Induced Seismicity in Oil and Gas Operations: Recent Activity, Monitoring and Regulations*

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Search and Discovery Article #41701 (2015)**
Posted October 19, 2015

*Adapted from oral presentation given at AAPG Annual Convention & Exhibition, Denver, Colorado, May 31-June 3, 2015

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Abstract

In 2012 the National Research Council published a study "Induced Seismicity Potential in Energy Technologies"1 which reviewed the occurrence of earthquakes with various energy operations, including oil and gas waste water disposal and hydraulic fracturing. The report found only two documented examples of felt earthquakes related to hydraulic fracturing. Since the report was published, the rate of suspected induced earthquakes related to oil and gas operations has continued to rise. Hydraulic fracturing earthquakes in multiple areas of British Columbia, reported after the release of the NRC report, suggest in special cases that hydraulic fracturing is capable of producing earthquakes that can be felt on the surface. Additional reports and analysis of suspected induced earthquakes from both waste water injection wells and hydraulic fracturing operations have been reported in many states in the USA, including Kansas, Colorado, Texas, Ohio and in particular, Oklahoma, which has experienced a continued and dramatic rise in suspected induced earthquakes. This presentation will discuss recent occurrences of induced seismicity related to oil and gas operations and the seismic monitoring techniques used to understand the issue, along with new and proposed regulations suggested by authorities in the affected areas to ensure continued safe operations.

Selected References

McNamara, D.E., H.M. Benz, R.B. Herrmann, E.A. Bergman, P. Earle, A. Holland, R. Baldwin, and A. Gassner, 2015, Earthquake Hypocenters and Focal Mechanisms in Central Oklahoma Reveal a Complex System of Reactivated Subsurface Strike-Slip Faulting: Geophys. Res. Lett., v. 42, p. 2742-2749. doi: 10.1002/2014GL062730

Petersen, M.D., C.S. Mueller, M.P. Moschetti, S. Hoover, J.L. Rubinstein, W.L. Ellsworth, A. Holland, and J.G. Anderson, 2015, Incorporating Induced Seismicity in the 2014 United States National Seismic Hazard Models — Results of 2014 Workshop and Sensitivity Studies: U. S. Geological Survey Open-File Report 2015-1070, p. 69. doi.org/10.3133/ofr20151070.

Stein, S., and M. Wysession, 2003, An Introduction to Seismology, Earthquakes, and Earth Structure: Blackwell Publishing, Oxford, England, 498 p.

Websites Cited

http://stateimpact.npr.org/oklahoma/2015/03/25/regulators-issue-tougher-disposal-well-directives-as-oklahomas-quake-risk-rises/

https://apps.occeweb.com/RBDMSWeb_OK/OCCOGOnline.aspx

https://cogcc.state.co.us/Staff_Reports/2014/201407_StaffReport.pdf

http://oilandgas.ohiodnr.gov/portals/oilgas/pdf/seismicity/RECENT_EARTHQUAKE_EPICENTERS_IN_OHIO.pdf

http://earthquake.usgs.gov/hazards/products/conterminous/2014/HazardMap2014_lg.jpg

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Induced Seismicity in Oil and Gas Operations:

Recent Activity, Monitoring and Regulations

AAPG SESSION: What's Shakin'? Causes and Cures for Induced Seismicity (AAPG/DEG)
June 3, 2015
Denver, Colorado

Induced Seismicity Recent Headlines:

Okla. agency linked quakes to oil in 2010, but kept mum amid industry pressure

Mike Soraghan, E&E reporter

EnergyWire: Tuesday, March 3, 2015

Economy

Washington Post Jan 28 2015

Oklahoma worries over swarm of earthquakes and connection to oil industry

U.S. Maps Pinpoint Earthquakes Linked to Quest for Oil and Gas

New York Times April 23, 2015

Induced Seismicity Legal Issues Break New Ground

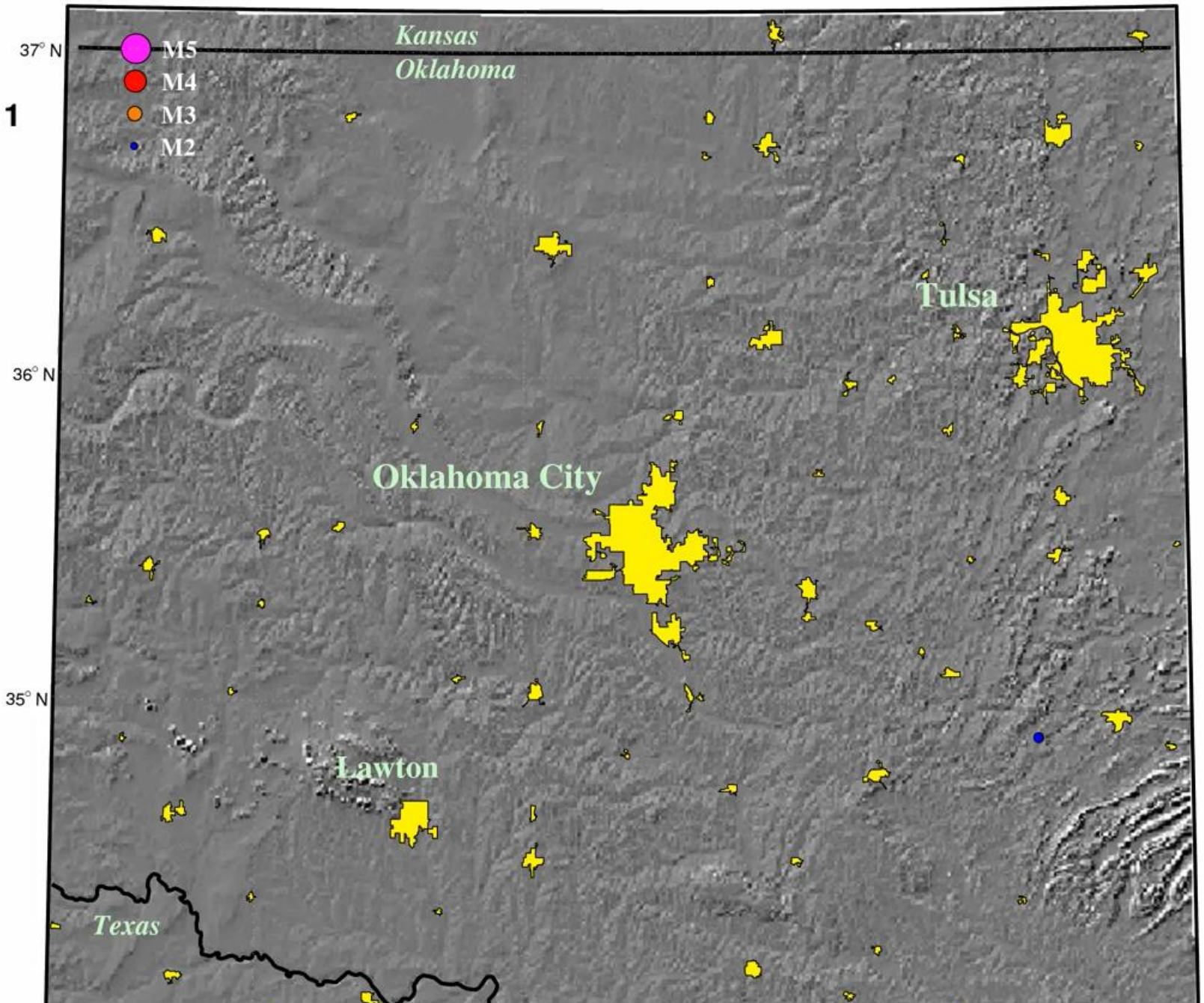
Law360 May 15,2015

http://stateimpact.npr.org/texas/tag/earthquake/

APRIL 29, 2015

Could Evidence of Manmade Quakes Bring Tectonic Shift in Texas Regulation?

Earthquakes from: 02–Jan–2008 to: 13–Apr–2015



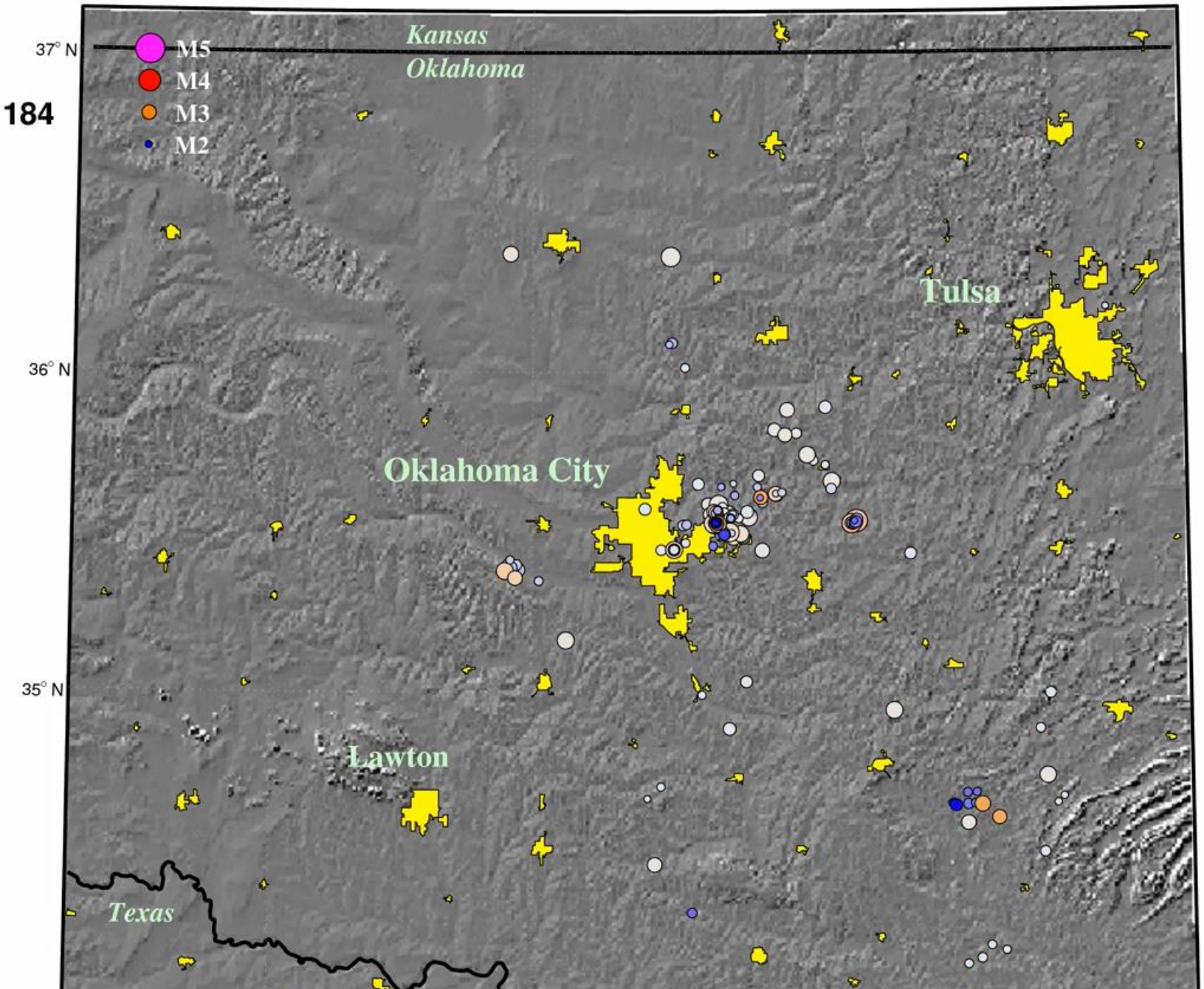
Earthquake Count: 1

Date: 02–Jan–2008

Earthquakes are from the Oklahoma Geological Survey website. Earthquakes displayed have a minimum magnitude of 2.0 and are complete above magnitude 3.0.

USGS
science for a changing world

Earthquakes from: 02–Jan–2008 to: 13–Apr–2015



Earthquake Count: 184

Date: 02–May–2010

Earthquakes are from the Oklahoma Geological Survey website. Earthquakes displayed have a minimum magnitude of 2.0 and are complete above magnitude 3.0.

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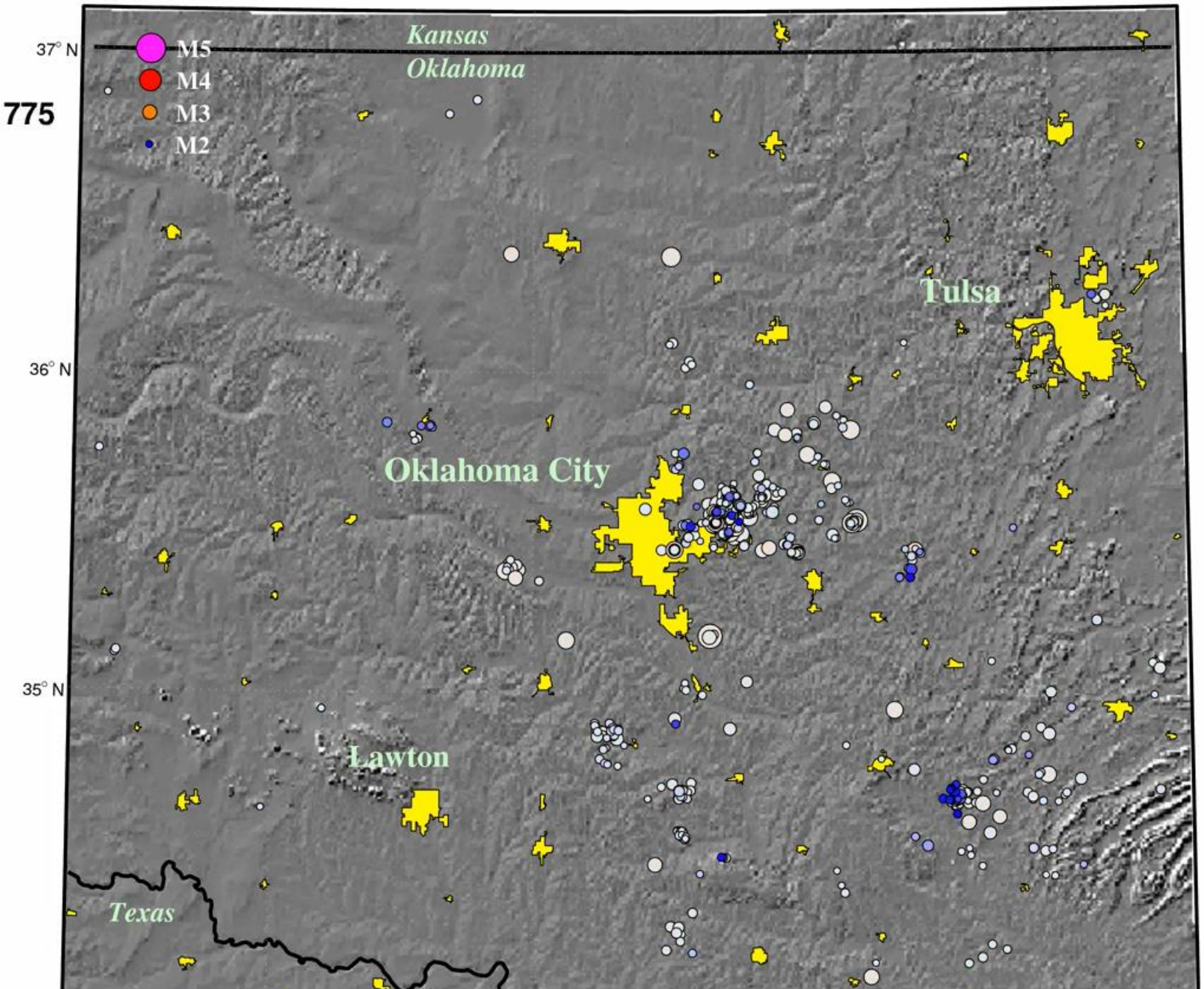
Earthquakes from: 02–Jan–2008 to: 13–Apr–2015



Earthquake Count: 775

Date: 01–Jul–2011

Earthquakes are from the Oklahoma Geological Survey website. Earthquakes displayed have a minimum magnitude of 2.0 and are complete above magnitude 3.0.

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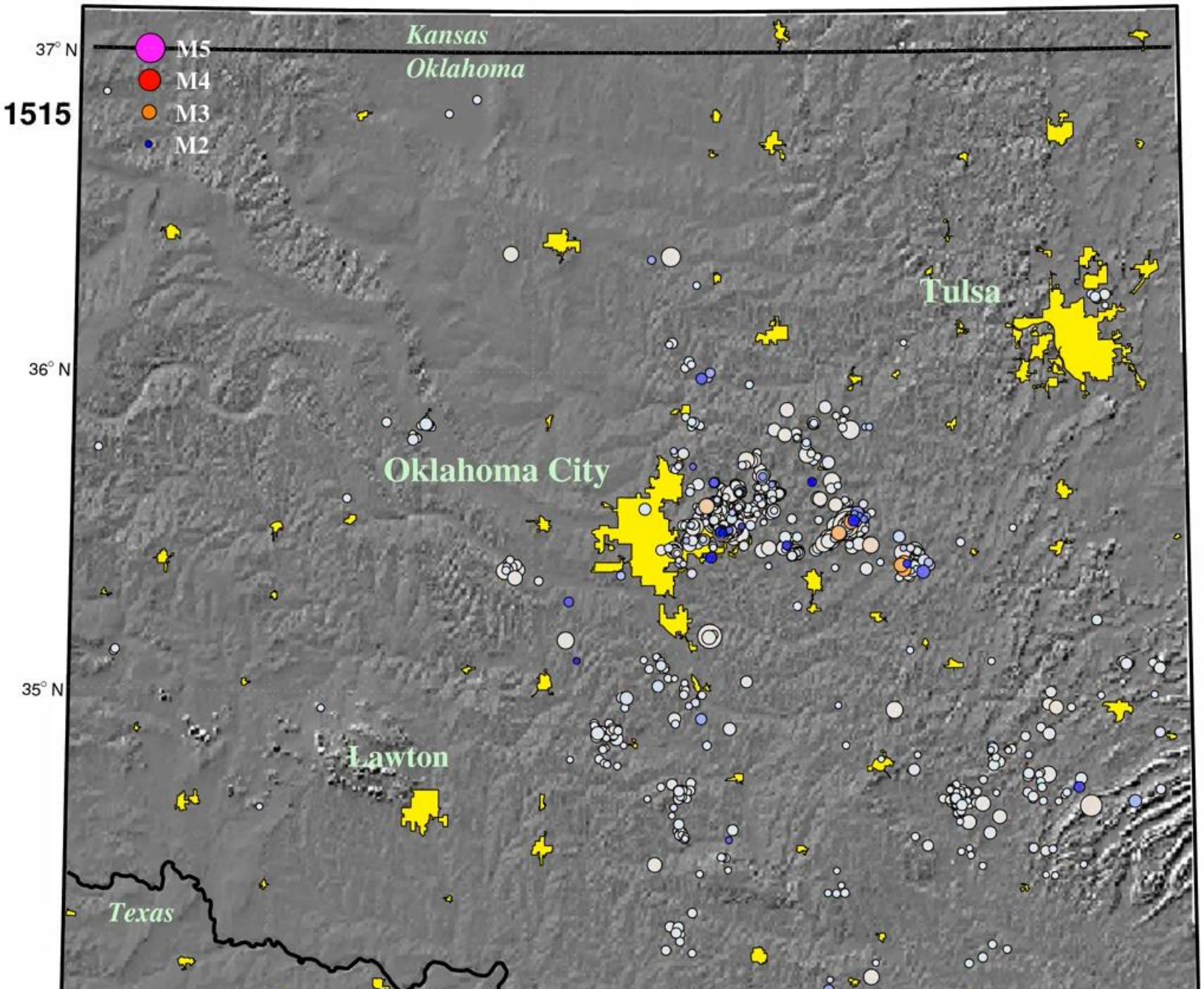
Earthquakes from: 02–Jan–2008 to: 13–Apr–2015



Earthquake Count: 1515

Date: 28–Aug–2012

Earthquakes are from the Oklahoma Geological Survey website. Earthquakes displayed have a minimum magnitude of 2.0 and are complete above magnitude 3.0.

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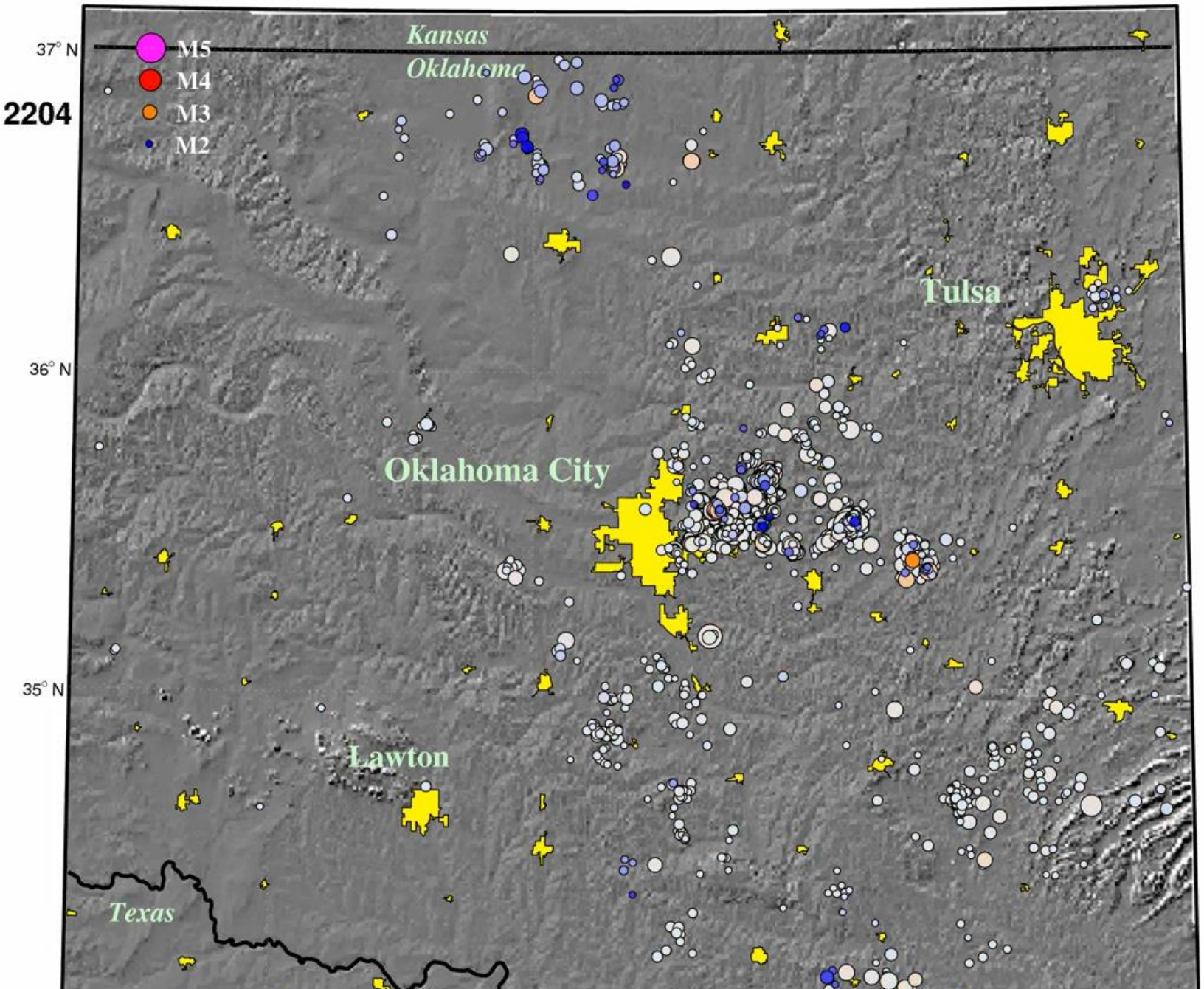
Earthquakes from: 02–Jan–2008 to: 13–Apr–2015



Earthquake Count: 2204

Date: 21–Sep–2013

Earthquakes are from the Oklahoma Geological Survey website. Earthquakes displayed have a minimum magnitude of 2.0 and are complete above magnitude 3.0.

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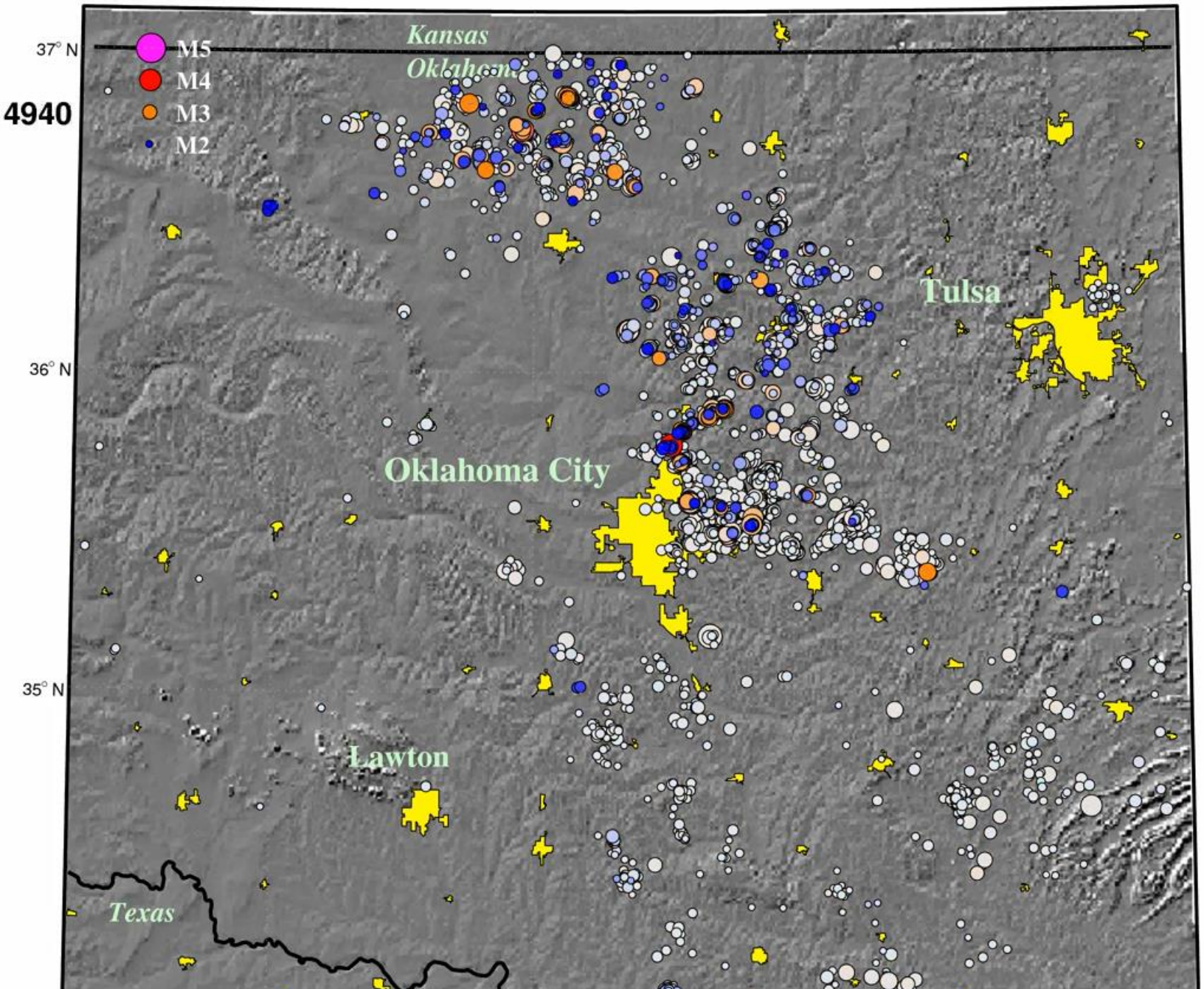
science for a changing world

Earthquakes from: 02–Jan–2008 to: 13–Apr–2015



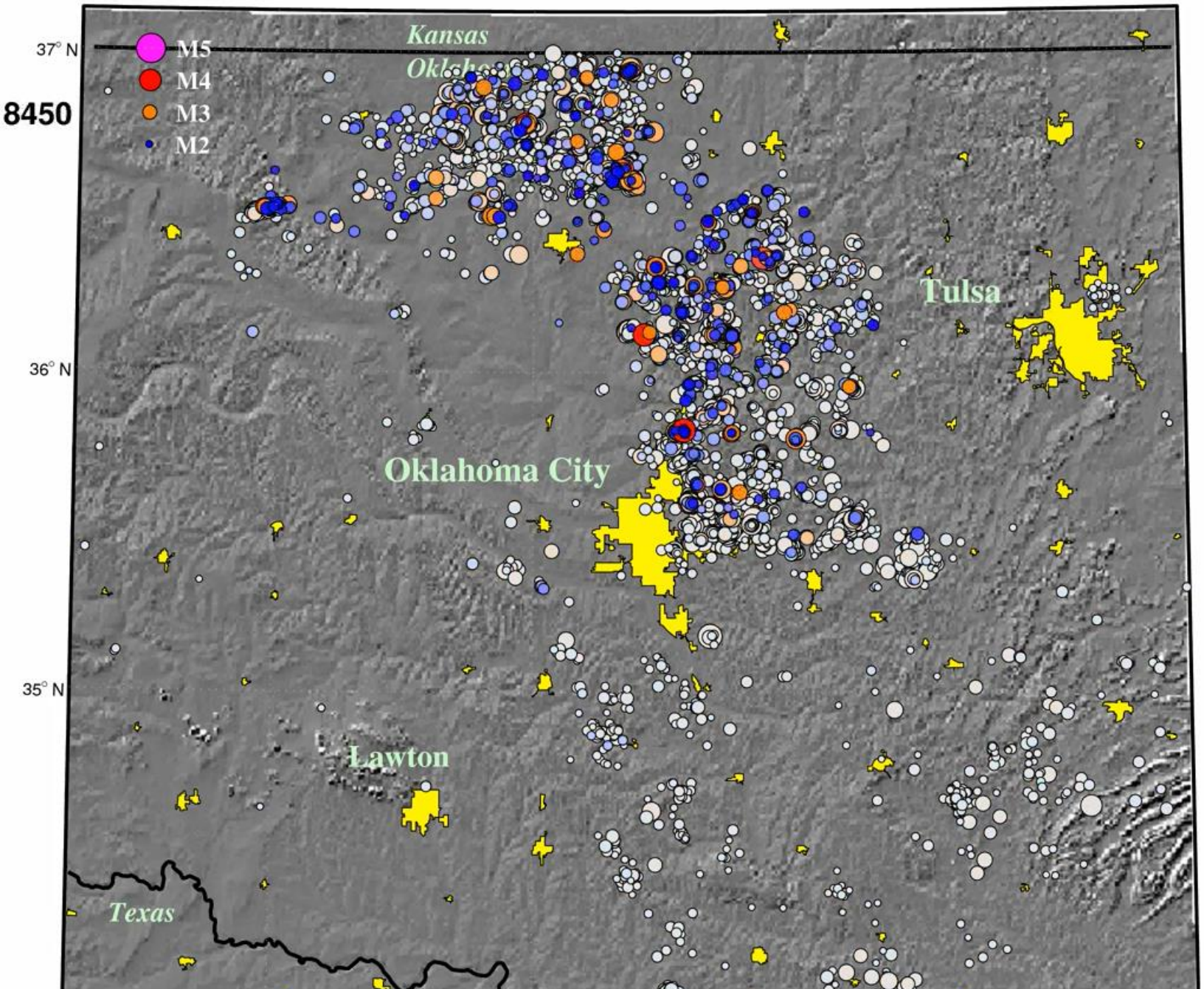
Earthquake Count: 4940

Date: 22–Aug–2014

Earthquakes are from the Oklahoma Geological Survey website. Earthquakes displayed have a minimum magnitude of 2.0 and are complete above magnitude 3.0.

USGS
science for a changing world

Earthquakes from: 02–Jan–2008 to: 13–Apr–2015



Earthquake Count: 8450

Date: 11–Apr–2015

Earthquakes are from the Oklahoma Geological Survey website. Earthquakes displayed have a minimum magnitude of 2.0 and are complete above magnitude 3.0.

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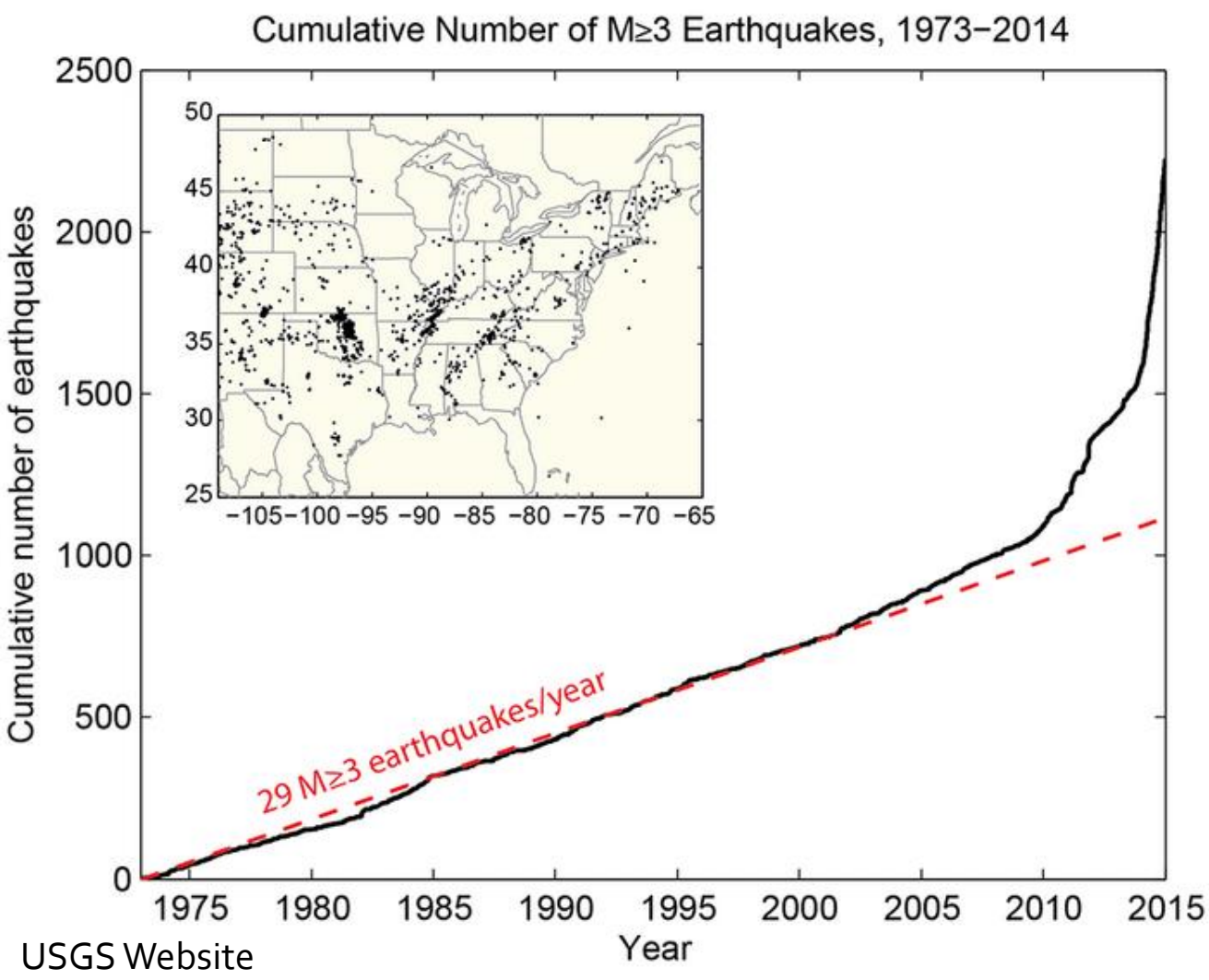
The bumpy road

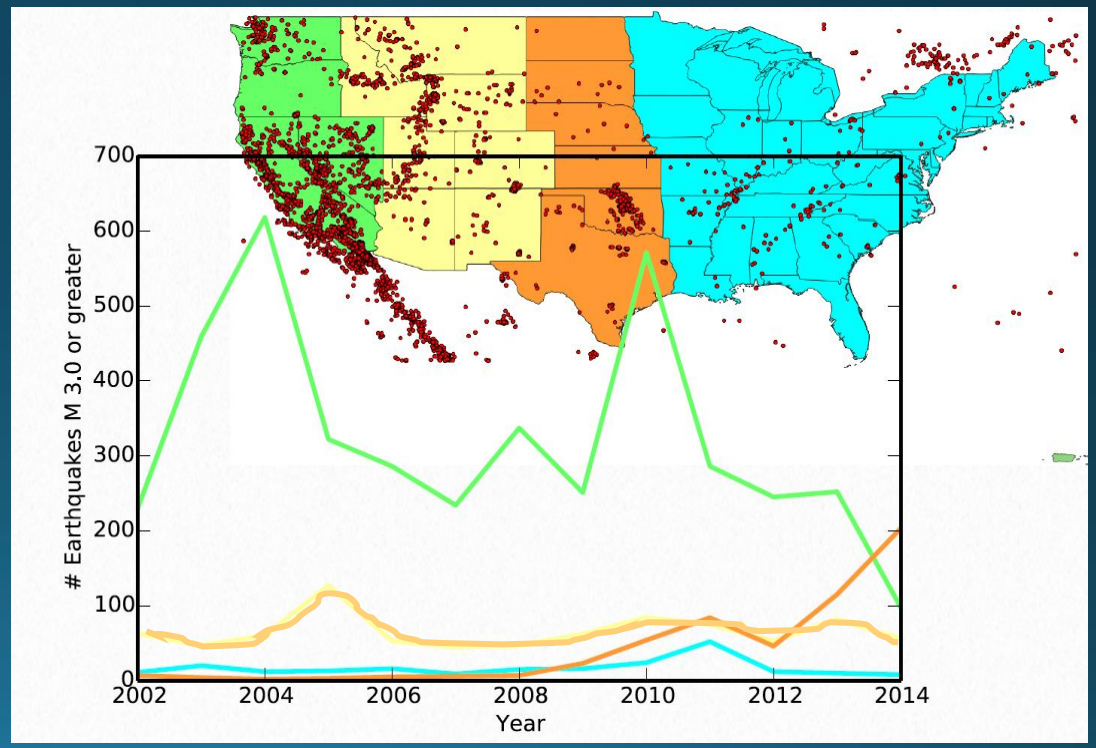
- Why so much attention right now?
- Earthquake Size
- Areas of concern from disposal and frac wells
  - Regulation response
- EQ Hazards from induced seismicity?

Why the fuss?

Rate of earthquakes have increased in central and eastern US



USGS Website



Courtesy Amberlee Darold, OGS

Earthquake Size

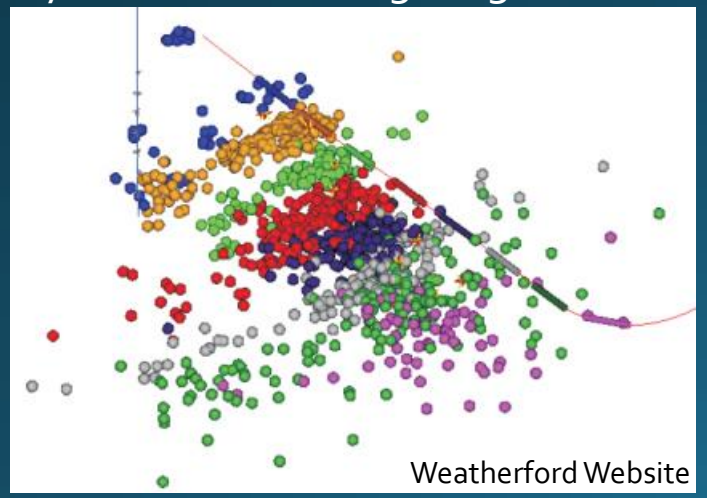
The size of an earthquake depends the area of the break, amount of slip and the properties of the rock.

Dimensions:

Length: Microscopic - hundreds-to-thousands of kilometers long
Depth: microscopic to tens of kilometers.
Displacement: millimeters to meters.

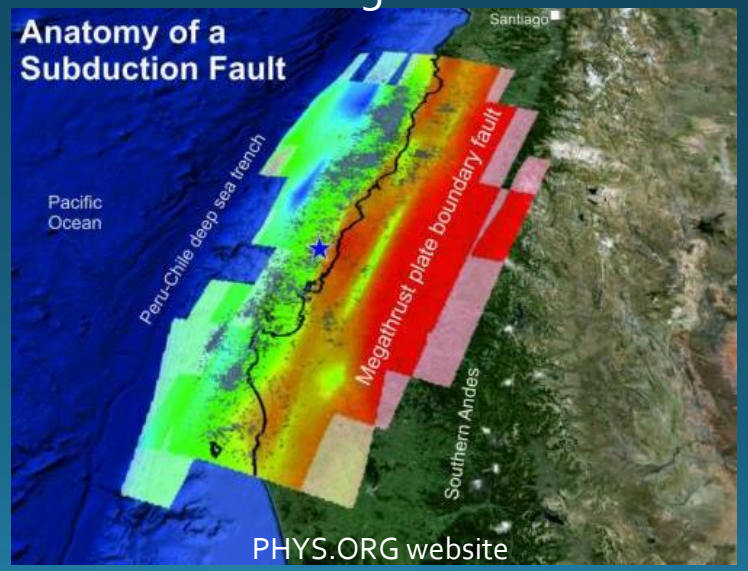
We have the ability to measure earthquakes from lab studies on core to very large earthquakes.

Hydraulic Fracturing Magnitude -1



Weatherford Website

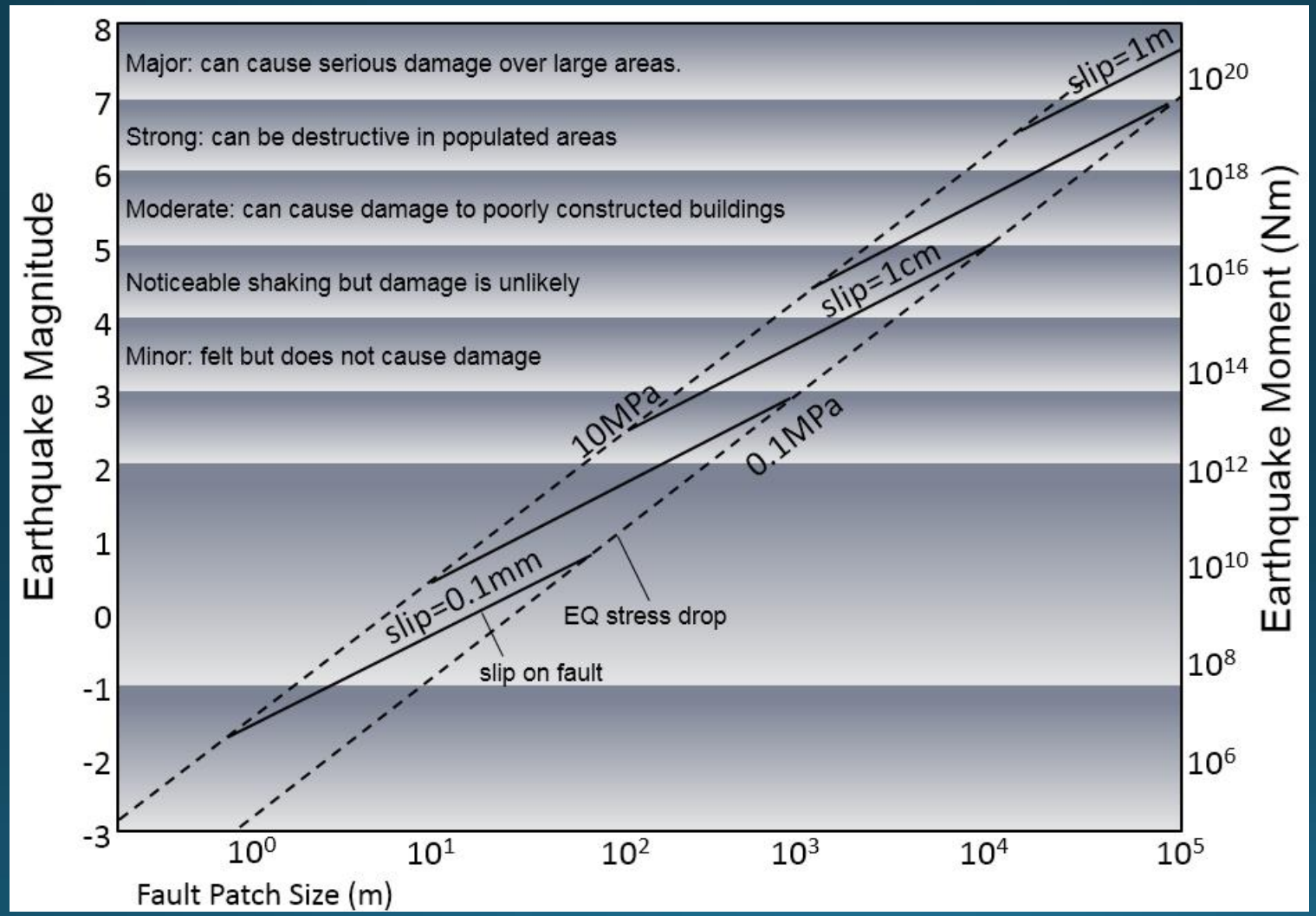
Chile 2011 Magnitude 8.8



PHYS.ORG website

Earthquake size related to fault size and slip

Felt earthquakes



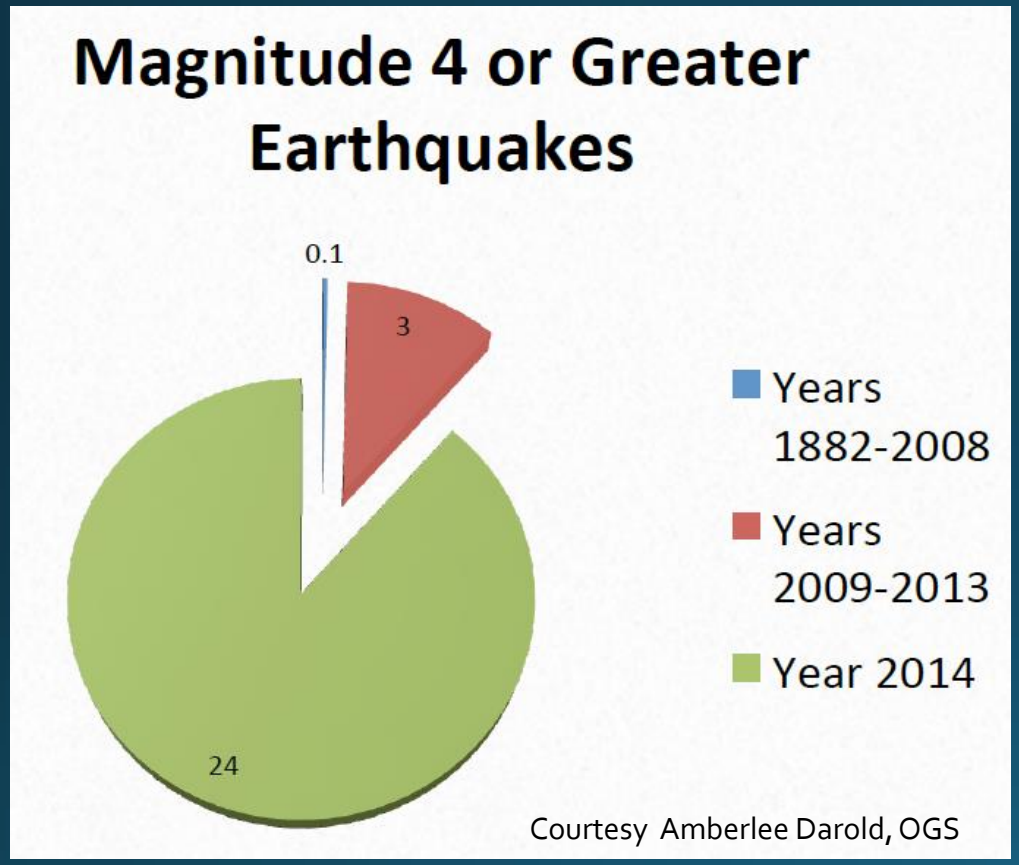
PRAUGE, OK

Typical frac monitoring event

1 MPa = 145 PSI

Courtesy of M. Zoback, based on Stein and Wysession, 2003

Oklahoma



Courtesy Amberlee Darold, OGS

Oklahoma Geological Survey

Statement on Oklahoma Seismicity: April 21, 2015

"…the rates and trends in seismicity are very unlikely to represent a naturally occurring process".

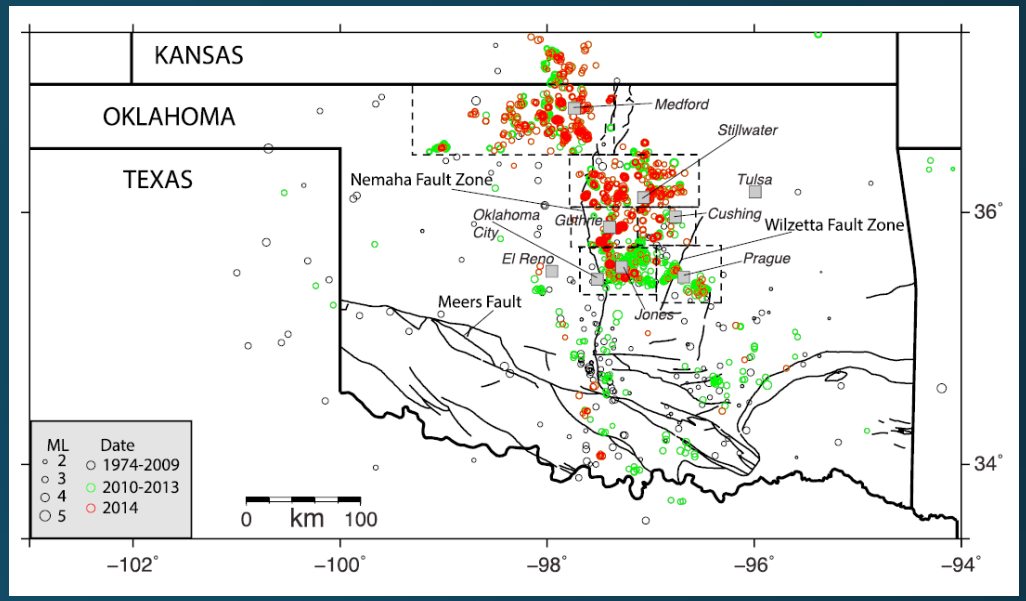
"…it very likely that the majority of recent earthquakes, particularly those in central and north-central Oklahoma, are triggered by the injection of produced water in disposal wells"

"The seismicity rate is now about 600 times greater than the background seismicity rate"

"…reactivation of deeper basement faults from water injection/disposal at shallower depths is often observed in cases of triggered seismicity".

Oklahoma

- **Earthquakes occurring on vertical optimally oriented (NE-SW and NW-SE) strike slip faults in the shallow crystalline basement.**
- Regional compressive stress direction is N85E.
  - Majority of faults are oriented favorably for slip.
  - Faults are up to 10 km (6 mi) long
- Largest events M 4.8, 5.6 and 4.8 in November 2011 near Prague, OK.
- Events on reactivated ancient faults (Pennsylvanian period) at shallow depths (<6 km).
- The faults cut through Arbuckle Group and extend into basement rocks.



Toppled chimney from Prague EQ

McNamara, D. E., H. M. Benz, R. B. Herrmann, E. A. Bergman, P. Earle, A. Holland, R. Baldwin, and A. Gassner (2015), Geophys. Res. Lett., 42.

New Regulations

Oklahoma Corporate Commission Regulation on Injection Wells

- March 2015 Letters to operators within 6 km of seismic activity in OCC "AREAS OF INTEREST"
  - Must prove well is not in communication with basement rocks
  - Plug back wells
  - Non compliance volumes cut by 50%.

RE: Wells located within Areas Of Interest for Induced Seismicity

Your company has been identified as operating one or more Arbuckle disposal well(s) located within one or more of the Oil and Gas Conservation Division's (OGCD) Areas Of Interest for induced seismicity. A map of the Areas Of Interest is available at www.occeweb.com under "Hot Topics."

As part of the continued evolution of the OGCD's "traffic light" system in regards to induced seismicity, delineation of **Areas Of Interest** now includes "**seismic swarms**."

a. "Swarm" is defined as an area consisting of at least two (2) events with epicenters within .25 miles of one another, with at least one (1) event with a magnitude 3.0 or higher.
b. Area Of Interest is a ten (10) kilometers area (approximately six miles) with the central mass of the swarm serving as the area center.

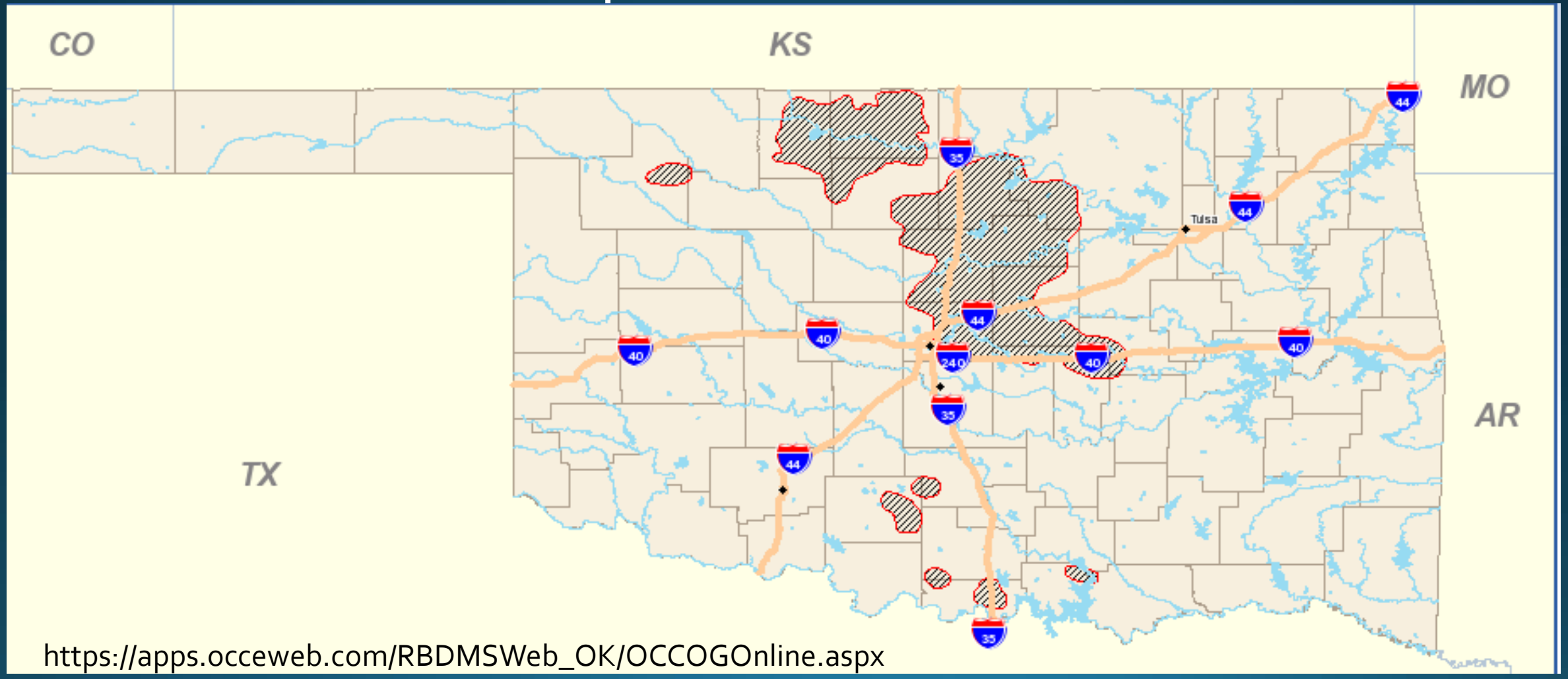
As you are aware, Oklahoma has experienced a dramatic increase in the number of earthquakes over the past few years. There is general agreement among seismologists that fluid disposal into or in communication with the crystalline basement rock presents a potential risk for induced seismicity. As part of the effort to reduce this risk, the OGCD is directing you establish that your well(s) listed on the attached page are not disposing into or in communication with the crystalline basement rock. Wells disposing into the Reagan Sand or Granite Wash are considered to be in communication with the crystalline basement rock. All wells found to be in contact or communication with the crystalline basement rock must be plugged back. To be in compliance with this directive, the following criteria have been established:

A. The following criteria have been established as sufficient information to satisfy the OGCD that a well is not in contact or communication with the crystalline basement rock:
   1) Driller's logs, gamma ray logs, and formation evaluation logs.
   2) If logs need to be run, a gamma ray log to total depth will be acceptable.
   3) Additional evaluation processes are possible, but must be approved by OGCD.

SERVICE • ASSISTANCE • COMPLIANCE
EXCELLENCE IS OUR STANDARD

http://stateimpact.npr.org/oklahoma/2015/03/25/regulators-issue-tougher-disposal-well-directives-as-oklahomas-quake-risk-rises/

Oklahoma Corporate Commission
Area of interest map



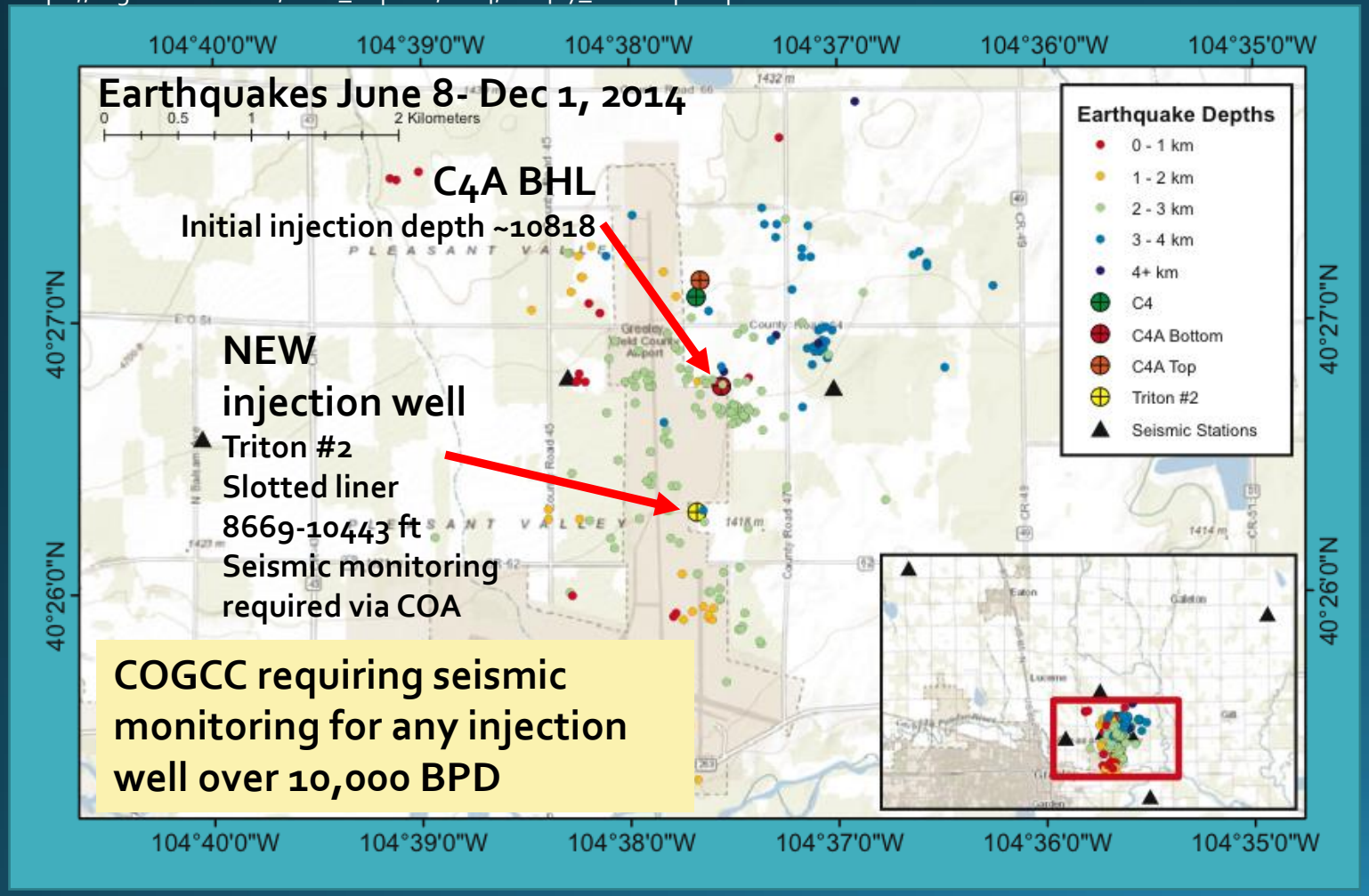
https://apps.occeweb.com/RBDMSWeb_OK/OCCOGOnline.aspx

Greeley, CO Earthquake

May 31, 2014 (MDT) Magnitude 3.4
260 felt reports Felt 60 miles from epicenter

Ellsworth, S., Eisinger, C., Morgan, M., Sheehan, A., 2015. Case study on Induced Seismicity - Greely, CO. Ground Water Protection Council, Document on Induced Seismicity, draft document.

https://cogcc.state.co.us/Staff_Reports/2014/201407_StaffReport.pdf



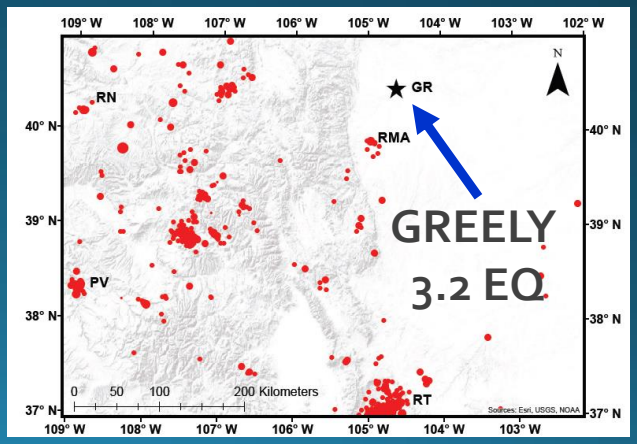
Seismic monitoring initiated by CU Boulder (Anne Sheehan and others).

Located near SWD C4A well in Lyon and Fountain formation, 500 ft above basement rock.

C4A Injection started April 2013, increased in August 2013.

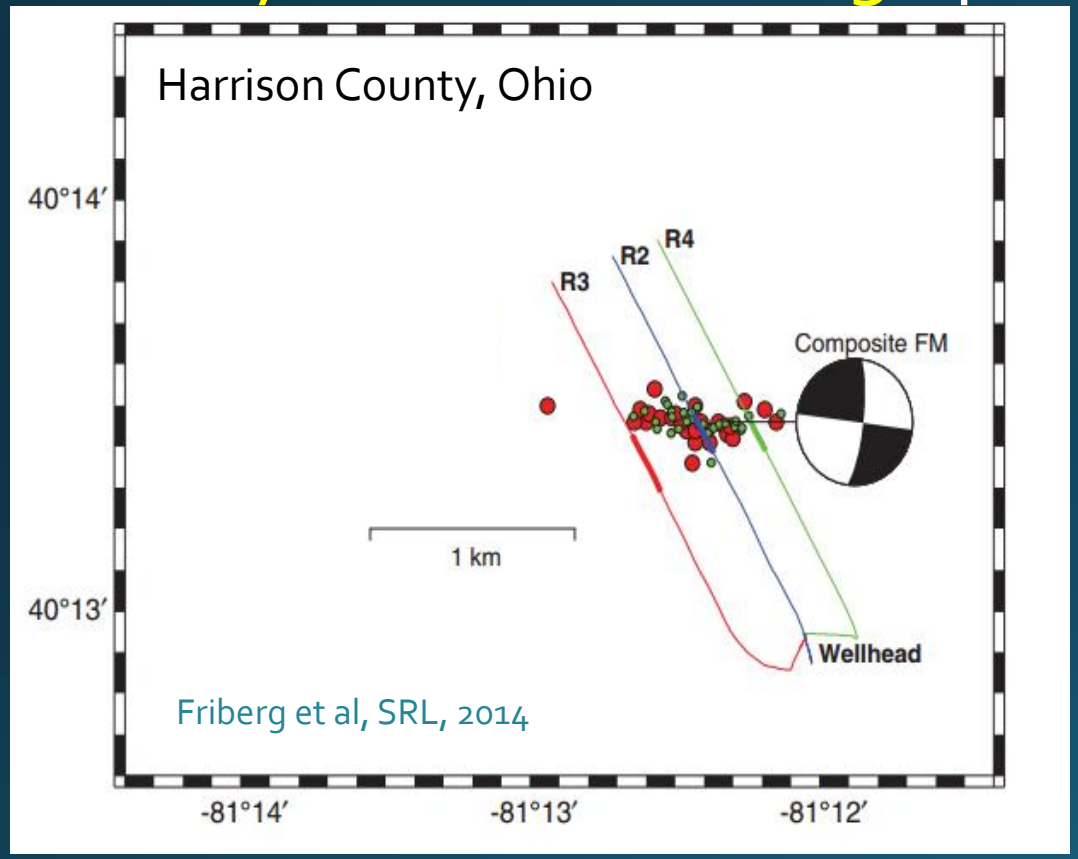
SWD shut in on June 23, 2014 and cemented back 458 feet. Injection restarted July 2014.

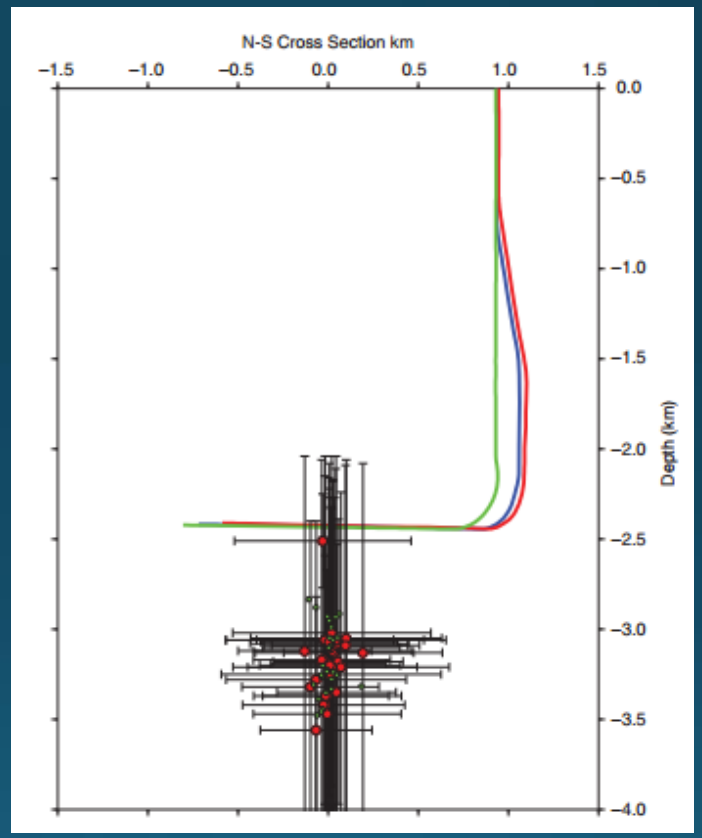
COGCC used a Seismic monitoring protocol:
No M 2.5 within 2.5 miles of well.



Ohio Earthquakes in the Utica Shale

near hydraulic fracturing operations



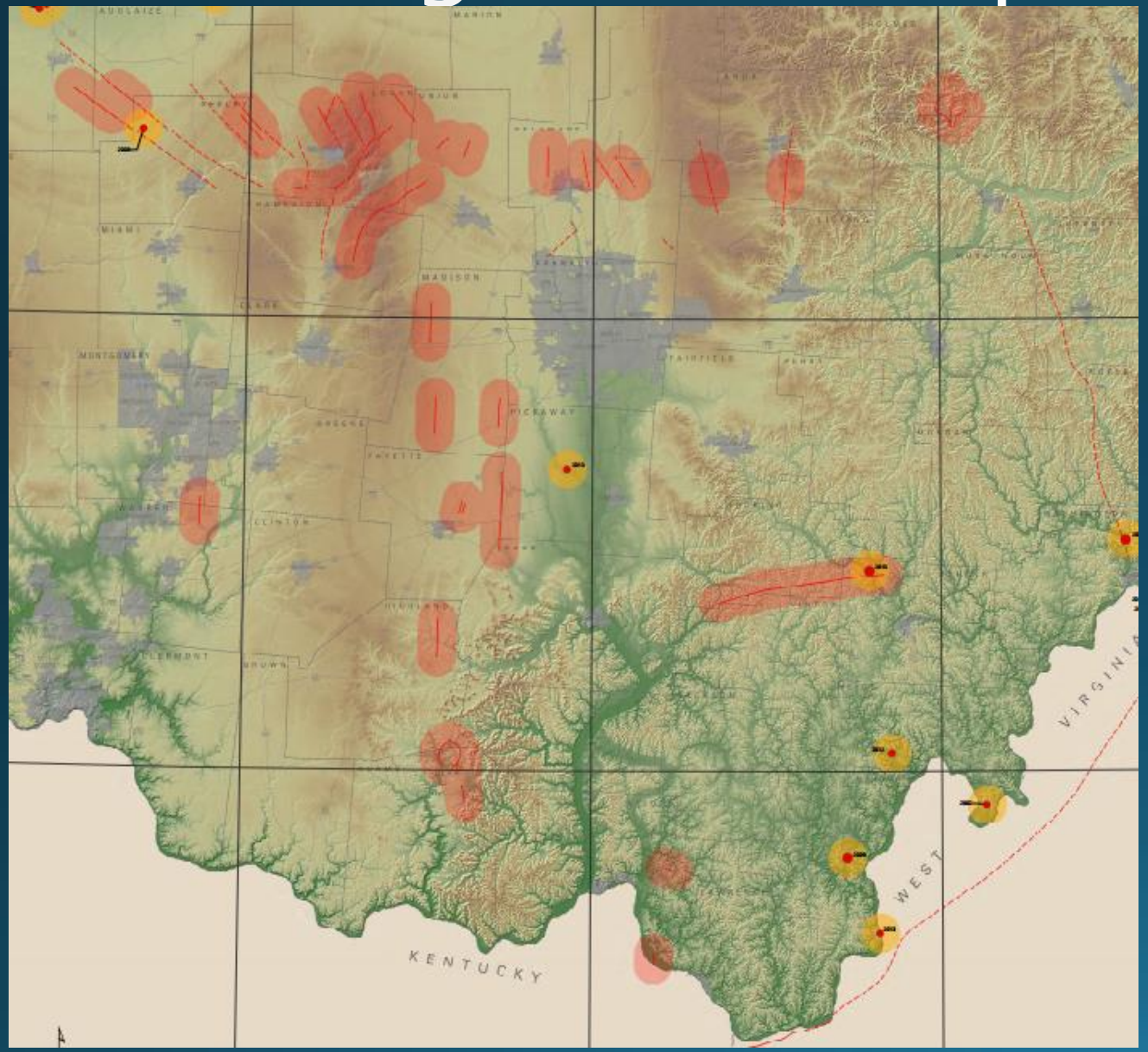


Earthquake activity occurred on pre-existing fault in the basement rocks below the fracturing interval.

Table courtesy Steven Dade, ONDR

Hydraulic Fracturing Events	Date	Magnitude	Felt (Y/N)
Harrison County, Ohio	October 2, 2013	2.0	N
Poland Township, Mahoning County, Ohio	March 10, 2014	3.0	Y

Ohio Regulation Response



EXPLANATION

Earthquake Epicenter - 3 mile buffer

Known Fault - 3 mile buffer

Magnitude	Instrumental event
2.0–2.9	
3.0–3.9	
4.0–4.9	
5.0–5.4	

Faults

Known

Inferred

ODNR Map of buffer zones for hydraulic fracturing operations

http://oilandgas.ohiodnr.gov/portals/oilgas/pdf/seismicity/RECENT_EARTHQUAKE_EPICENTERS_IN_OHIO.pdf

Ohio permitting changes related to hydraulic fracturing

Horizontal drilling within 3 miles of a known fault or area of seismic activity greater than a 2.0 magnitude would require companies to install sensitive seismic monitors.

If those monitors detect a seismic event in excess of 1.0 magnitude, activities would pause while the cause is investigated.

If the investigation reveals a probable connection to the hydraulic fracturing process, all well completion operations will be suspended.

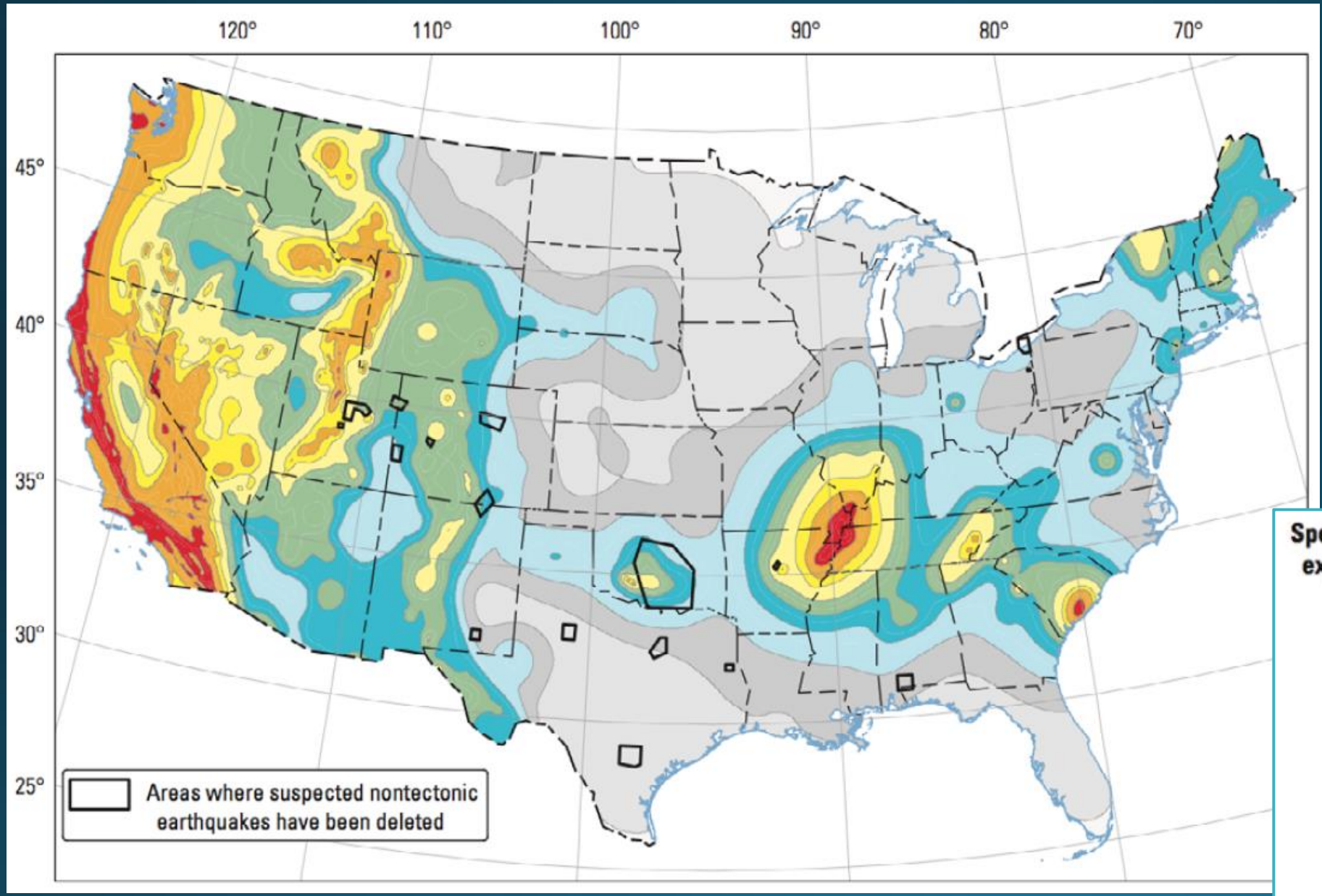
Industry Response

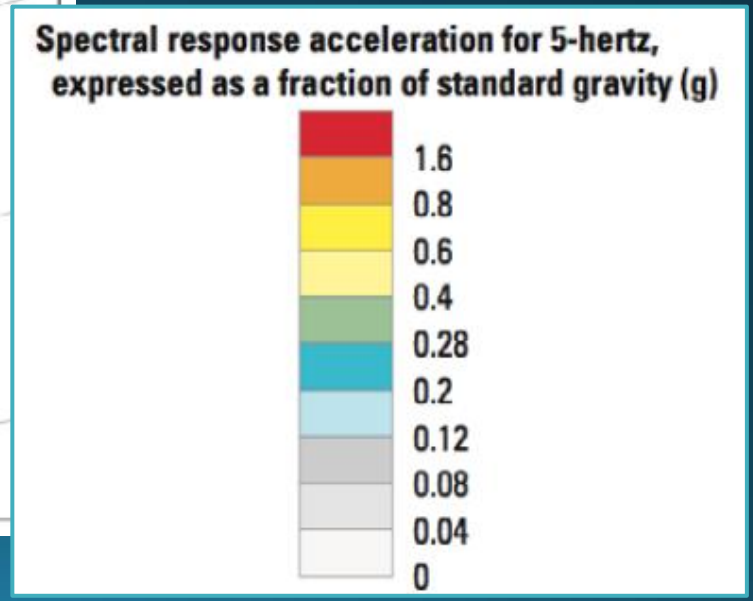
Ohio Oil and Gas Association (OOGA) established an Induced Seismicity Workgroup to recommend possible alternative permit conditions based on **ground motion** similar to Ohio mining regulations.

2014 USGS Seismic Hazard Map

5 Hz spectral acceleration map

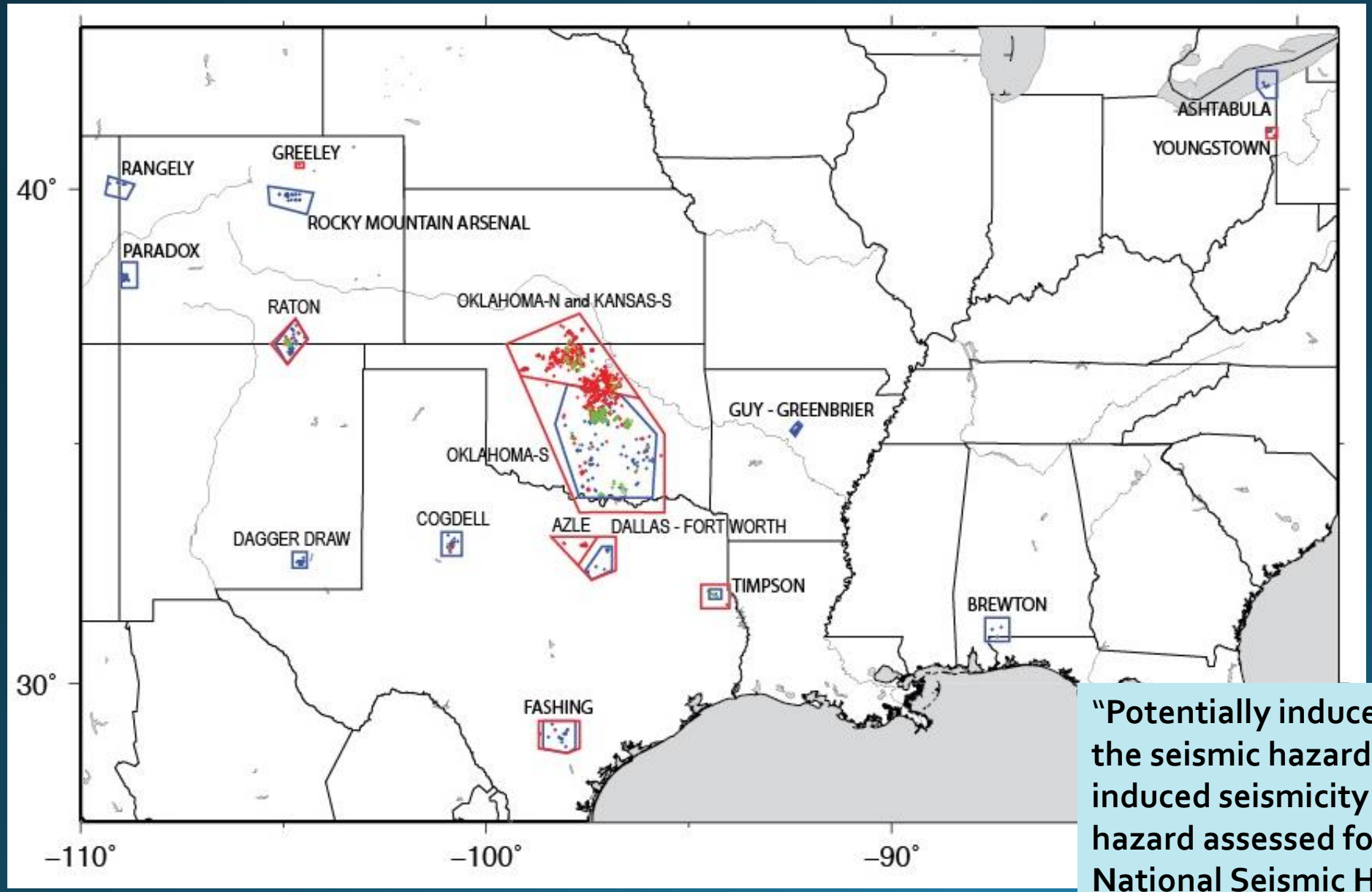
2% probability of exceedance in 50 years





http://earthquake.usgs.gov/hazards/products/conterminous/2014/HazardMap2014_lg.jpg

Petersen and others, U.S. Geological Survey Open-File Report 2015–1070



Potentially induced earthquakes removed from the USGS earthquake catalog before hazard assessment.

"Potentially induced seismicity greatly increases the seismic hazard in Oklahoma and in the other induced seismicity zones compared to seismic hazard assessed for the 2014 update of the National Seismic Hazard Model"

Final Comments

- Majority of wells with no problem
- Identified areas that may be of concern
- What is holding back the science?
  - Poor access to injection well data: rates, volumes, pressures.
  - High-quality earthquake seismic recordings
    - Current networks are designed to detect and locate M>4 earthquakes.
    - Current activity is not in historically seismic areas.
  - Information about local geology: faults, rock properties, earth stresses
  - Industry disinclination to share information or publish in peer-reviewed journals on the topic.

Thank you

AAPG
OGS, OOGA, USGS, BC Oil and Gas, ODNR
Anne Sheehan, CU Boulder
Stuart Ellsworth, COGCC

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