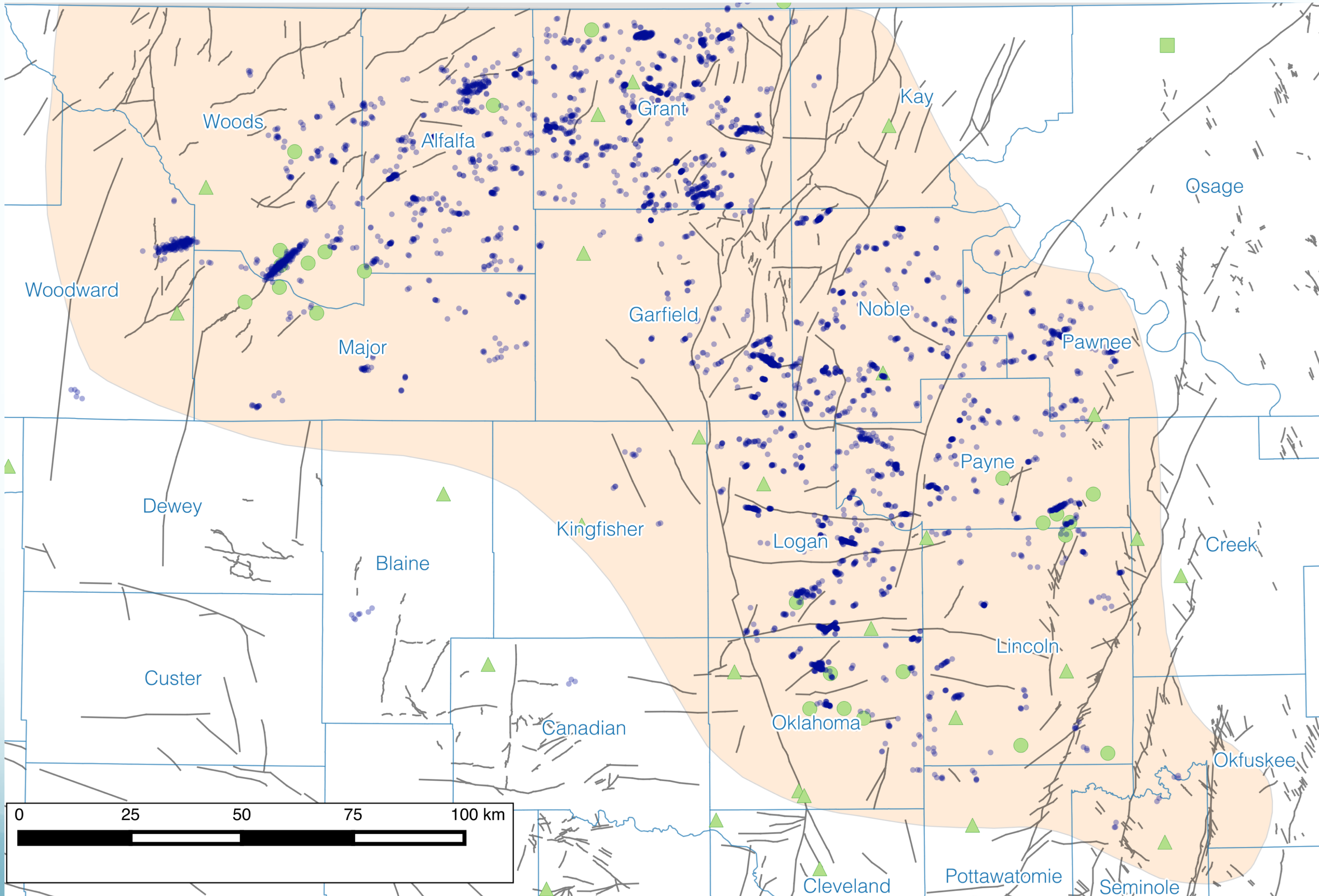
Natural Stresses and Earthquakes

- 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

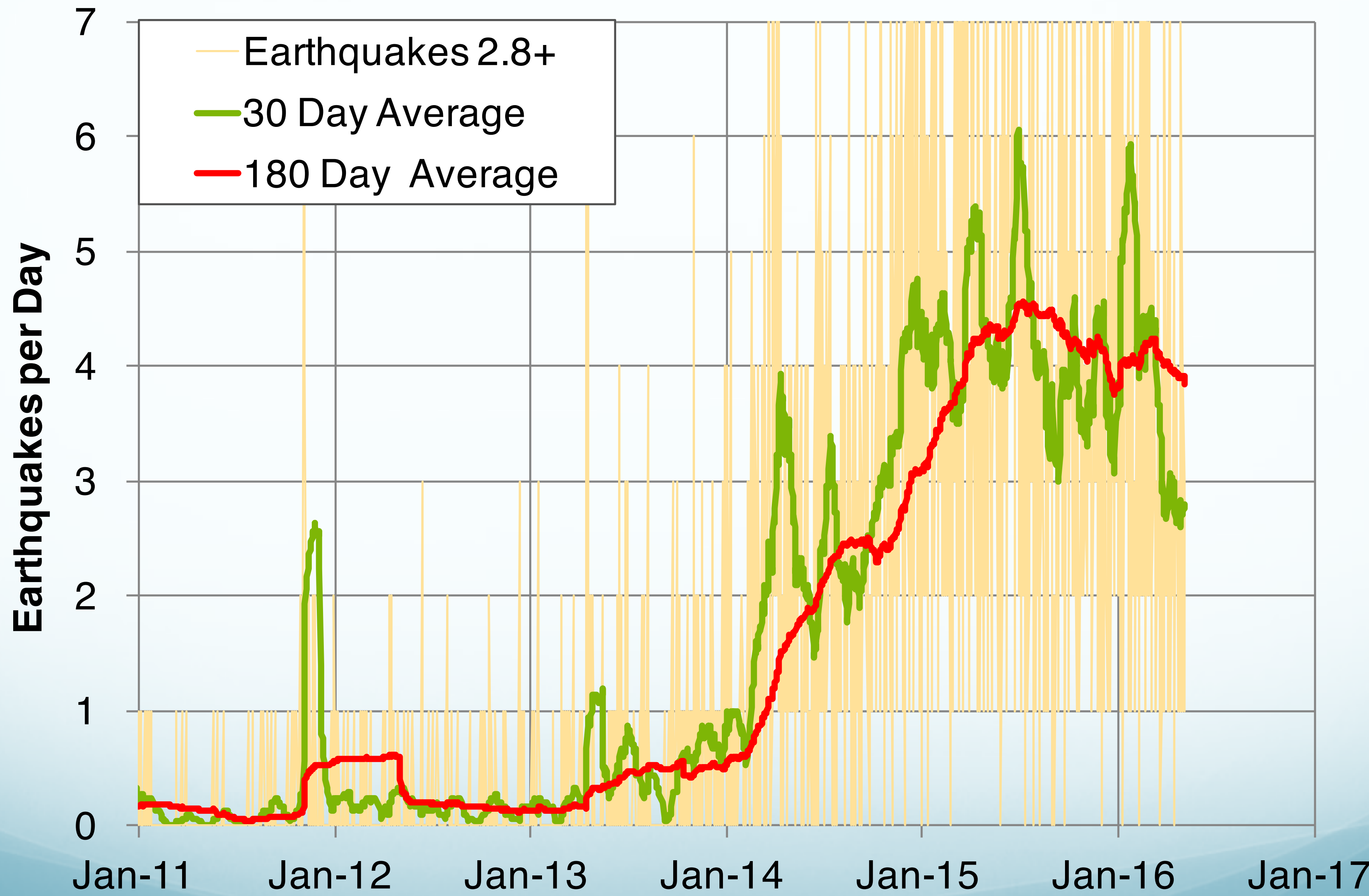
Earthquakes 2009-2015



Earthquakes 2015-2016

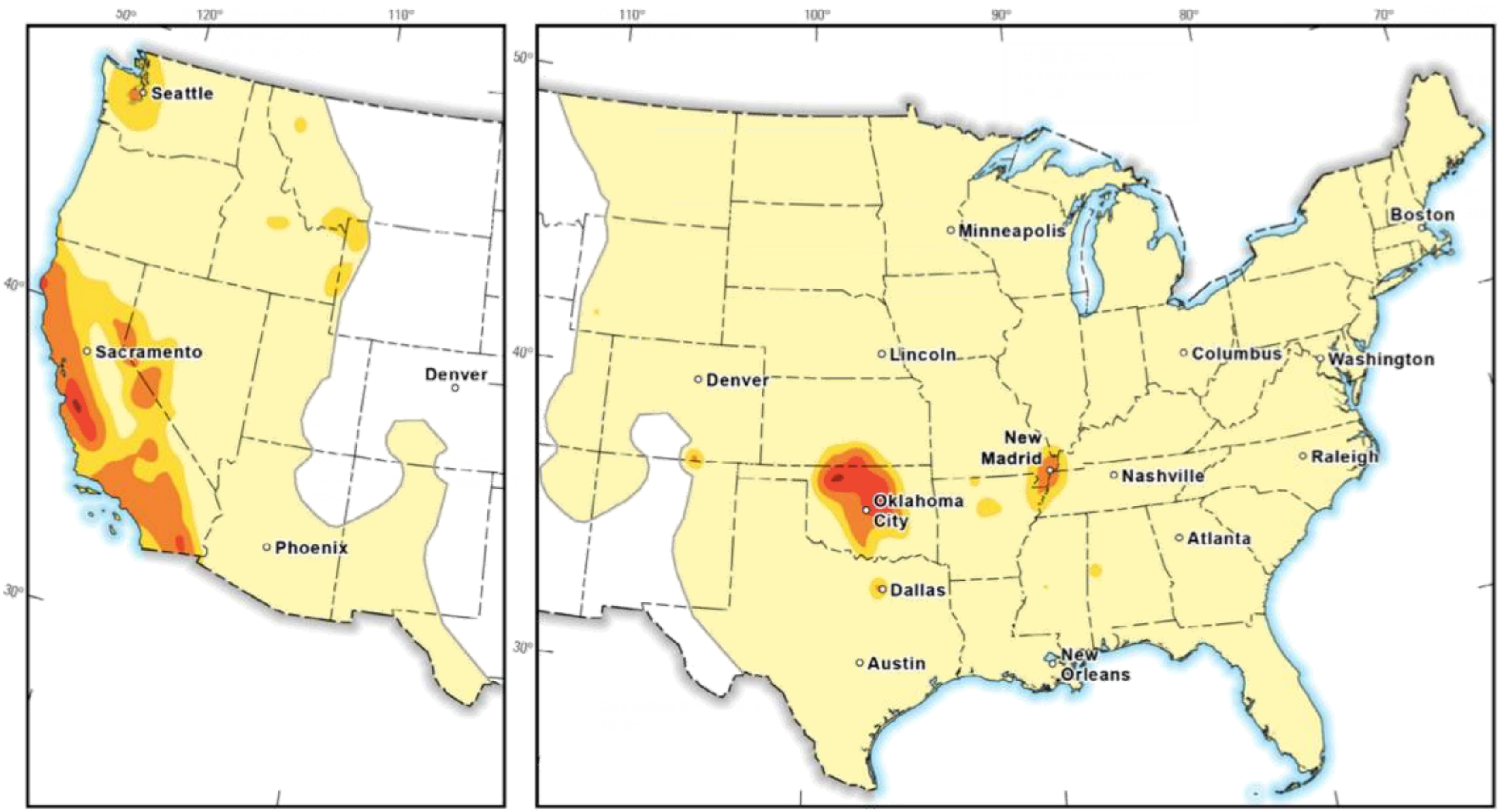


Oklahoma M2.8+ Earthquakes



Comparison of Damage Probabilities

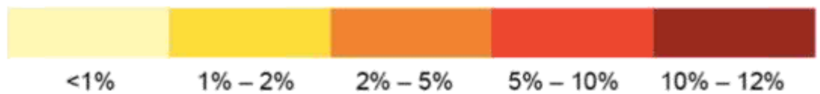
Damage defined as forecasted ground motions of MMI VI or greater (≥ 0.12g)



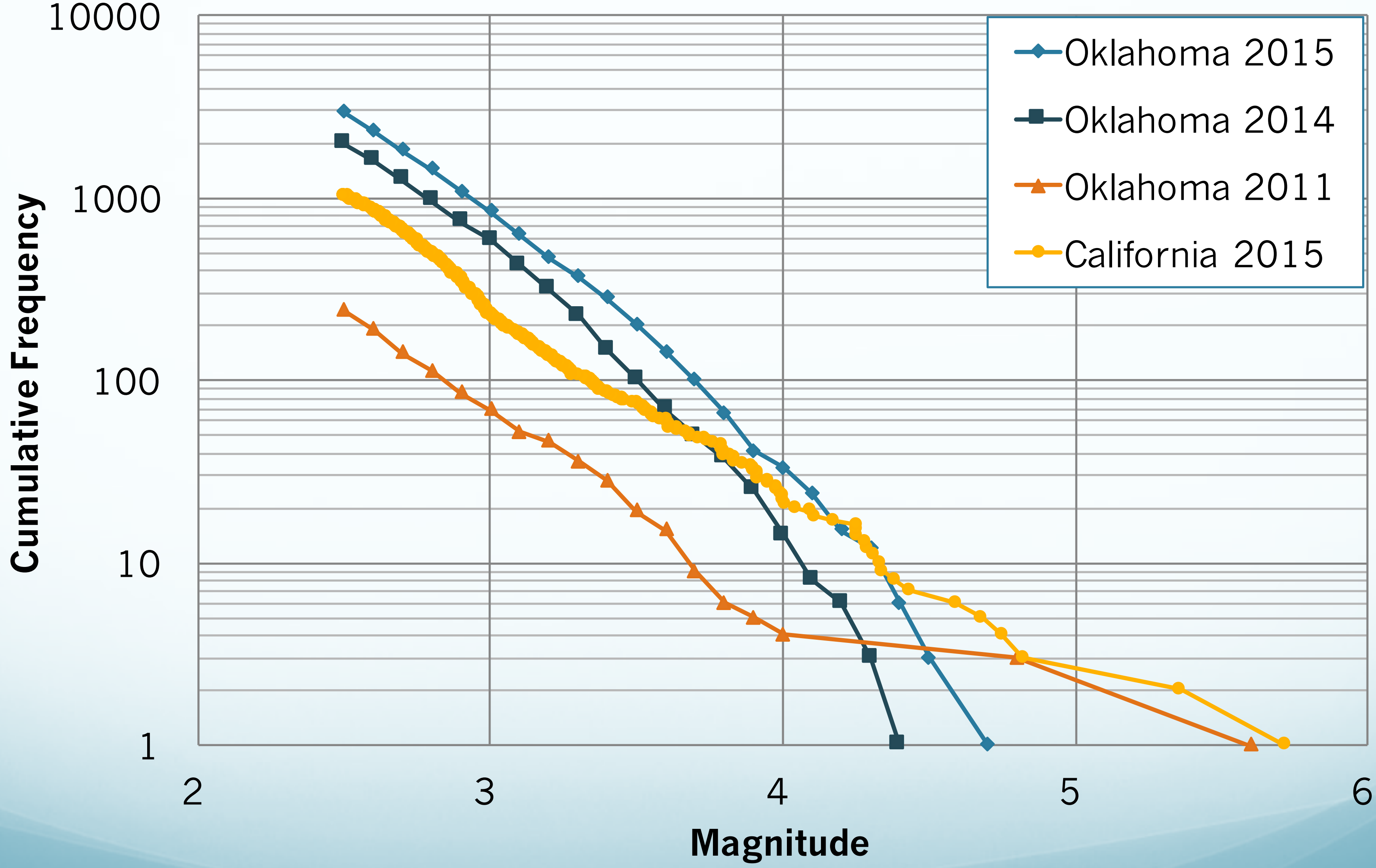
Based on results from the 2014 National Seismic Hazard Model

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

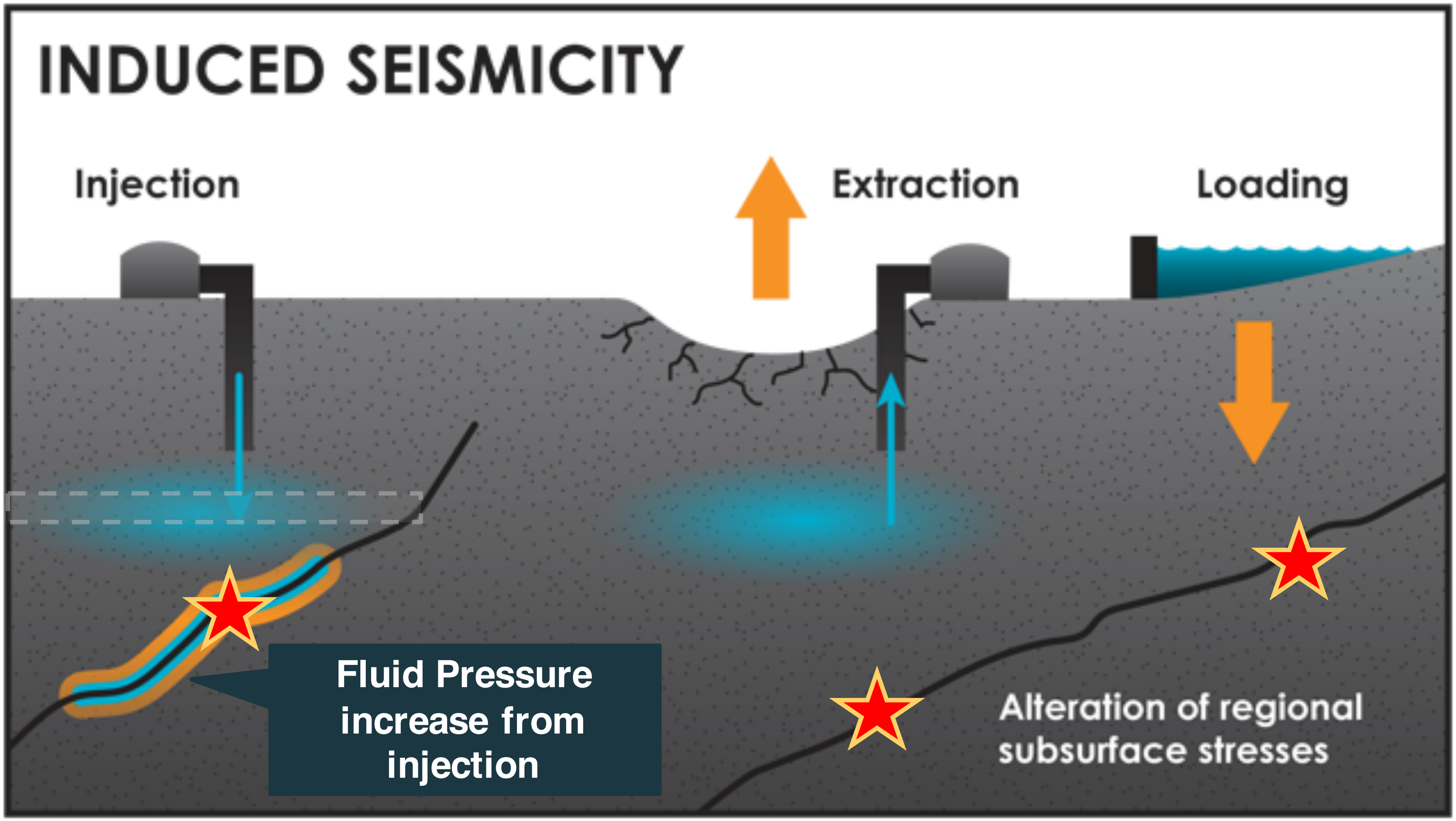
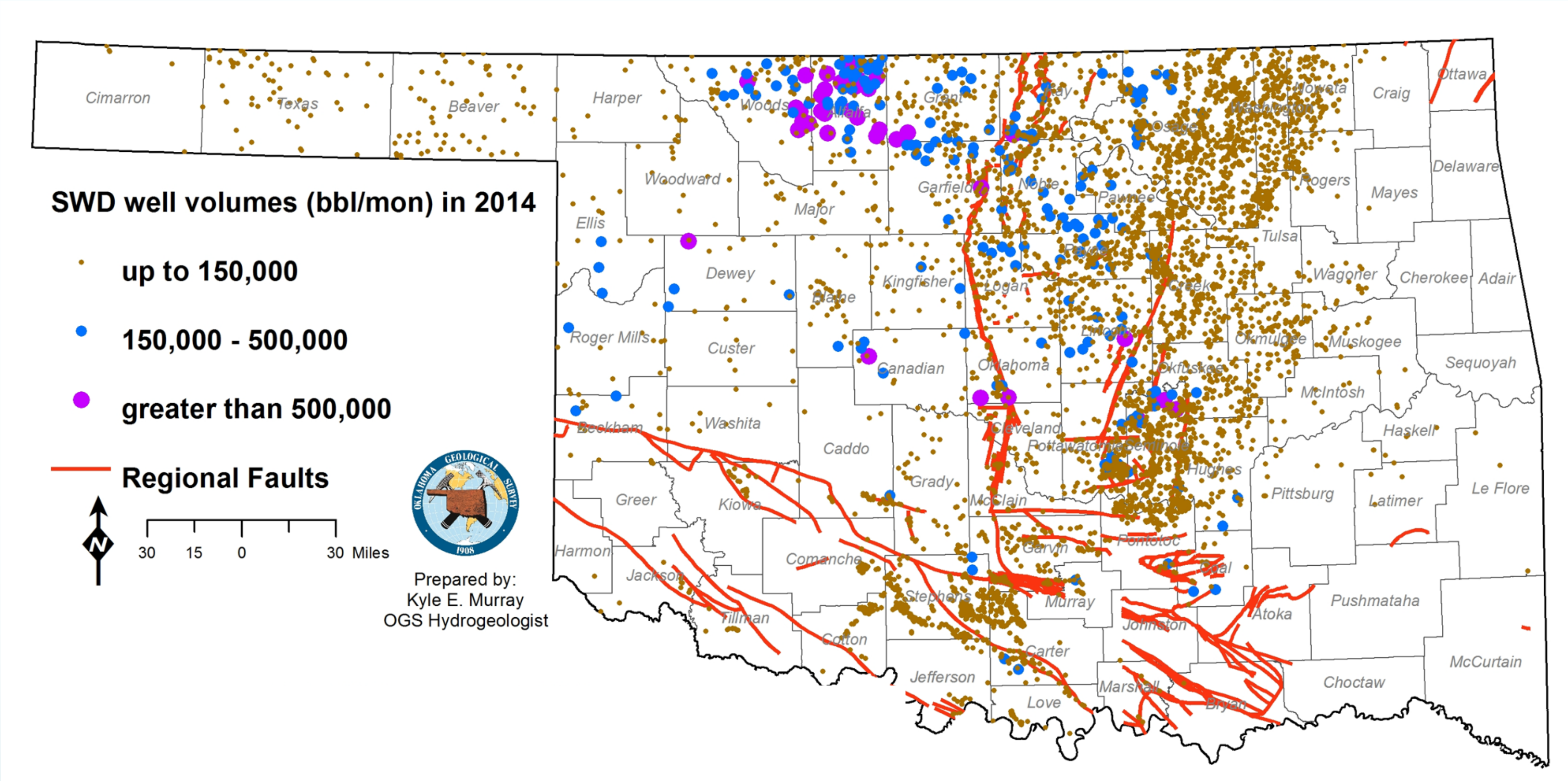


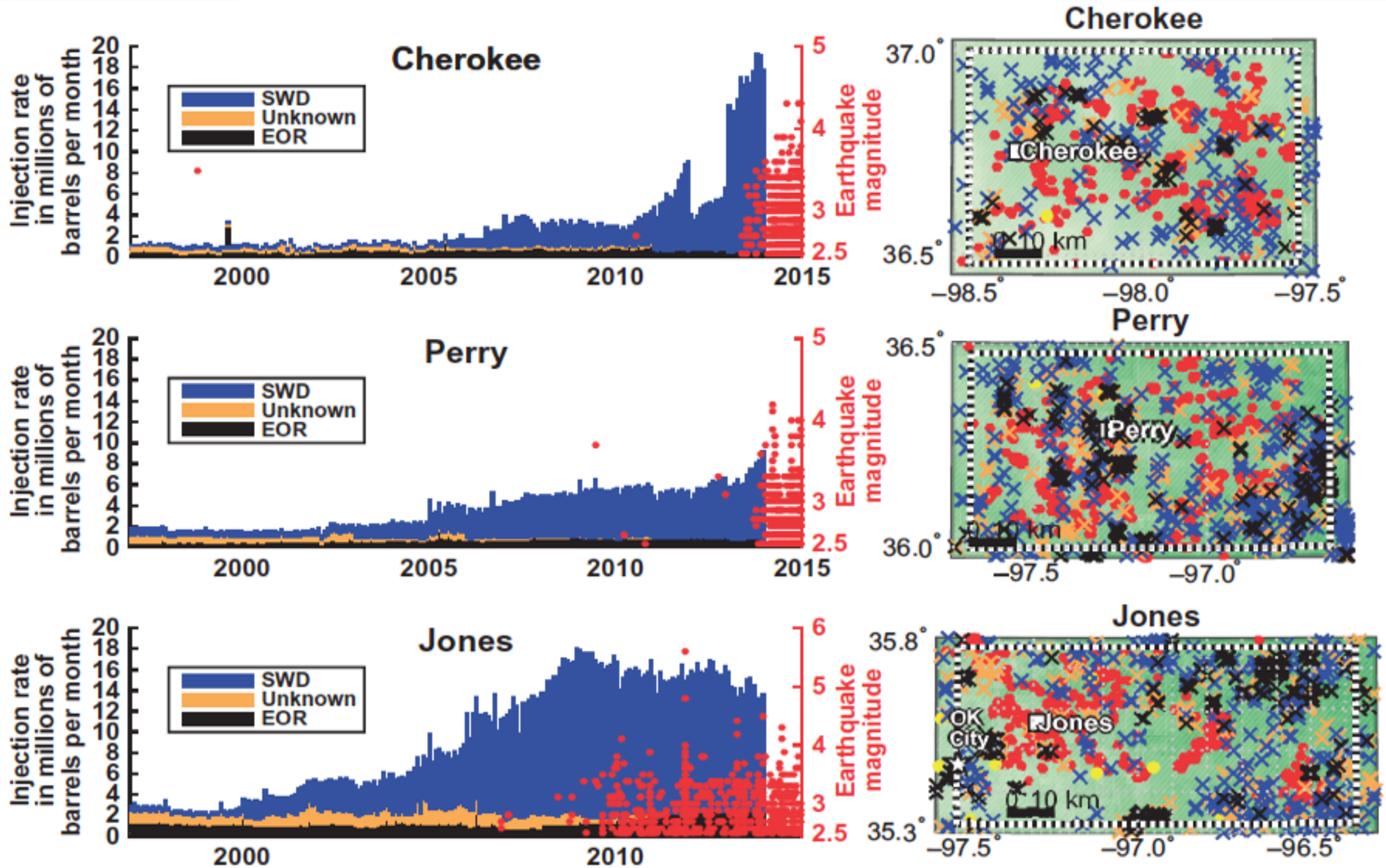
Figure modified from: http://www.earthmagazine.org/article/ground-shaking-research-how-humans-trigger-earthquakes

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



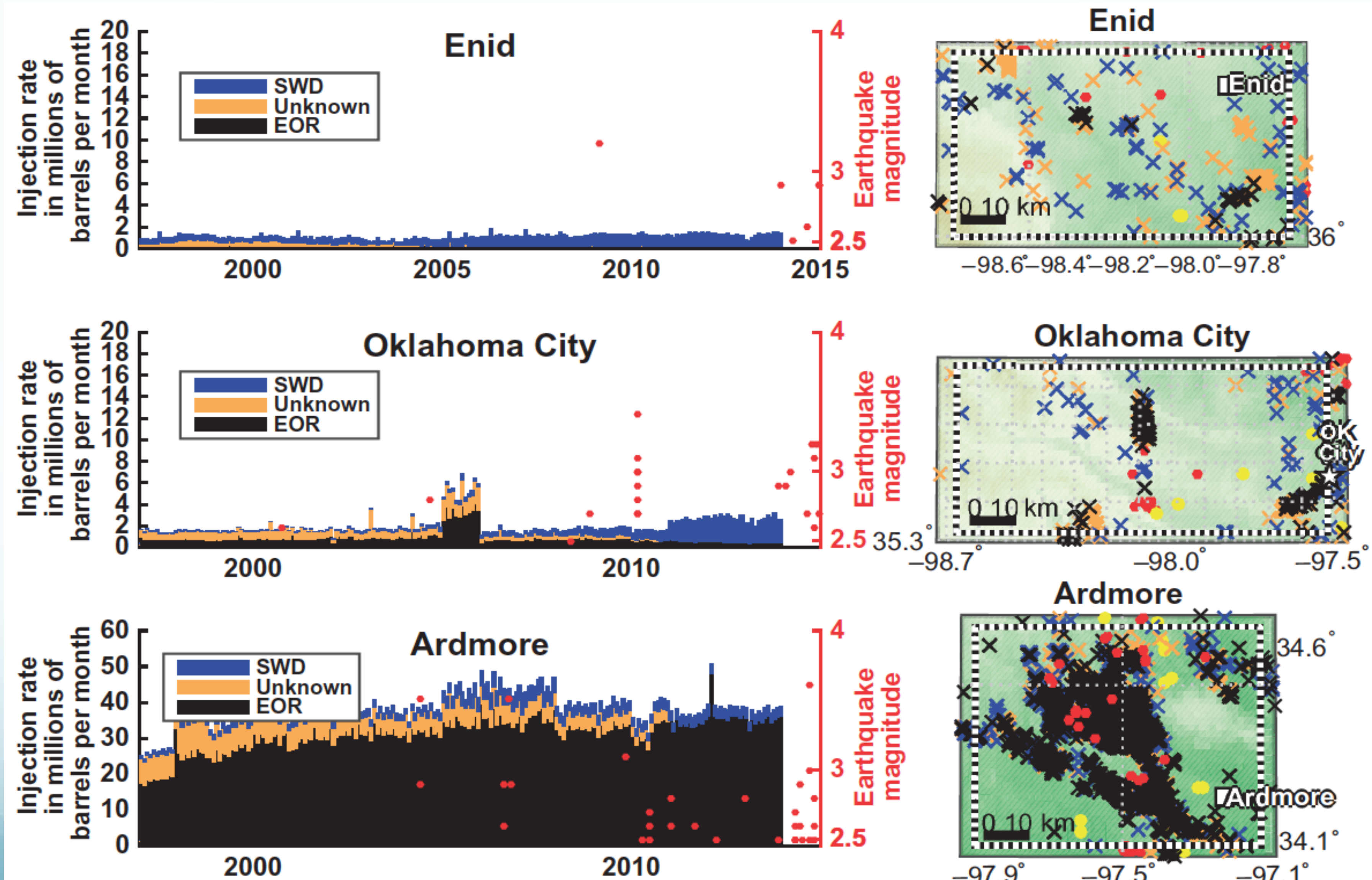
Murray 2014, OGS OF5-2015

Earthquake Activity Occurs Where Deep Injection Increases Substantially



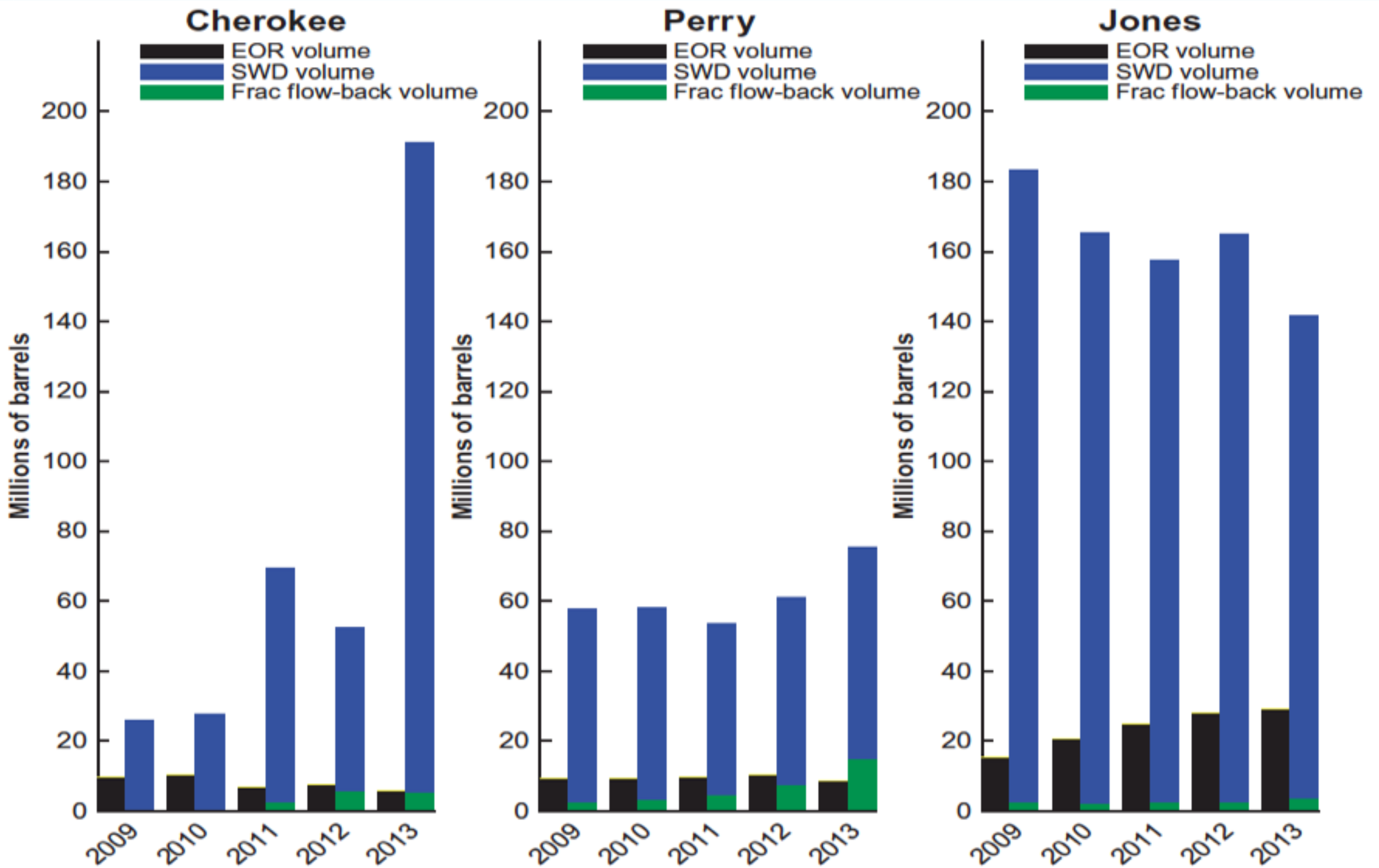
Source: Walsh, F. R., and Zoback, M. D. (2015) Oklahoma's recent earthquakes and saltwater disposal. Sci. Adv. 2015; 1:e1500195, 18 June 2015

Areas of Lower SWD Show Lower Earthquake Activity



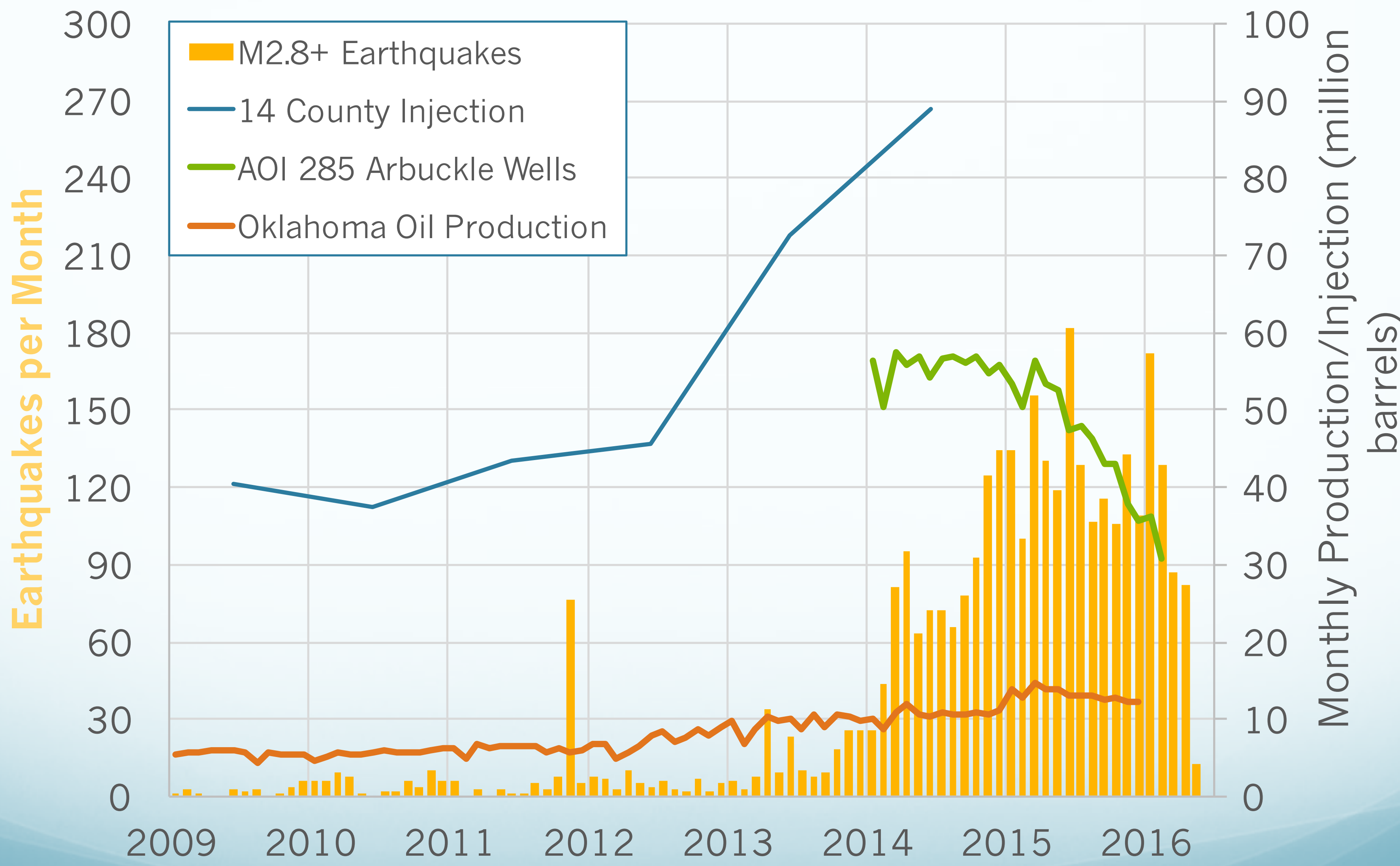
Source: Walsh, F. R., and Zoback, M. D. (2015) Oklahoma's recent earthquakes and saltwater disposal. Sci. Adv. 2015; 1:e1500195, 18 June 2015

SWD Includes Very Little Flowback Water from Hydraulic Fracturing

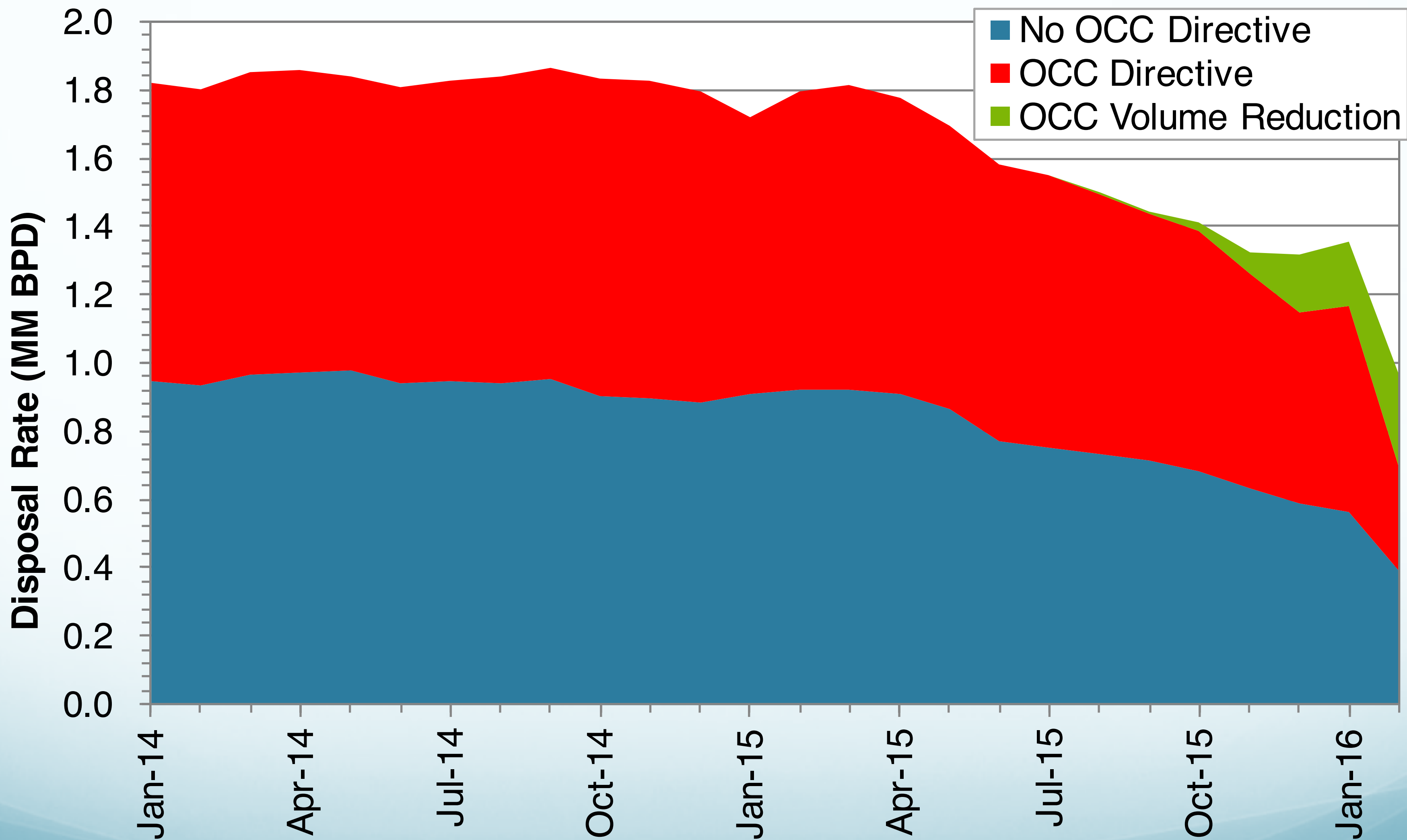


Source: Walsh, F. R., and Zoback, M. D. (2015) Oklahoma's recent earth-quakes and saltwater disposal. Sci. Adv. 2015; 1:e1500195, 18 June 2015

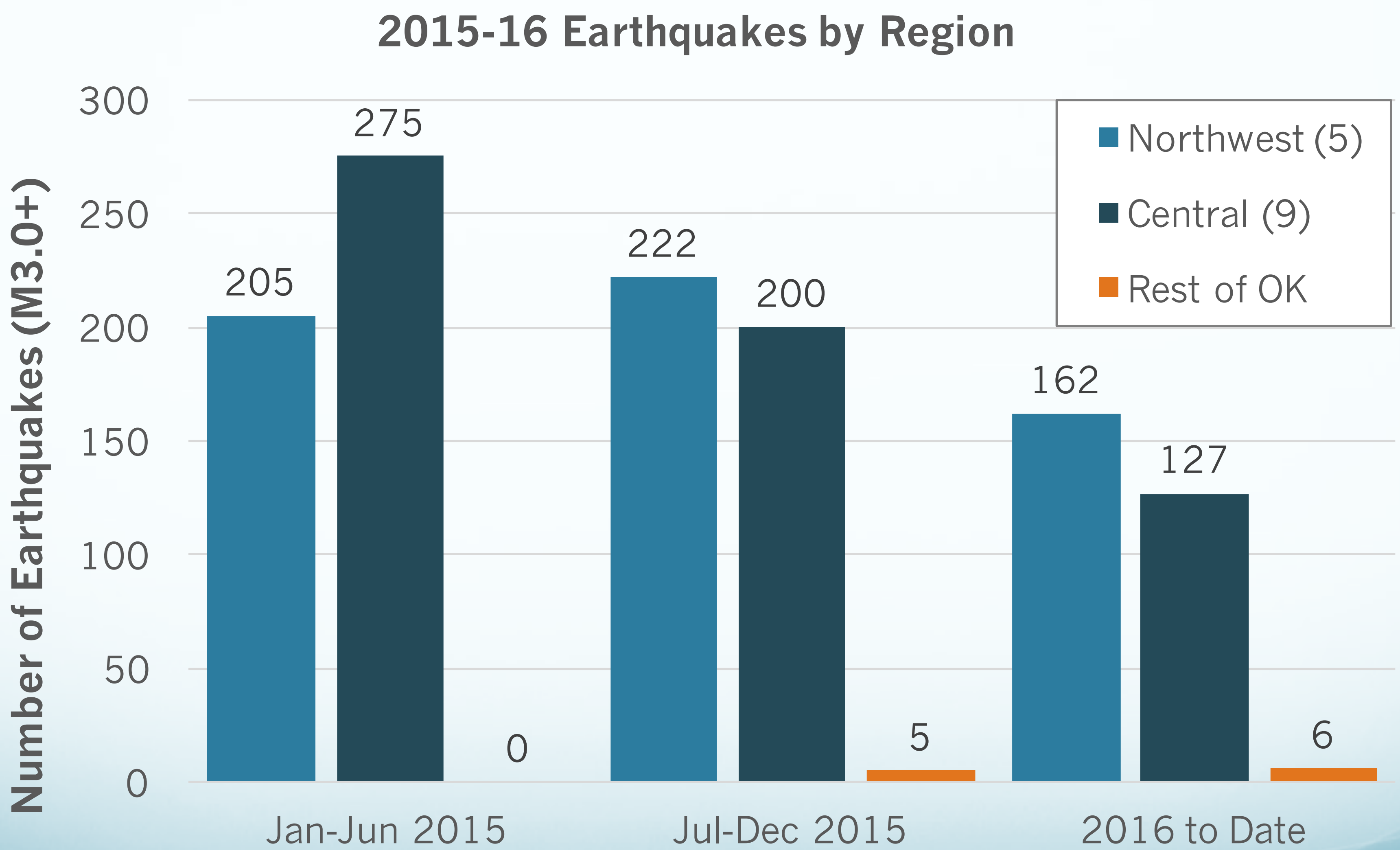
Earthquakes, Oil & Water



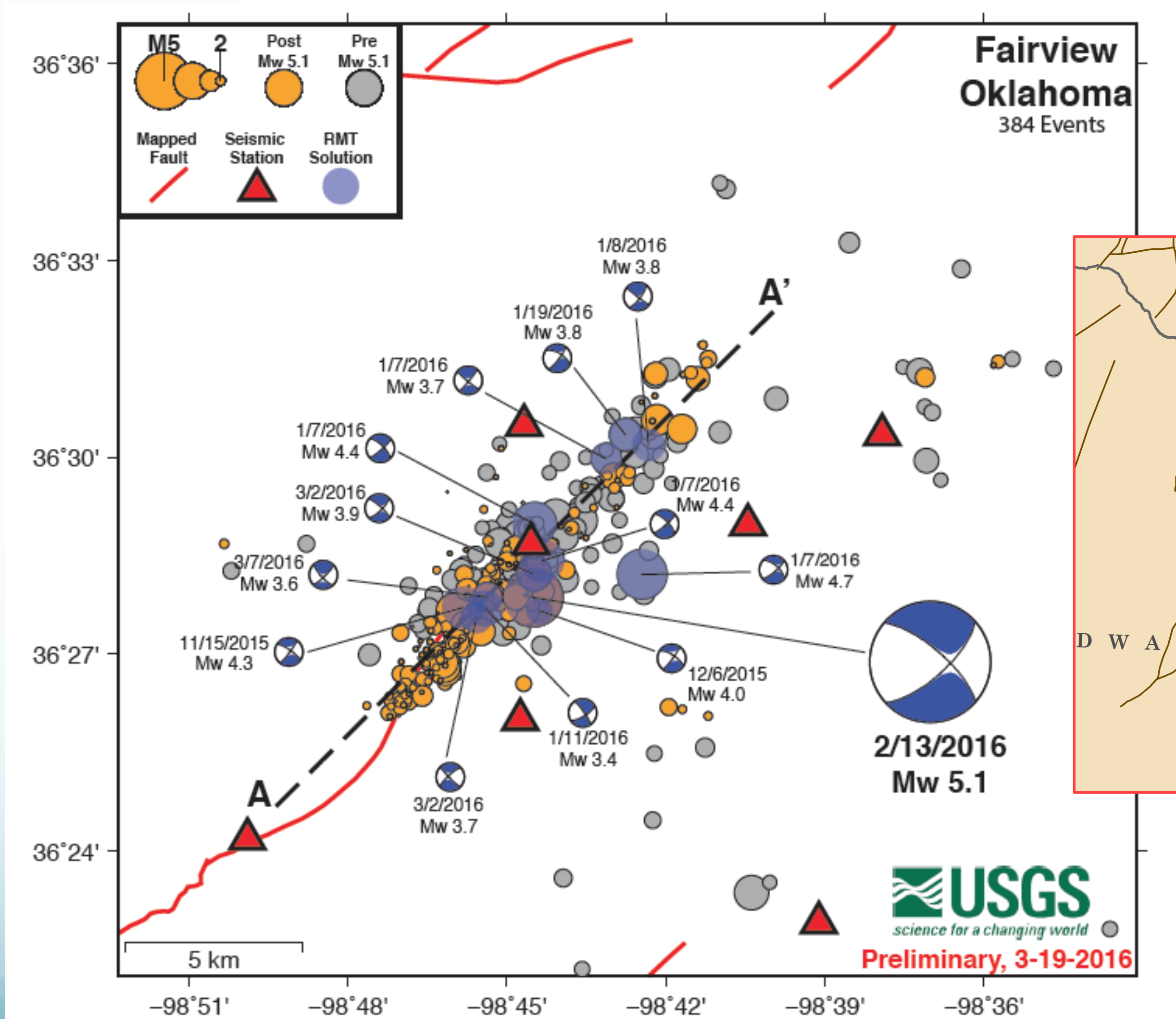
Injection rate decline in 285 Arbuckle SWD wells in seismic Area of Interest

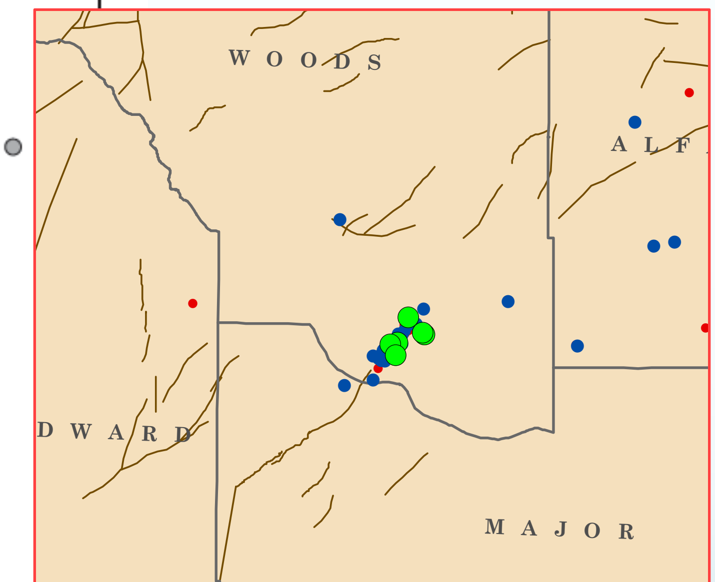


Focus of Seismic Activity Shifting to Northwest

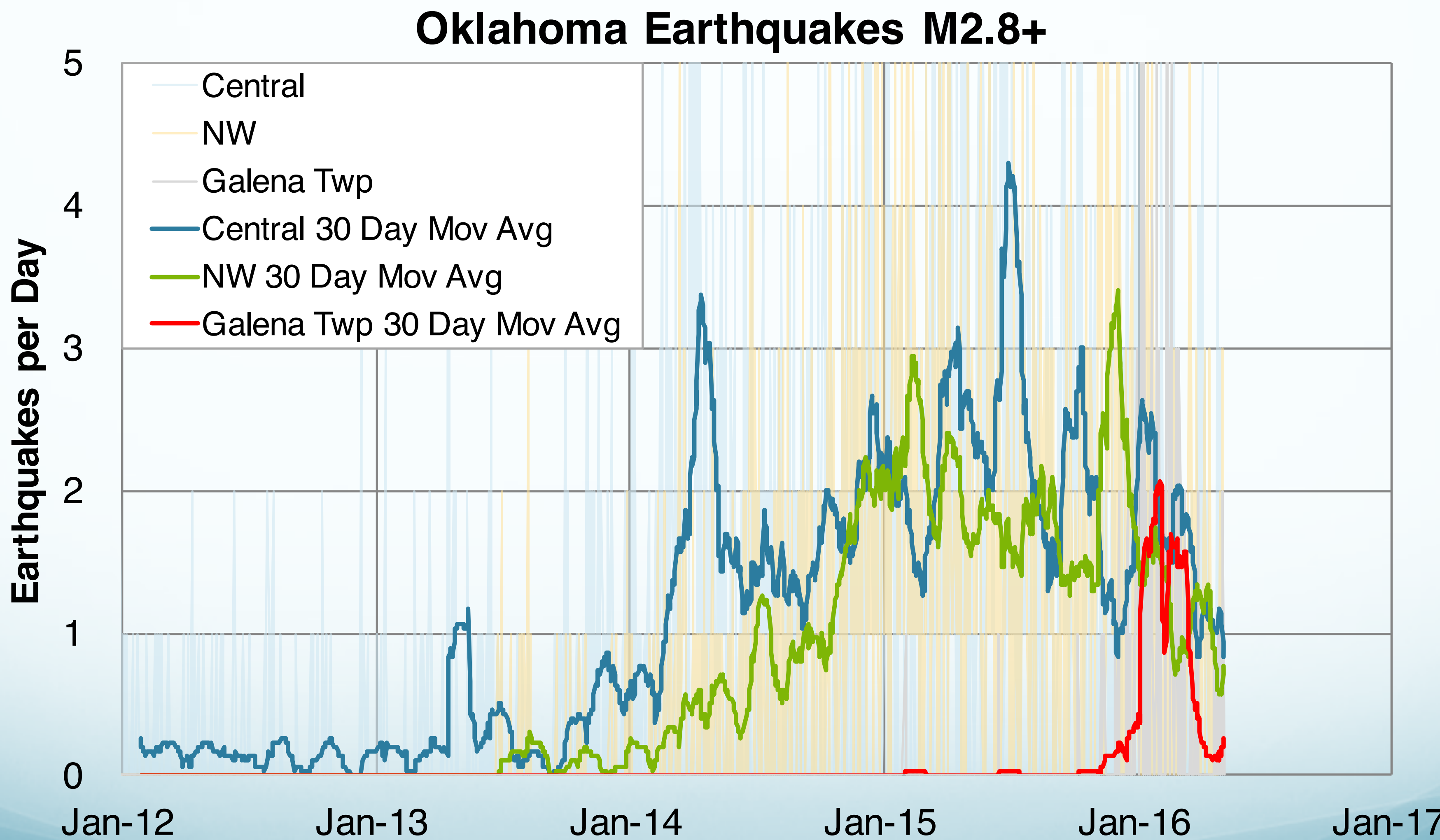


Recent Activity in Fairview/Waynoka Area

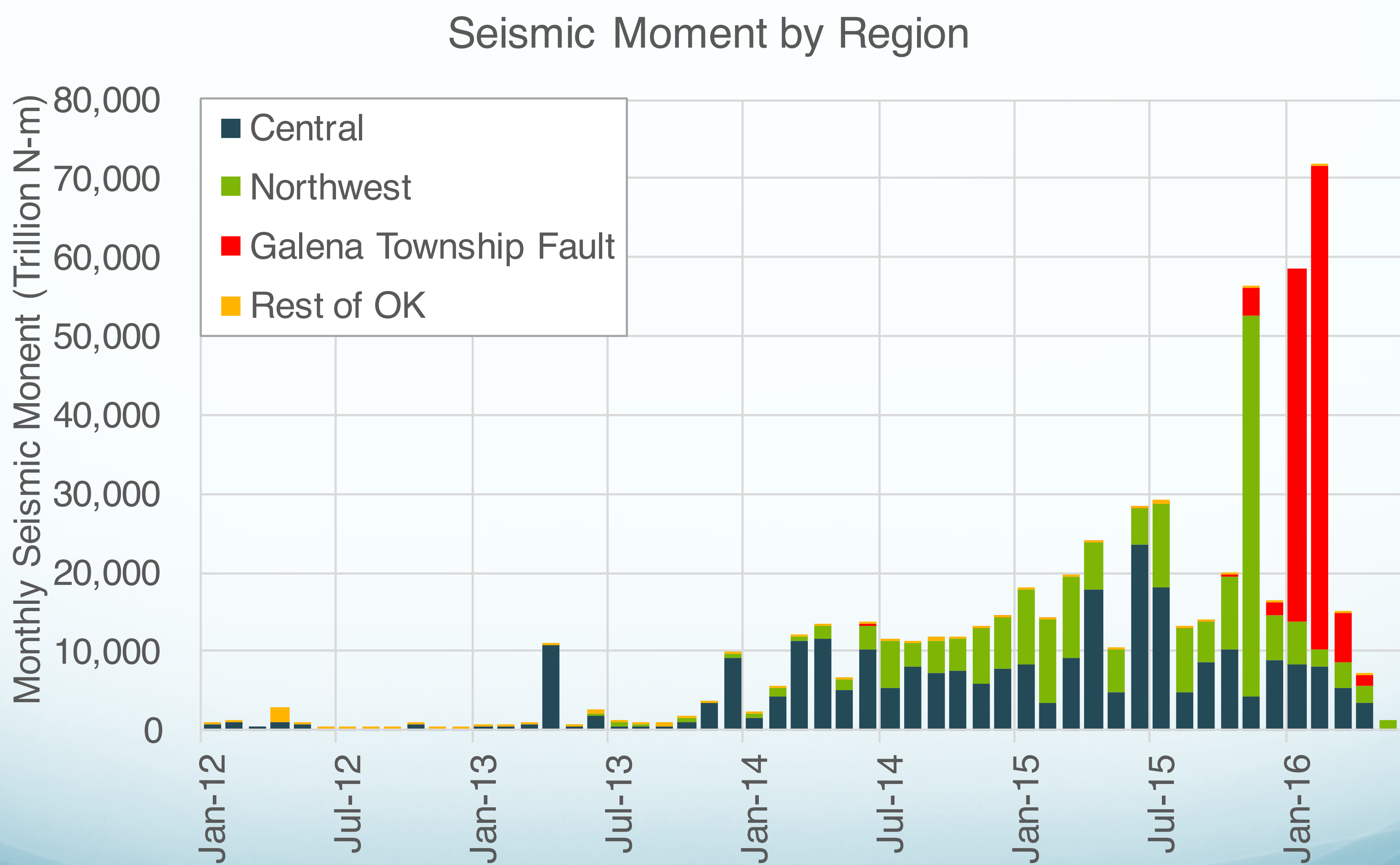




Galena Township Fault Activity is Major Element



Seismic Moment (Energy Release)



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

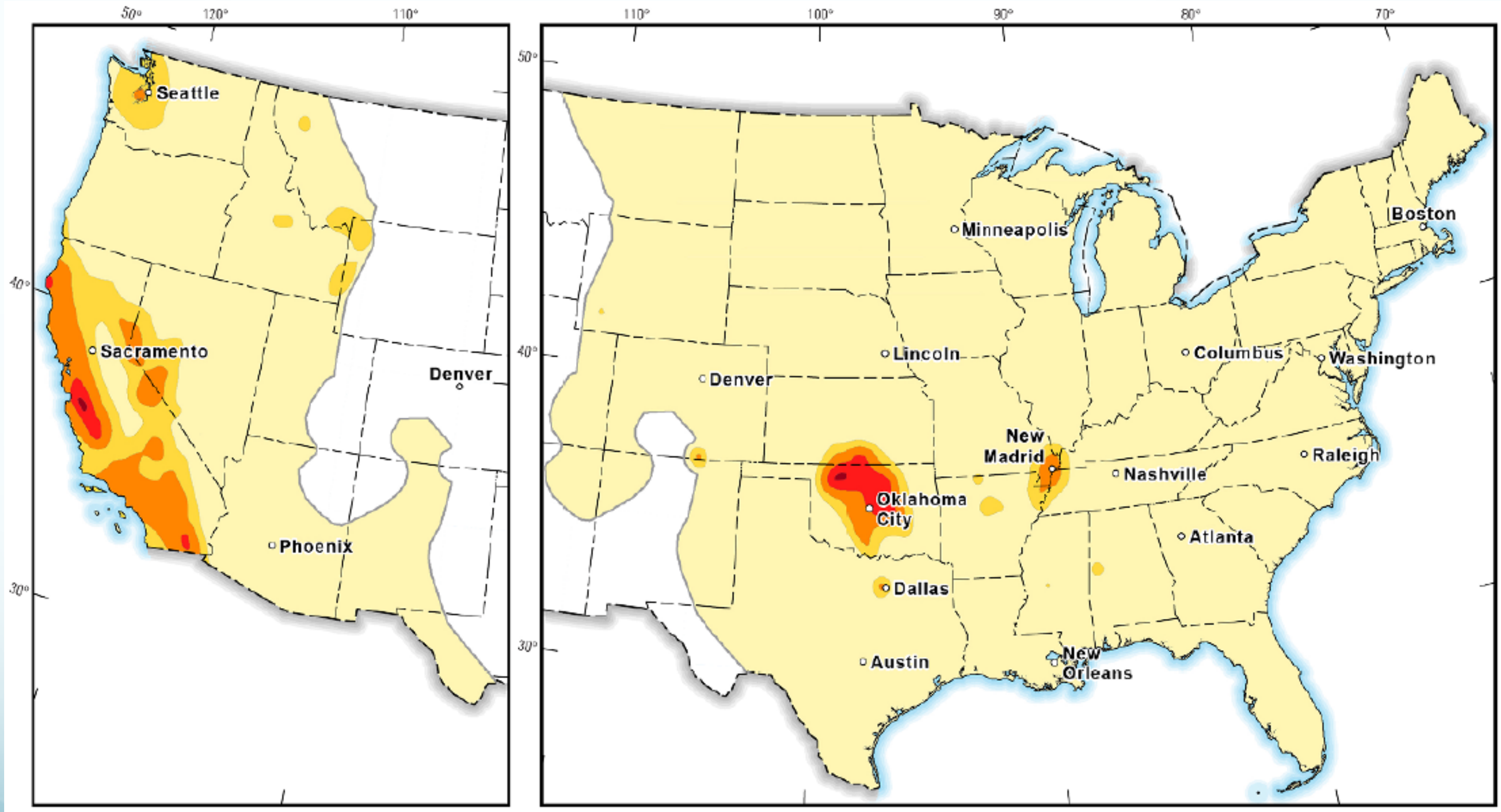
Intensity	Shaking	Description/Damage
I	Not felt	Not felt except by a very few under especially favorable conditions.
II	Weak	Felt only by a few persons at rest,especially on upper floors of buildings.
III	Weak	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people 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

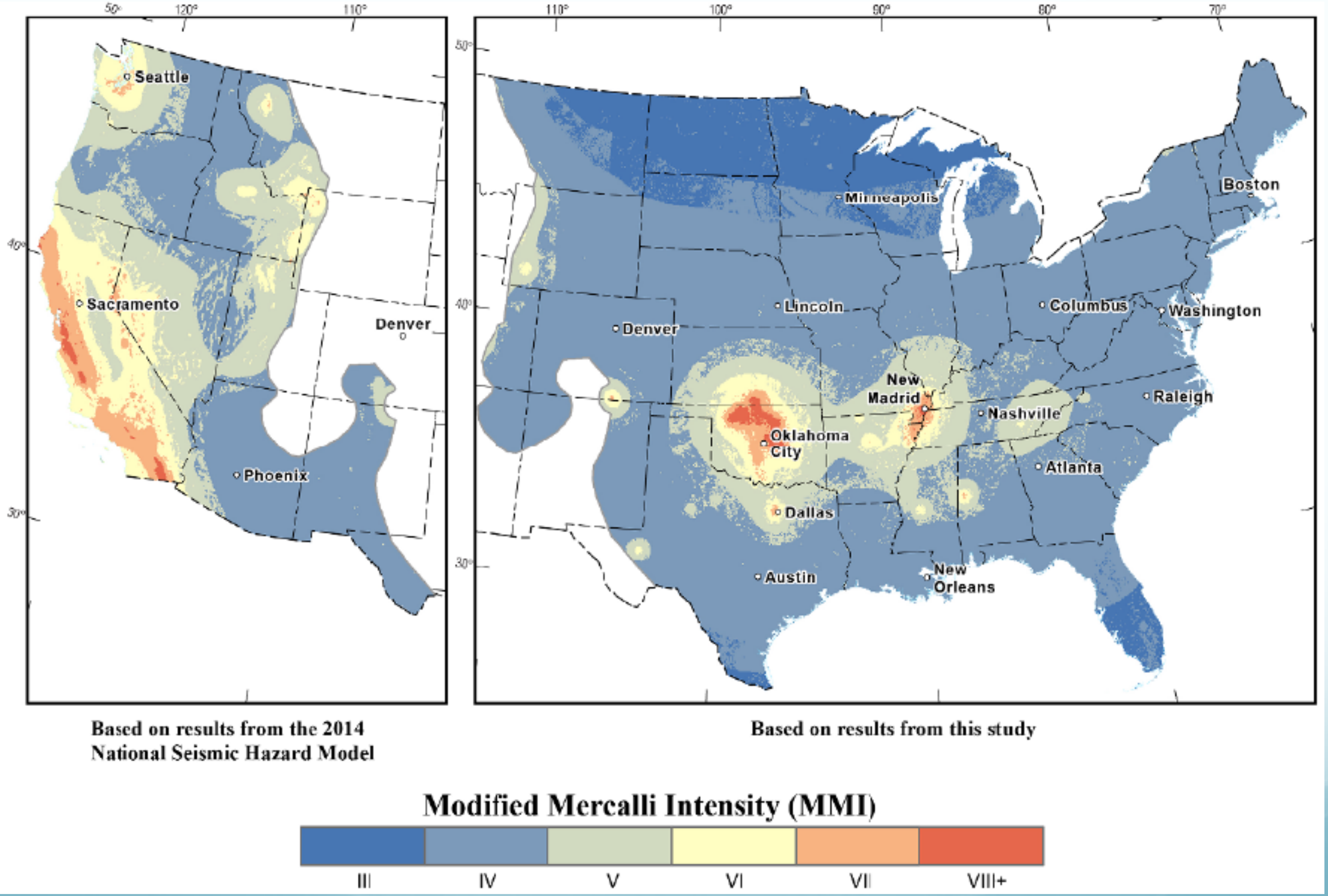
Source: http://earthquake.usgs.gov/earthquakes/shakemap/background.php

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+

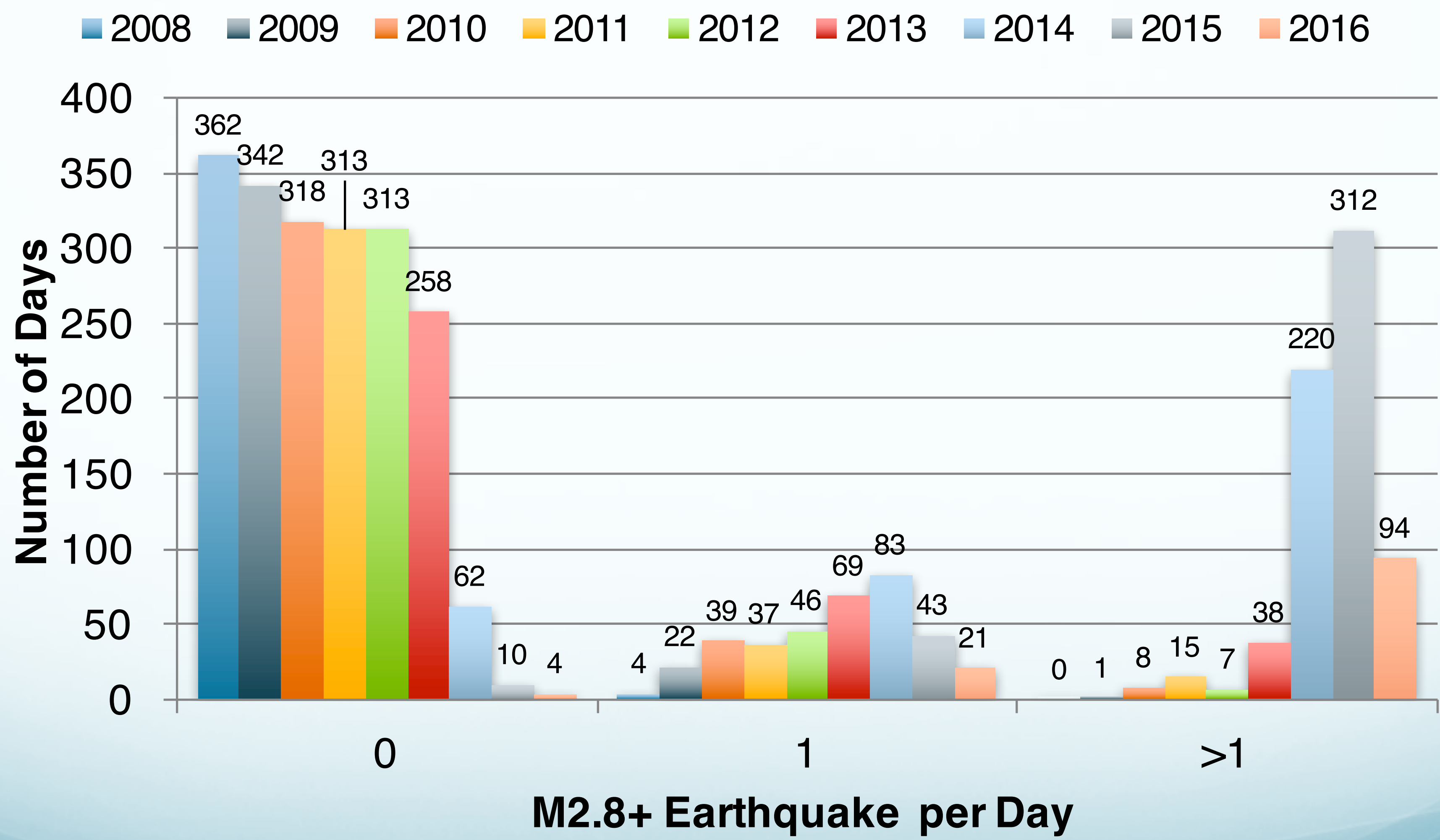


50°
120°
110°
Seattle
40°
Sacramento
Denver
Phoenix
30°
110°
100°
90°
80°
70°
50°
40°
30°
Boston
Minneapolis
Lincoln
Columbus
Washington
Denver
New Madrid
Raleigh
Nashville
Oklahoma City
Atlanta
Dallas
New Orleans
Austin

USGS 1% Hazard Map



A Change in the Seismic Weather



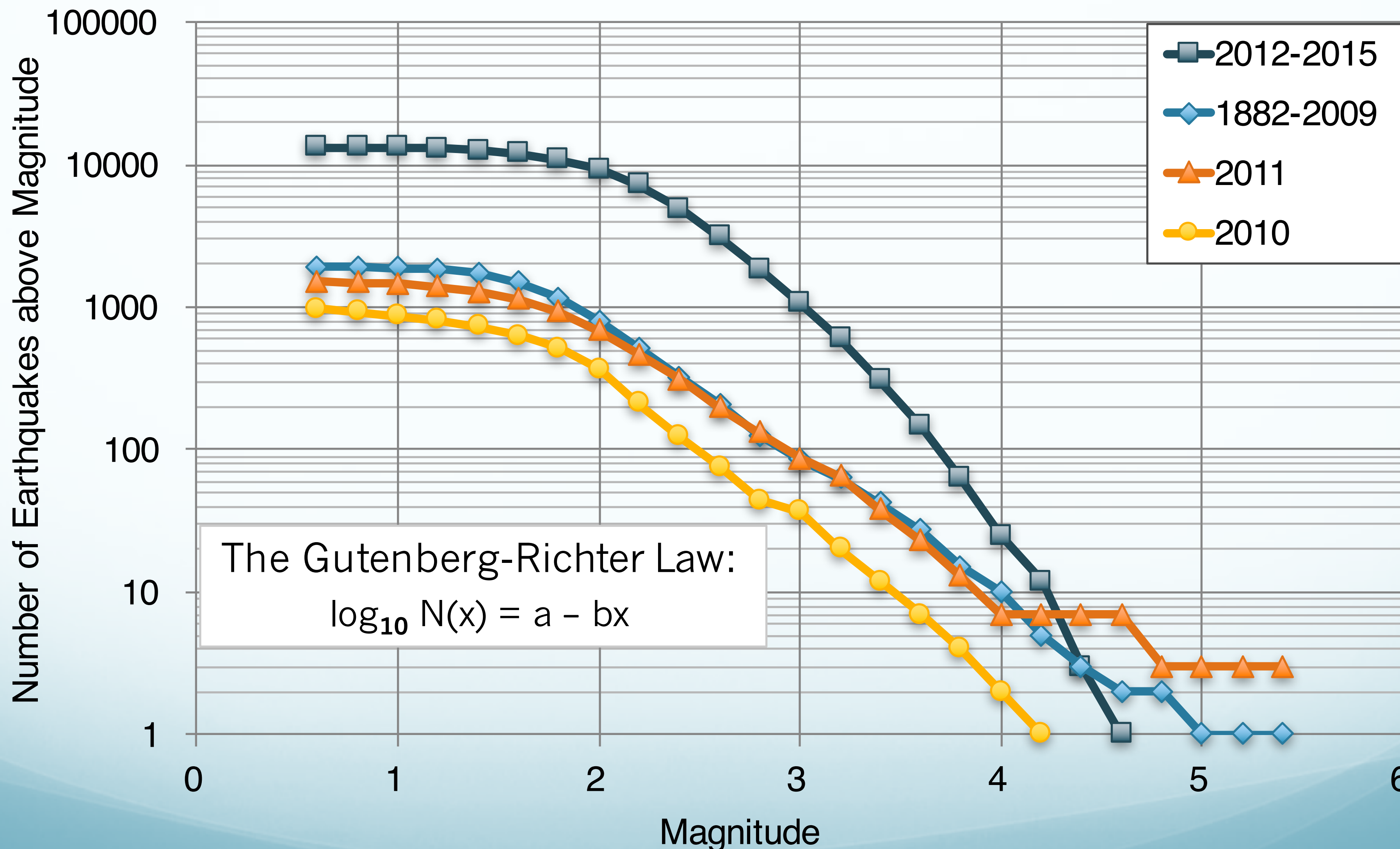
Earthquake Forecasting

- 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

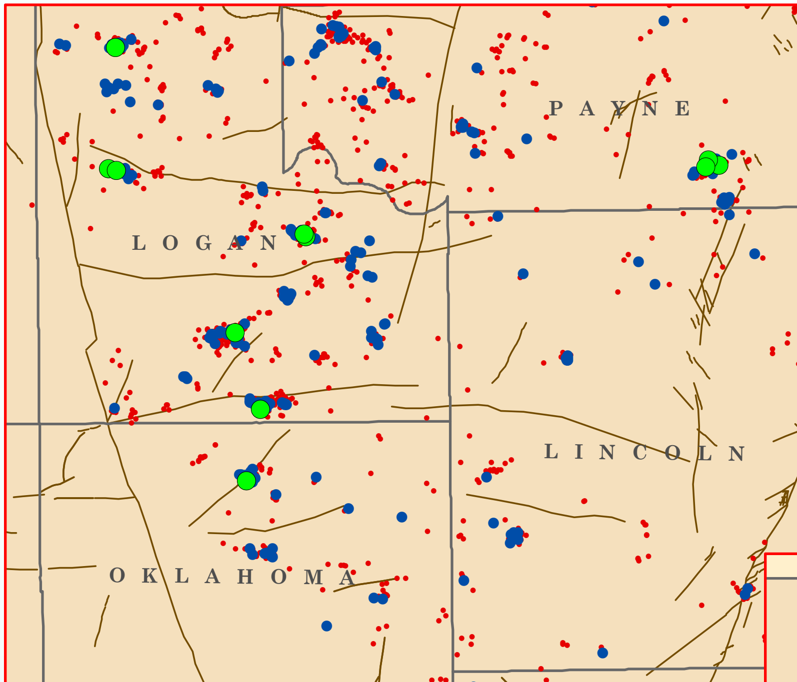
	Magnitude (M_L)					
Duration	**3.0**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**
4 Year	1.00	1.00	1.00	0.81	0.28	0.07
1 Year	1.00	1.00	1.00	0.71	0.24	0.06
6 months	1.00	1.00	0.98	0.63	0.21	0.06
30 days	1.00	0.87	0.39	0.11	0.02	0.007
10 days	1.00	0.74	0.31	0.09	0.03	0.007

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

Gutenberg-Richter Relationships

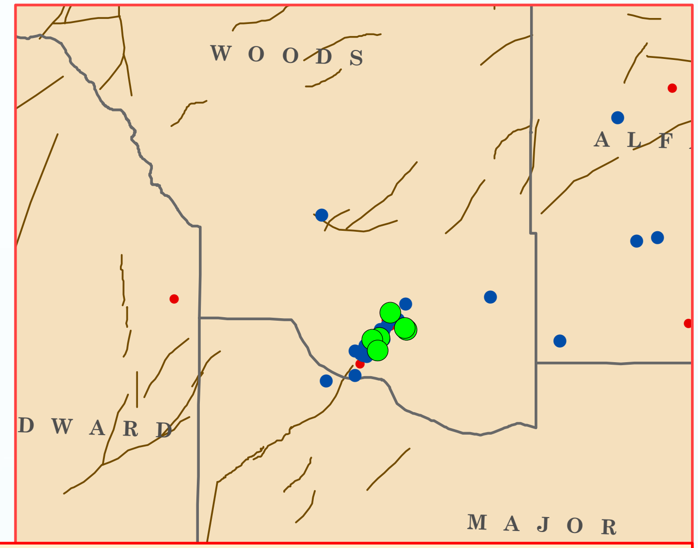


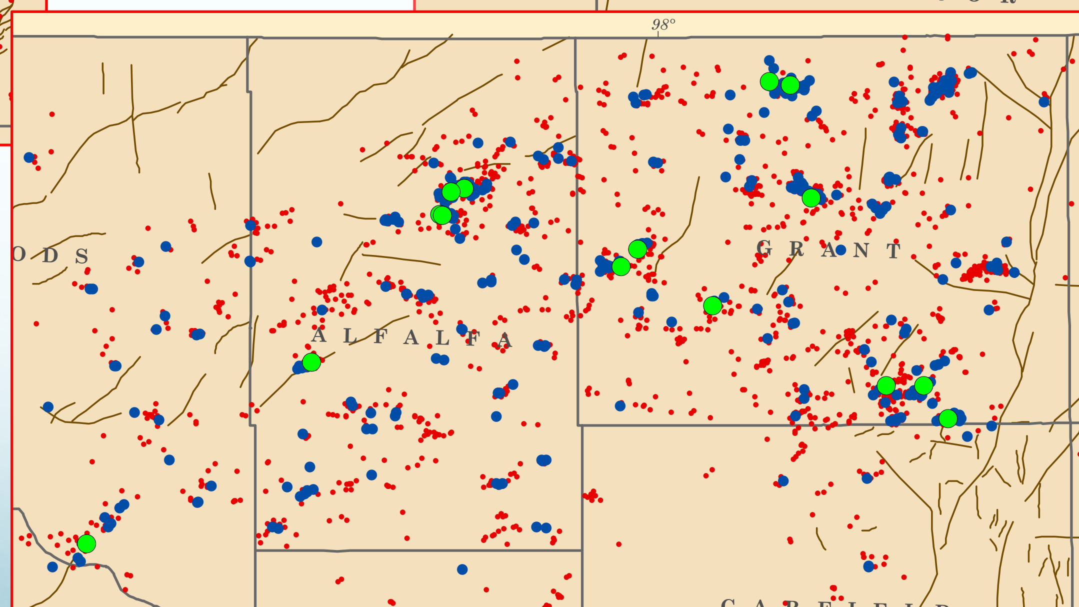
Recent Earthquake Activity



Edmond and Cushing Areas

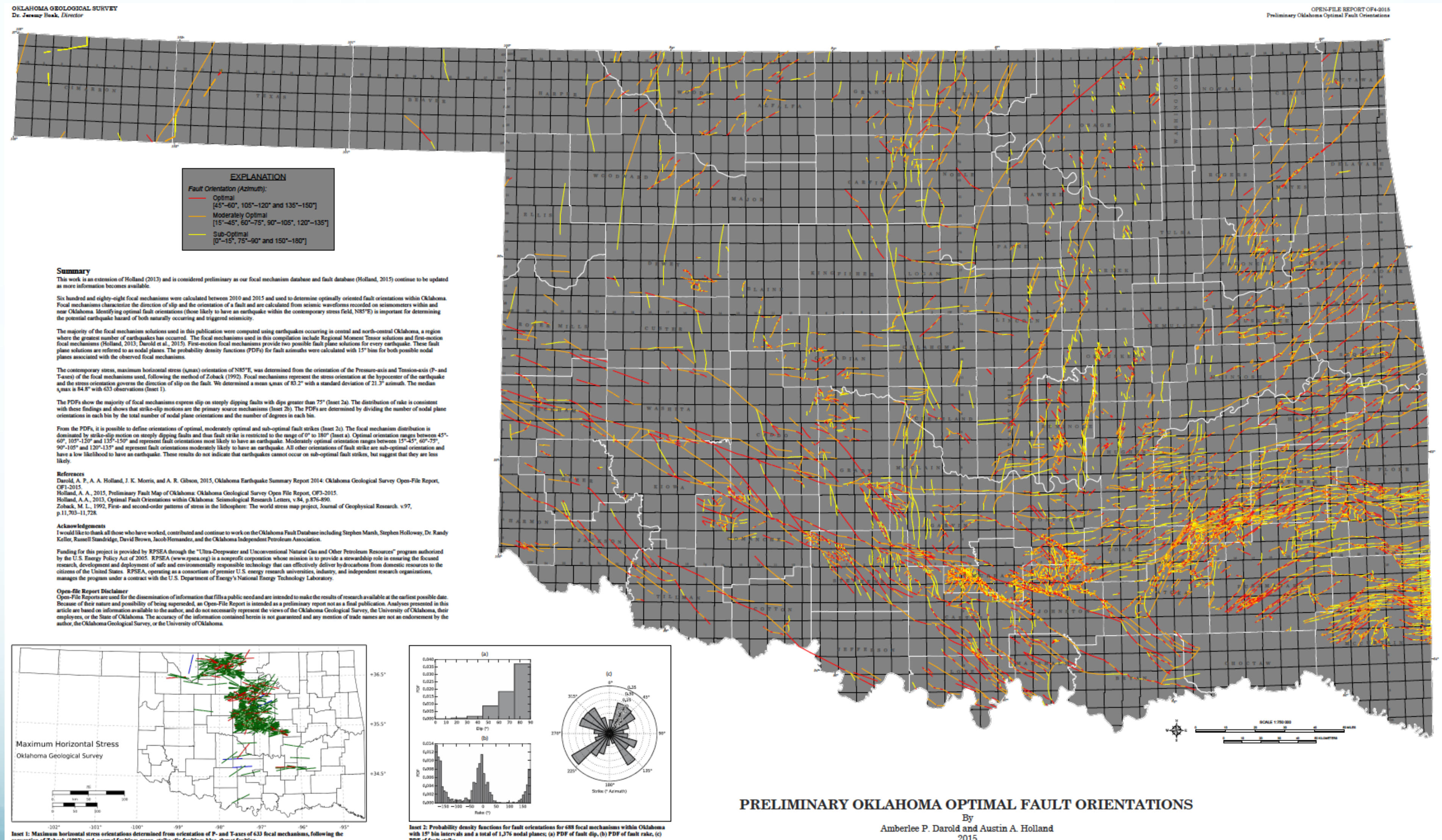
Fairview Area





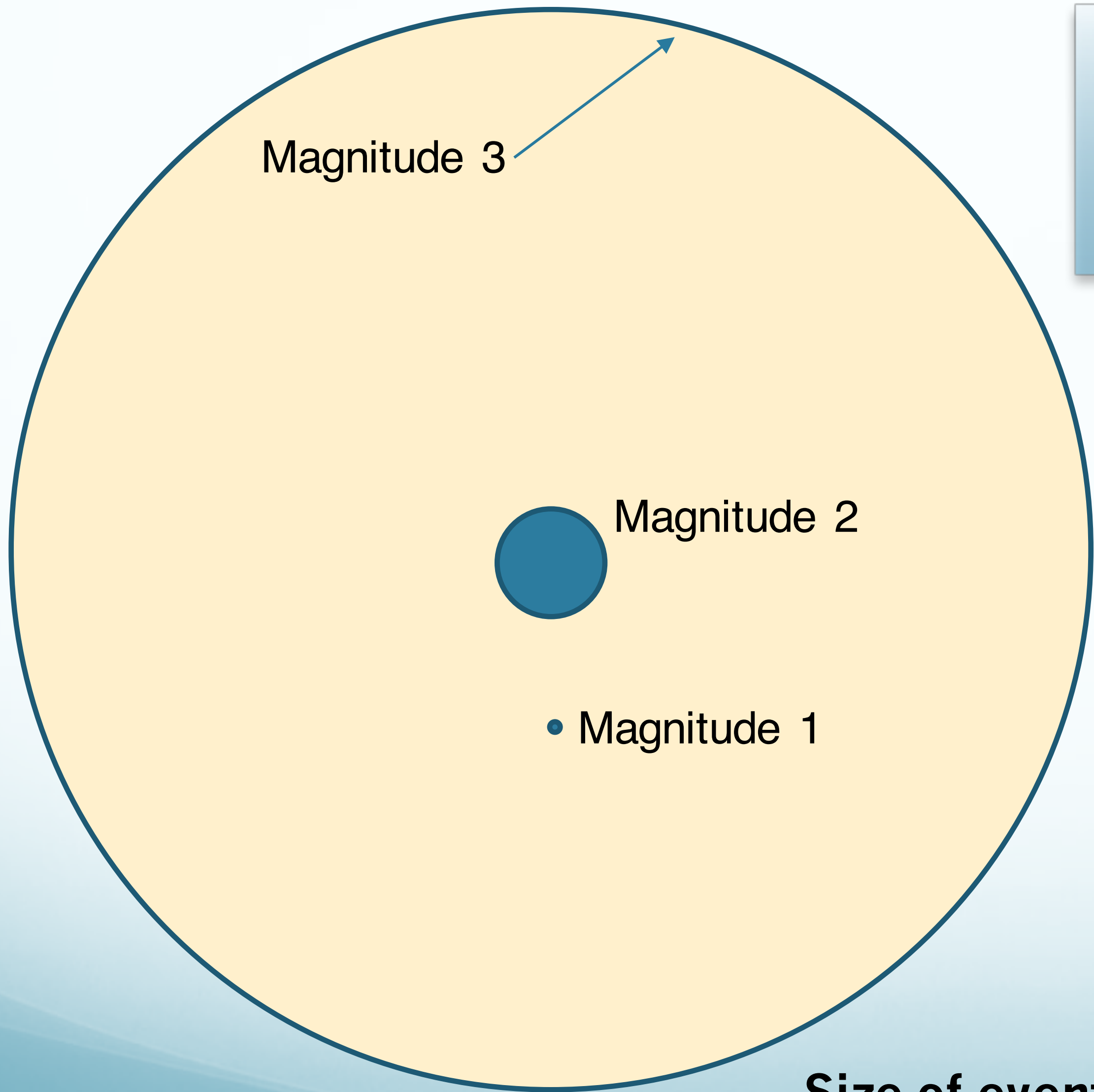
Grant, Alfalfa, Woods Counties

Optimally Oriented Faults in Oklahoma



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 <u>estimate</u> 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

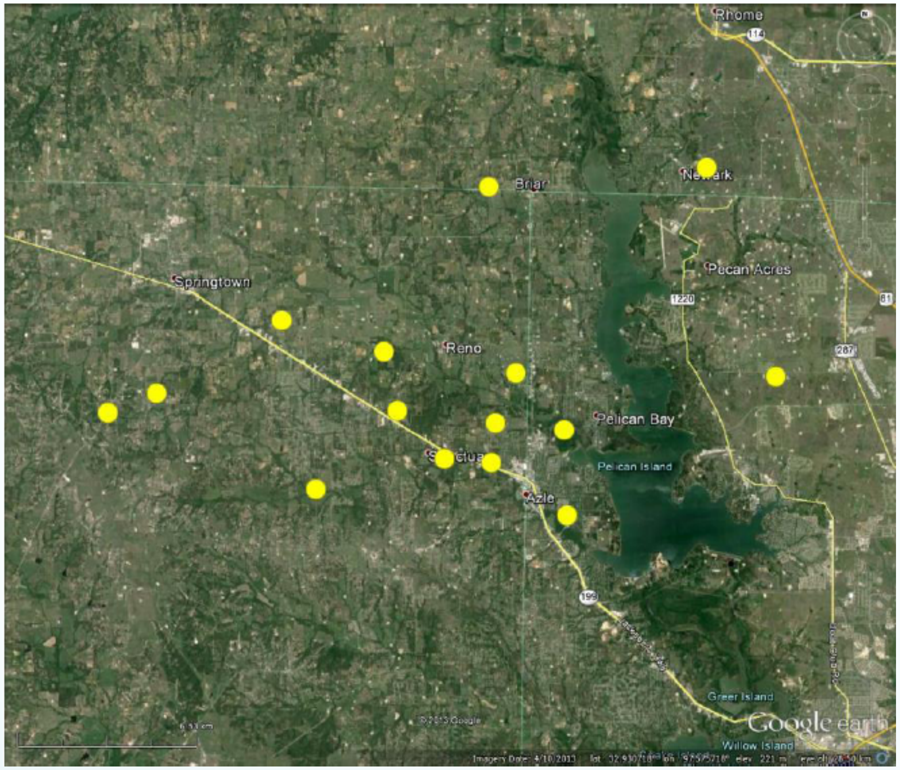


Figure 1. Earthquake epicenters determined by USGS-NEIC, November 1-26, 2013.

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