Recent Earthquakes in Oklahoma and the Mid-Continent: Significance and Potential for Induced Seismicity*

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Abstract

Currently Oklahoma and the Mid-Continent are experiencing more magnitude three and greater earthquakes than the tectonically active western United States. While few of these earthquakes have been damaging or strong, these earthquakes raise many concerns from earthquake seismologists to local residents. The significance of the rate increase is discussed, including the increased earthquake hazard associated with the rates of observed seismicity. While there are now documented cases of felt earthquakes triggered by hydraulic fracturing, most seismologists agree that wastewater disposal through injection poses the greatest chance of generating significant seismicity. At the present, it is unclear why Oklahoma has experienced the greatest increase in earthquake rates in the Mid-Continent. Throughout the Mid-Continent a number of potential cases of induced seismicity from disposal wells exist. These cases are summarized, and then we look at the challenges in identifying induced seismicity in areas of the Mid-Continent. Some of these challenges include the significant number of disposal wells operating within the region, a lack of geotechnical data on these wells, and the long history of such operations. The physics of induced seismicity are well understood, but the properties that can help control when and where this occurs are not. With modest amounts of data we may able to change this dynamic.

References Cited

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Website

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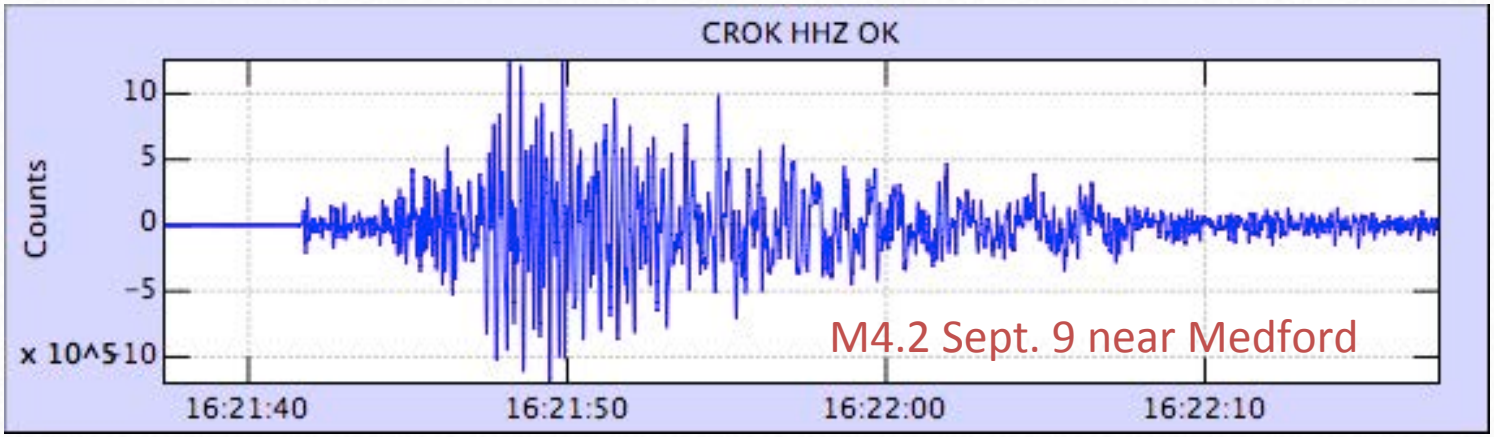
Austin Holland

Oklahoma State Seismologist

Outline

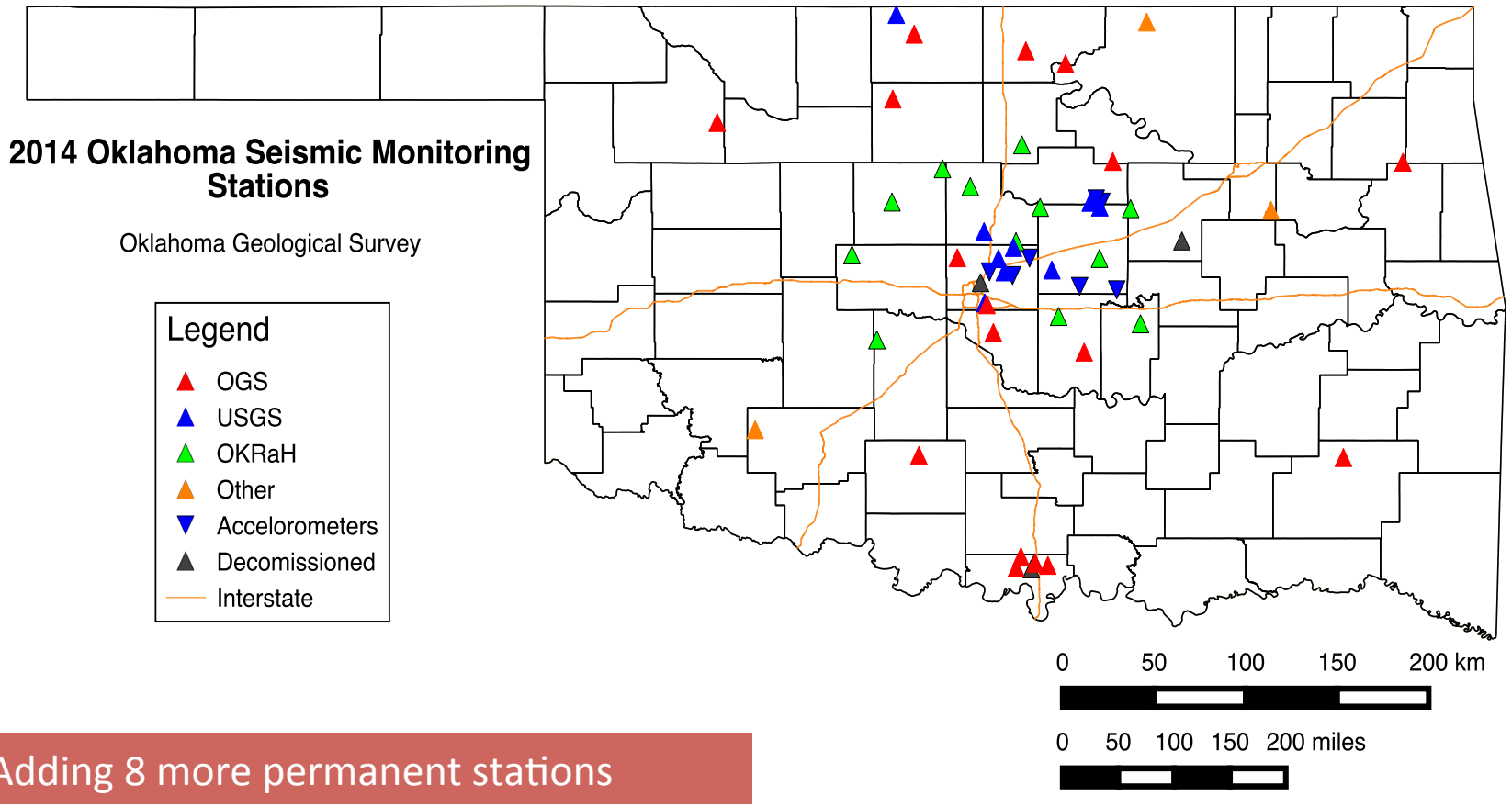
- Oklahoma Seismic Monitoring Program
  - Accurately document earthquakes occurring in Oklahoma
- Seismicity Rates in Mid-continent and Oklahoma
  - Last year recorded more than 100 years of “normal” Oklahoma seismicity in 1 year
  - Implications of these seismicity rates
- Potential for Induced Seismicity
- Case Examples from the Mid-continent/ Oklahoma
- Moving Forward



OGS Seismic Monitoring Program

- The OGS operates a network of seismic stations that began operating in 1978. A station was operating near Tulsa in 1962.
- All of our raw data is collected and archived. It is also shared in real-time with the USGS or vice-versa and then archived at an international data management center such that it is publicly available to all researchers.
- Seismologists and trained analysts process earthquake data manually. We do not have the computer automatically calculate an earthquake location, time, and magnitude.
- Our website provides earthquake catalogs, recent earthquake lists and maps as well as our research results and educational materials. These resources are provided to the Corporation Commission, other researchers and the general public.

Oklahoma Seismic Network

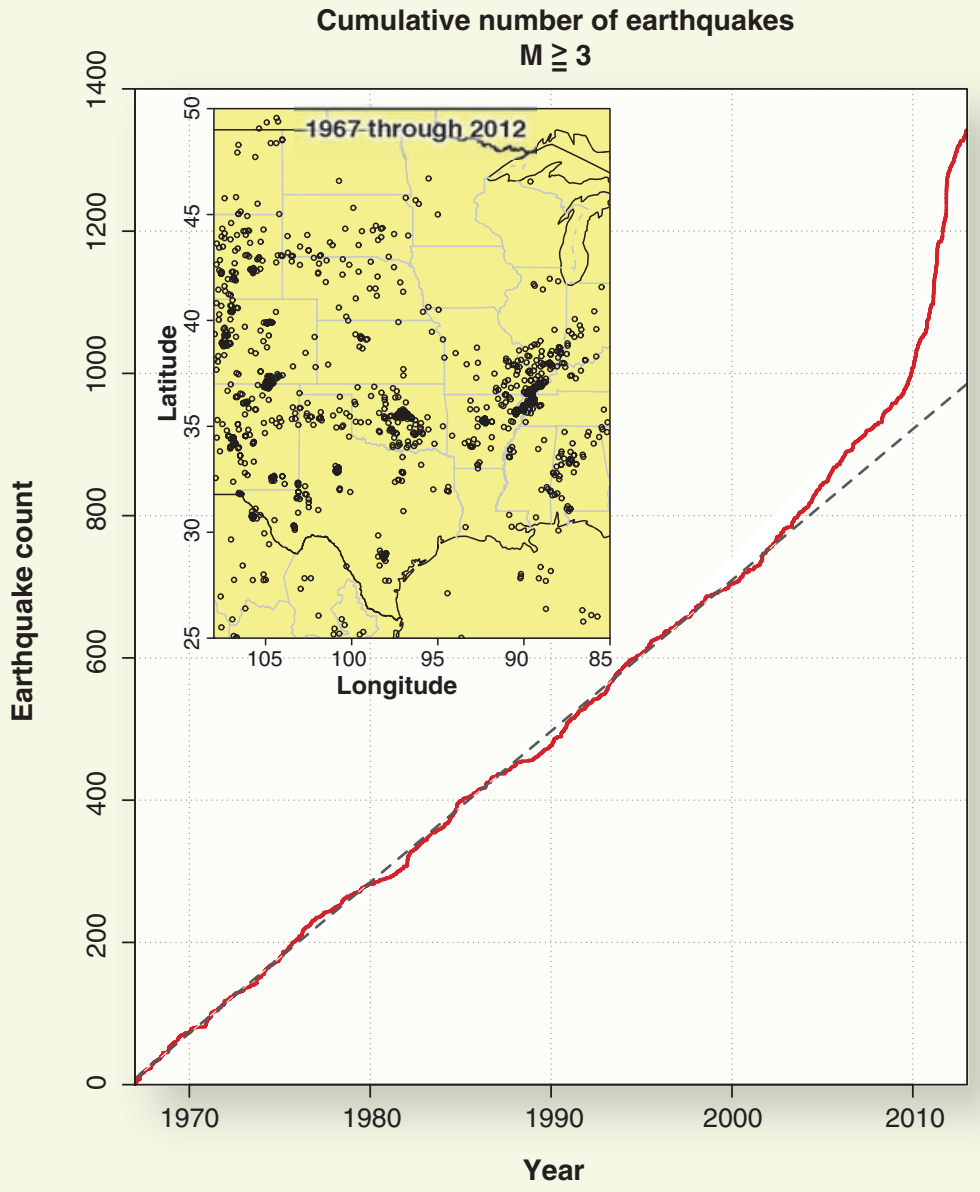


Adding 8 more permanent stations

OGS Seismic Monitoring Response to Increase in Earthquakes

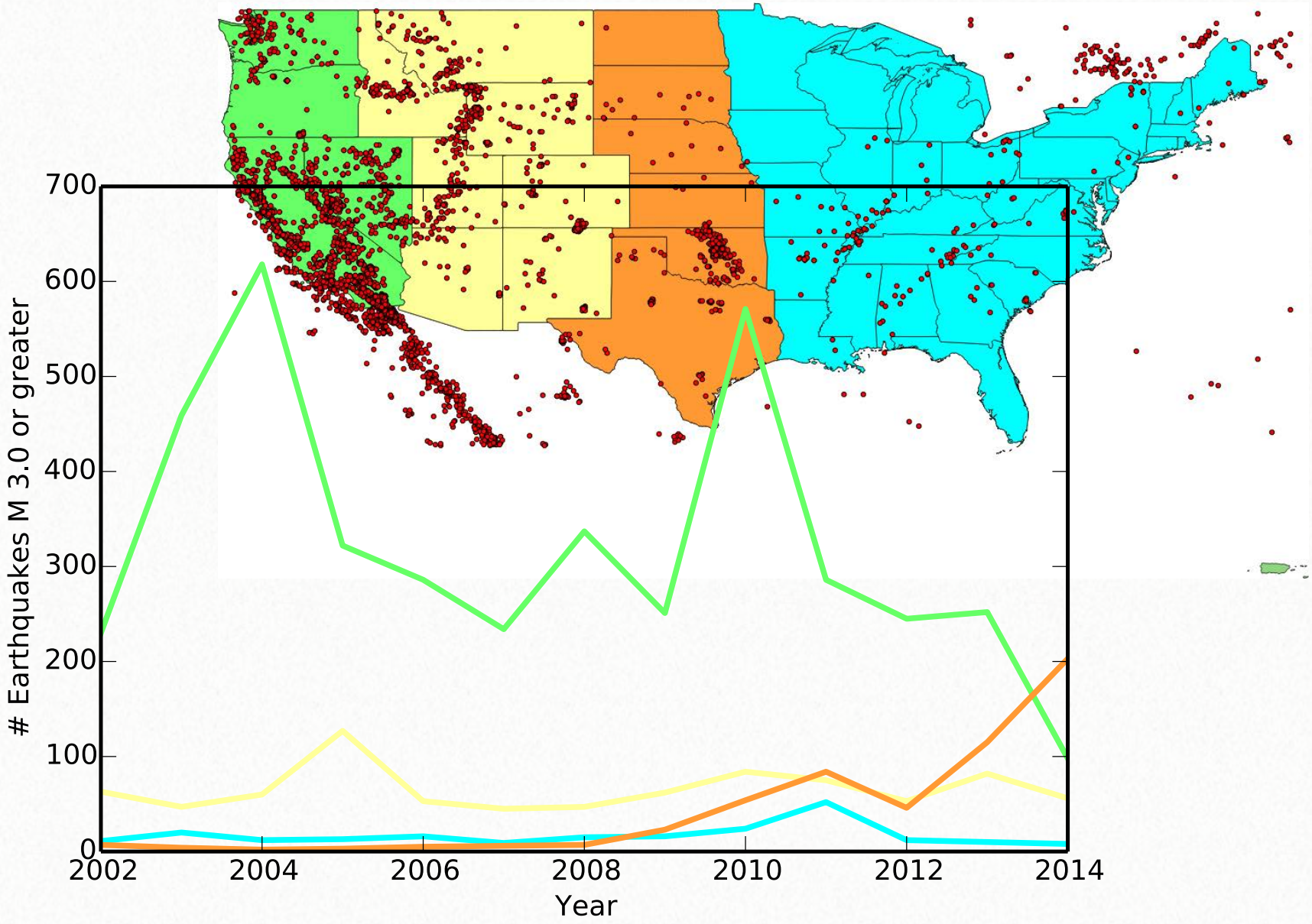
- Operating a temporary seismic station in Grant County and intend to move one to Alfalfa County as well
- Operating 16 temporary stations within Oklahoma (about to be 18)
- Adding 8 more permanent stations to the OGS regional network. (Funding provided from the OCC and Secretary of Energy and Environments office)
- Co-operating 5 USGS temporary stations provided installation and batteries
- Operating 6 USGS accelerometer stations
- Supporting more than three times as many stations than in 2009

Earthquake Rates for the Central and Eastern US



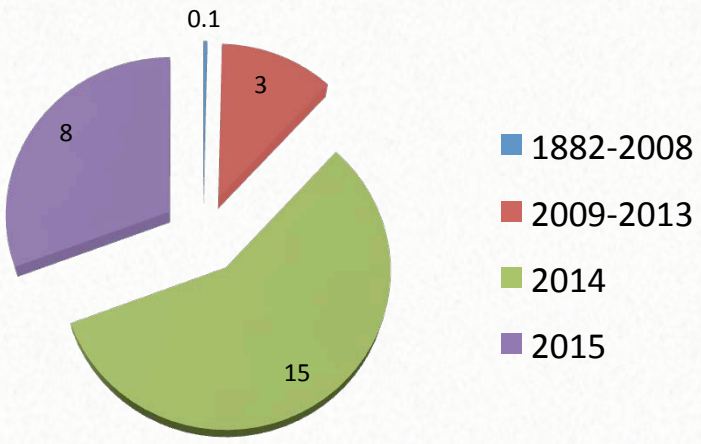
Ellsworth (Science, 2013)

ANSS Earthquakes by Region

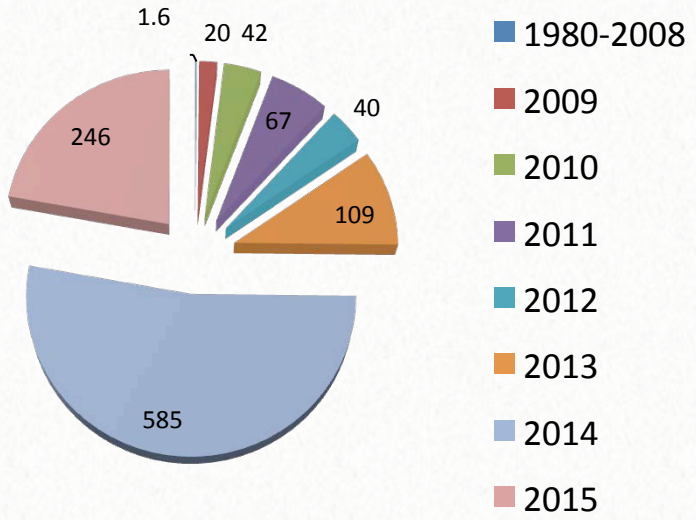


Oklahoma's Increase in Earthquakes
Number Earthquakes per Year

Magnitude 4 or Greater Earthquakes



Magnitude 3 or Greater Earthquakes



Increased Seismic Hazard

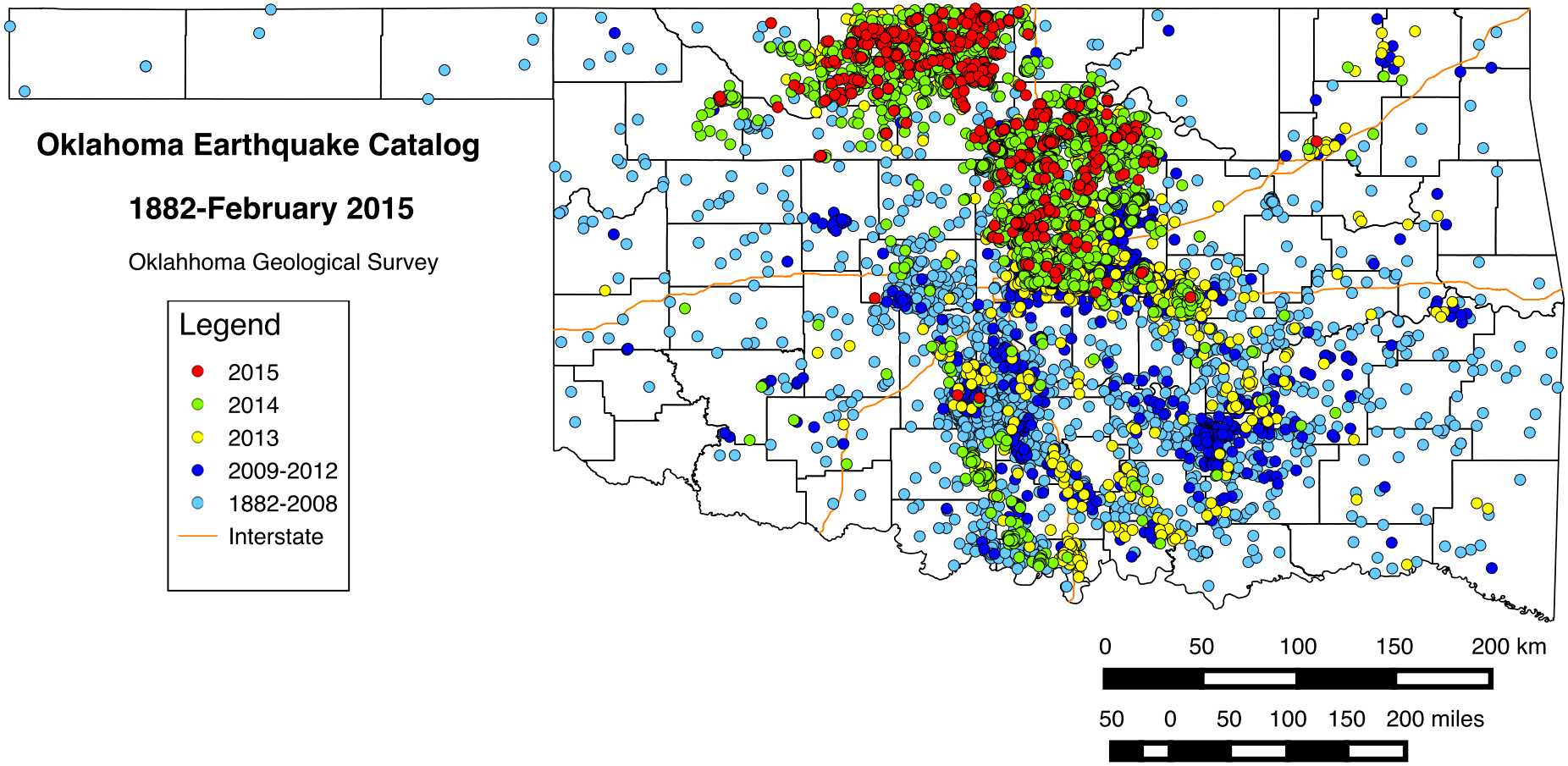
Record Number of Oklahoma Tremors Raises Possibility of Damaging Earthquakes

USGS/OGS Joint Press Release: 5/5/2014 11:30:00 AM

> "As a result of the increased number of small and moderate shocks, the likelihood of future, damaging earthquakes has increased for central and north-central Oklahoma."

- An increase like this has not been observed in modern seismology in an intra-plate setting
- Modern seismology is young compared to geologic process of 10's to 100's of thousands of years
- Increase is occurring over a large area ~15,000 sq. mi

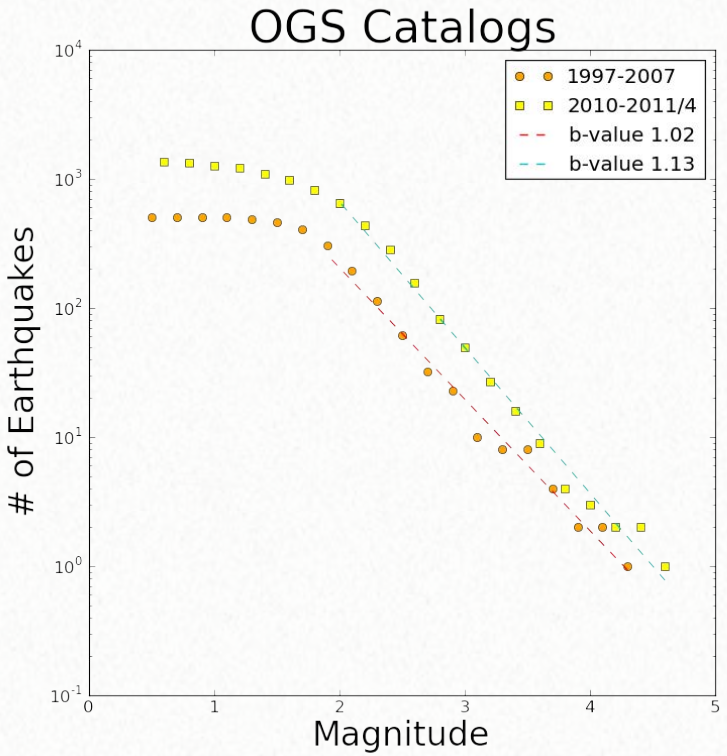
Oklahoma Earthquakes



Gutenberg-Richter Earthquake Scaling Law

- In general there are 10 M3 earthquakes for 1 M4
  - b-values generally very near 1
  - a-values can just be a total number or normalized by time
    - When a-values are normalized by time it provides the rate of occurrence of earthquakes of different magnitudes
- Does not allow for prediction of when and where earthquakes will occur
  - Allows for the calculation of probability of an earthquake of some magnitude occurring over a time period

$$log_{10}N = a - bM$$



Earthquake Forecasting

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

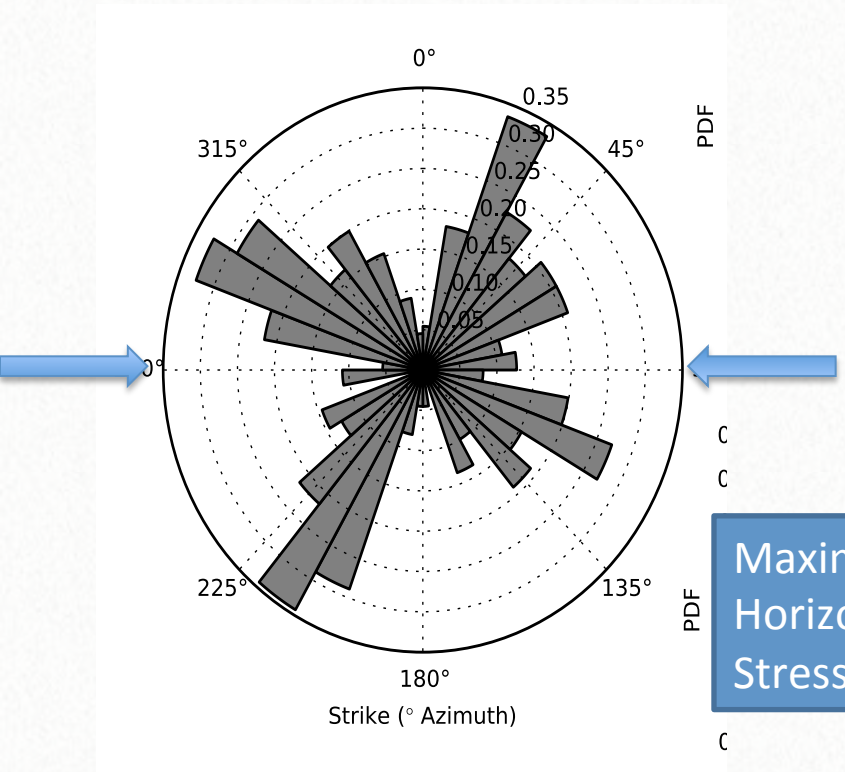
	Magnitude (m)					
Duration	**3.0**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**
4 Year	1.0000	1.0000	0.9212	0.4621	0.1404	0.0362
1 Year	1.0000	0.9983	0.7908	0.3179	0.0893	0.0226
6 months	1.0000	0.9755	0.5849	0.1882	0.0482	0.0117
30 days	1.0000	0.6067	0.2036	0.0540	0.0135	0.0033
10 days	0.9984	0.2470	0.0579	0.0125	0.0026	0.0006

Why the increase in earthquakes?

- Great Question!
  - Or as good “Why now? Or Why Oklahoma?”
- The observed rates of seismicity are very unlikely to represent a naturally occurring rate change and process.
  - This is based on observed rates and spatial patterns of migrating seismicity lagging major produced water plays
  - Likely contributing factor is the increase in disposal of large volumes of naturally occurring water “produced water”
- The increase in earthquakes and increase in seismic monitoring does a lot to advance earthquake science in Oklahoma
  - Earthquakes consistent with release of naturally occurring stress
  - Most earthquakes are occurring within Precambrian basement

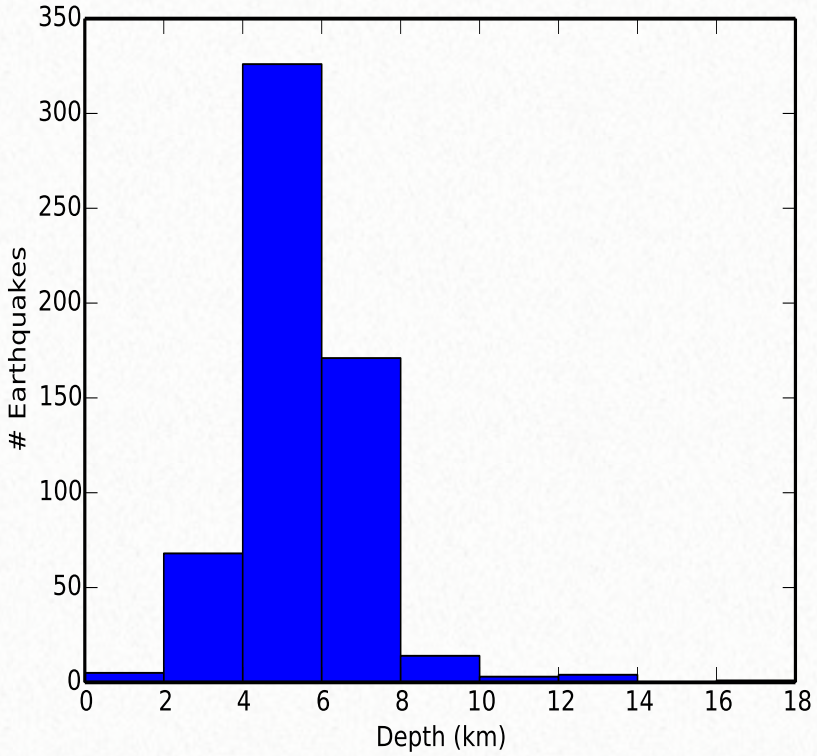
Earthquakes occurring on favorably oriented faults and in the basement

Active Fault Orientations 2014



Maximum Horizontal Stress

Earthquake Depth ~5.5 km avg



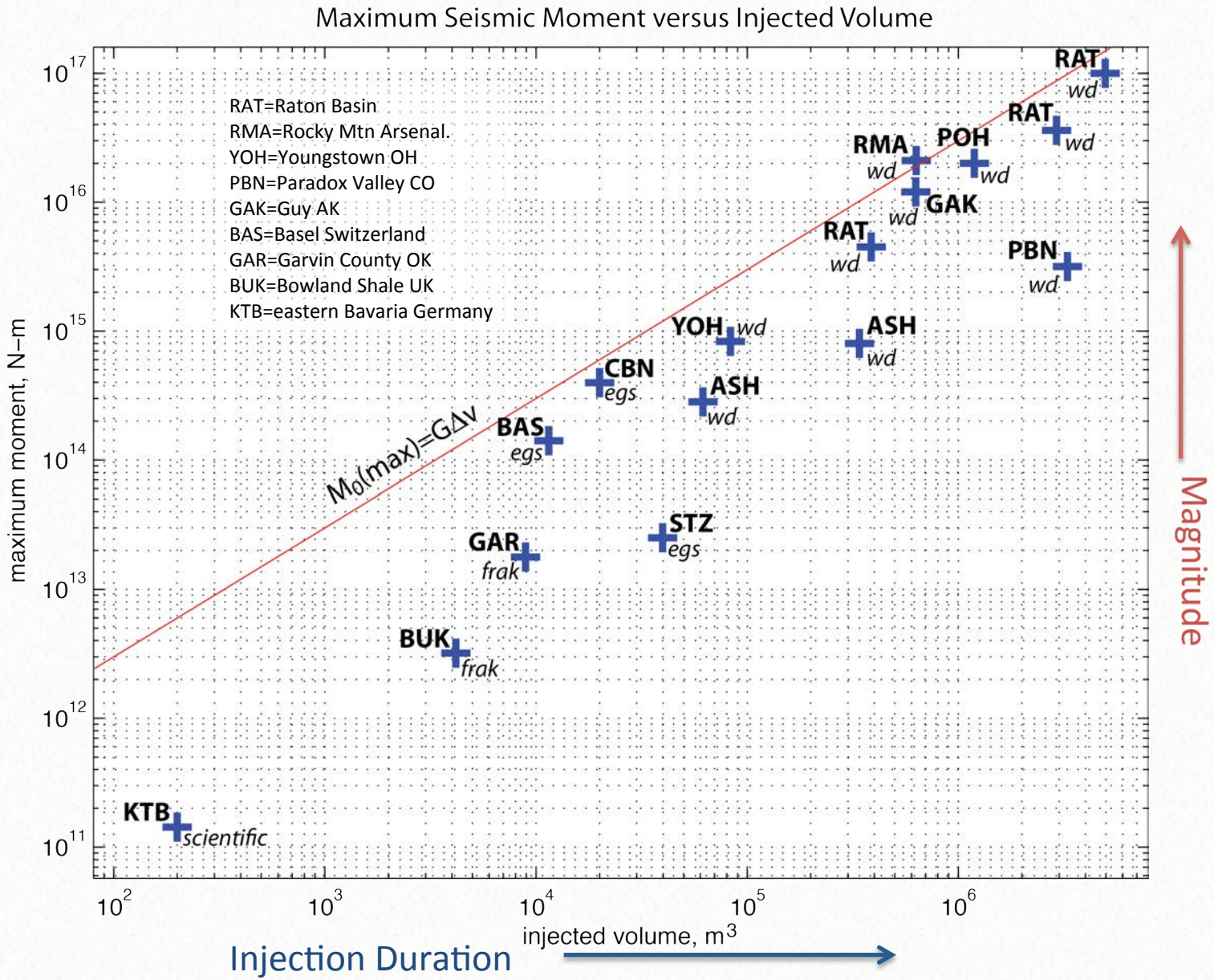
OGS OF1-2015

Summary for potential induced seismicity in Oklahoma

- No documented cases of induced seismicity have ever come close to the current earthquake rates or the area over which the earthquakes are occurring
  - Previously recognized rates of triggered seismicity about 1:4,000 wells (NRC study 2012)
- Long history of oil and gas activity and large number of wells
  - Require detailed research projects to understand induced seismicity well enough to mitigate future occurrences
  - The usual simple methods to identify potentially induced seismicity have only produced small numbers of identified cases
- Potential cases of induced seismicity have been identified both from hydraulic fracturing and disposal wells
  - Hydraulic fracturing only contributes a small amount to the observed rate of earthquakes
  - Disposal wells are thought to be a larger contributor

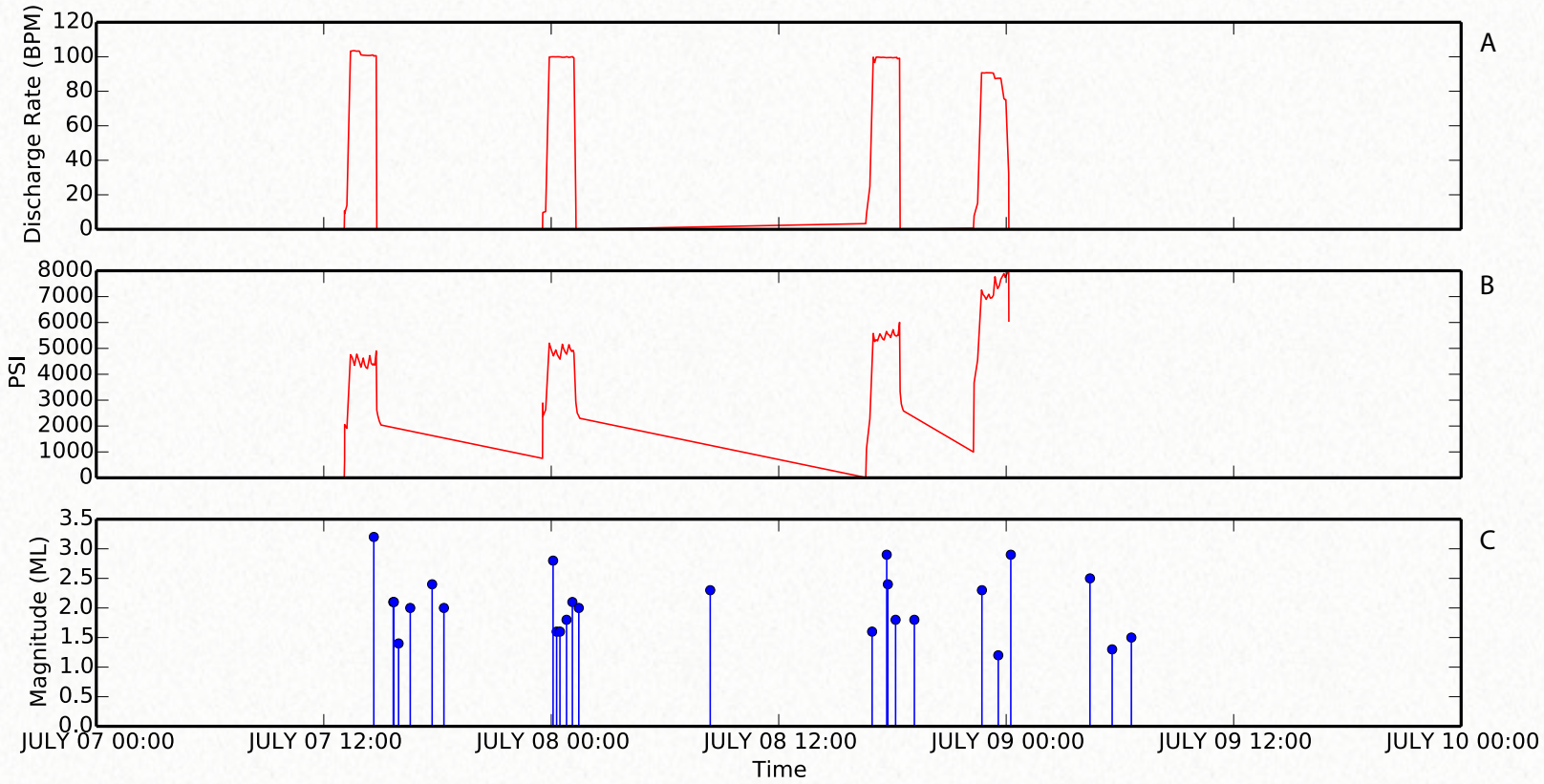
Earthquakes Triggered by Hydraulic Fracturing

- Growing number of recognized and documented cases
  - UK, Alberta, British Columbia, Ohio, and Oklahoma
- Maximum observed magnitude of 4.2
- Earthquakes are generally limited in time and space
- Easier to detect due to strong correlations in space and time
- Generally considered a lower risk than those triggered by SWD



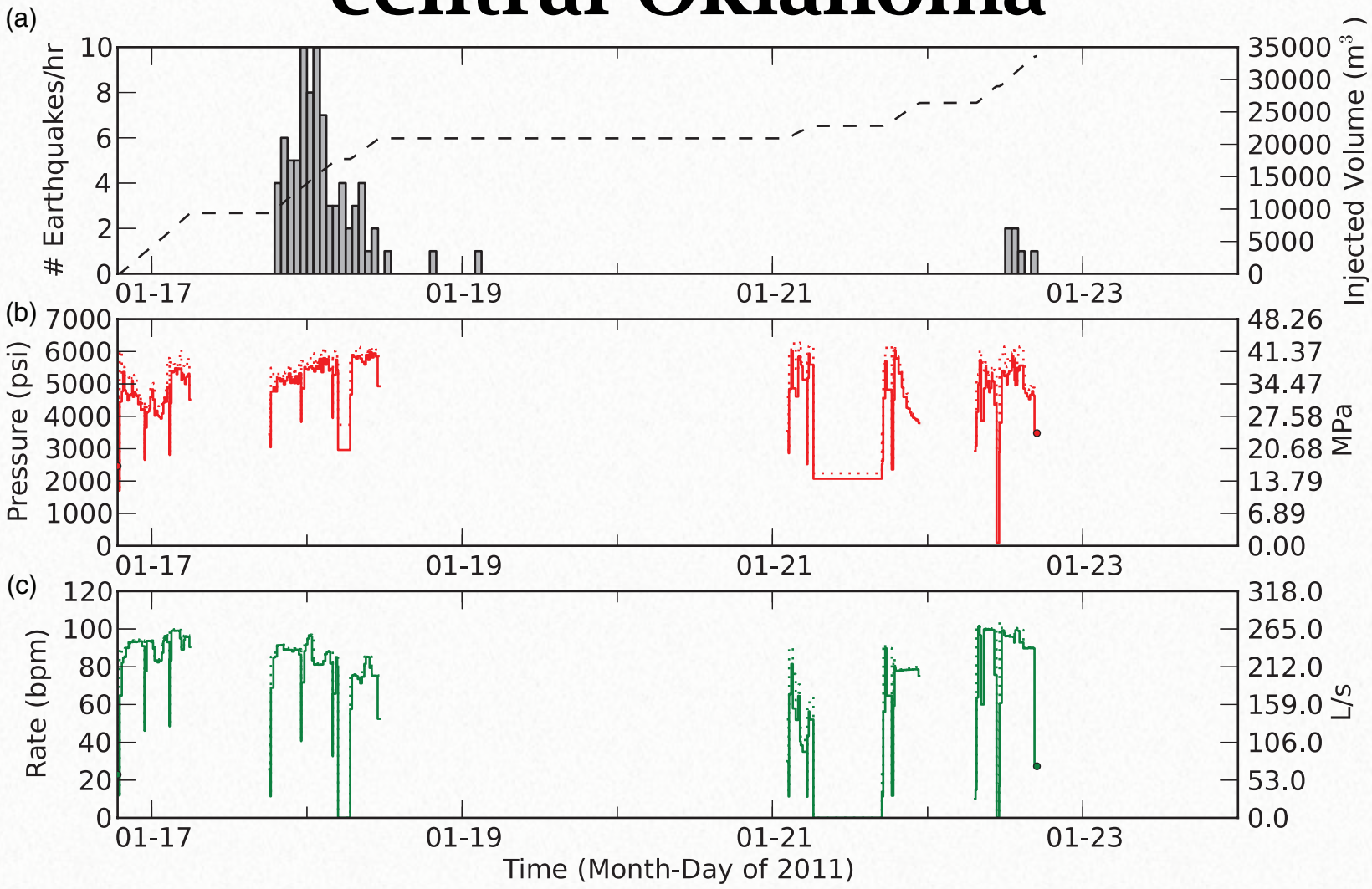
Courtesy of Art McGarr (USGS)

Earthquakes, Pressures and Injection Rates



Strong temporal correlation between injection parameters and the occurrence of earthquakes that is distinct from the background rate suggest a causal link. (Darold et al., 2015, OGS OF1-2015)

Another case from HF in south-central Oklahoma

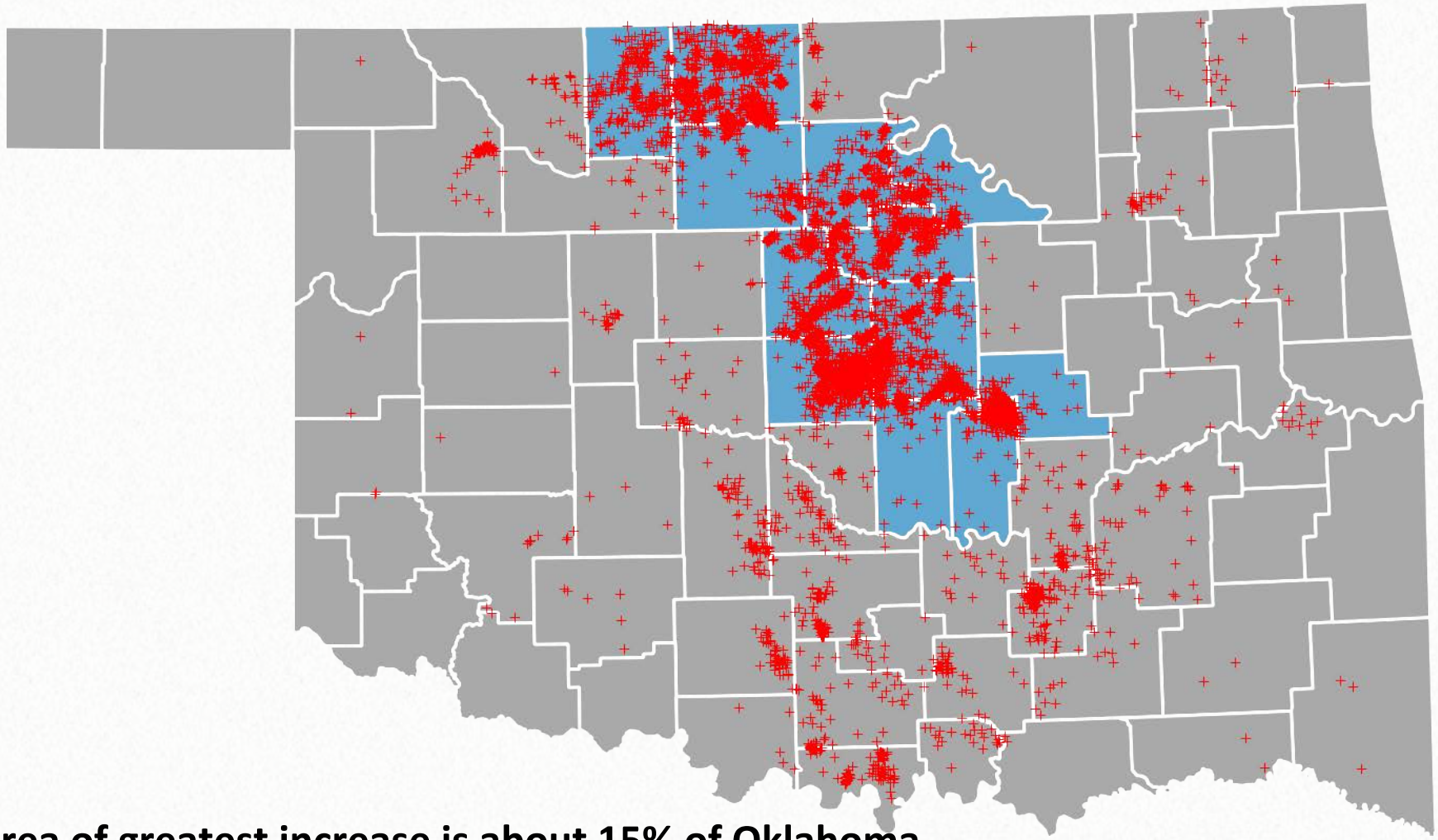


Holland, Bull. Seismol. Soc. Amer. (2013)

Recent potential cases of earthquakes triggered by disposal

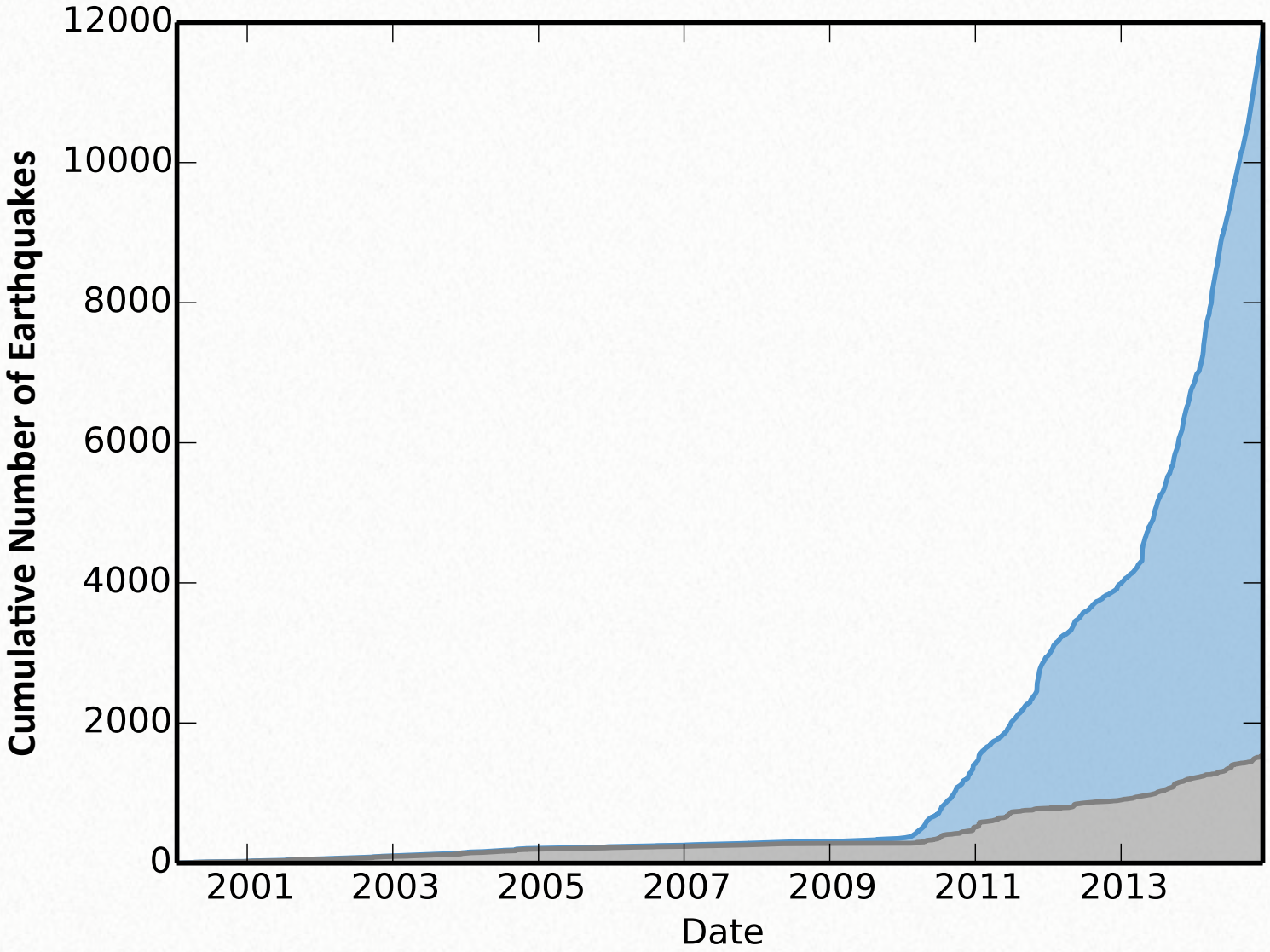
- Arkansas - Guy/Greenbrier
- Texas – DFW, Azle, Cleburne
- Ohio – Youngstown
- Colorado – Raton and Greely
- Oklahoma – Prague, Jones, Hunton dewatering? and Mississippi Lime…

Oklahoma Earthquakes 2009-2014

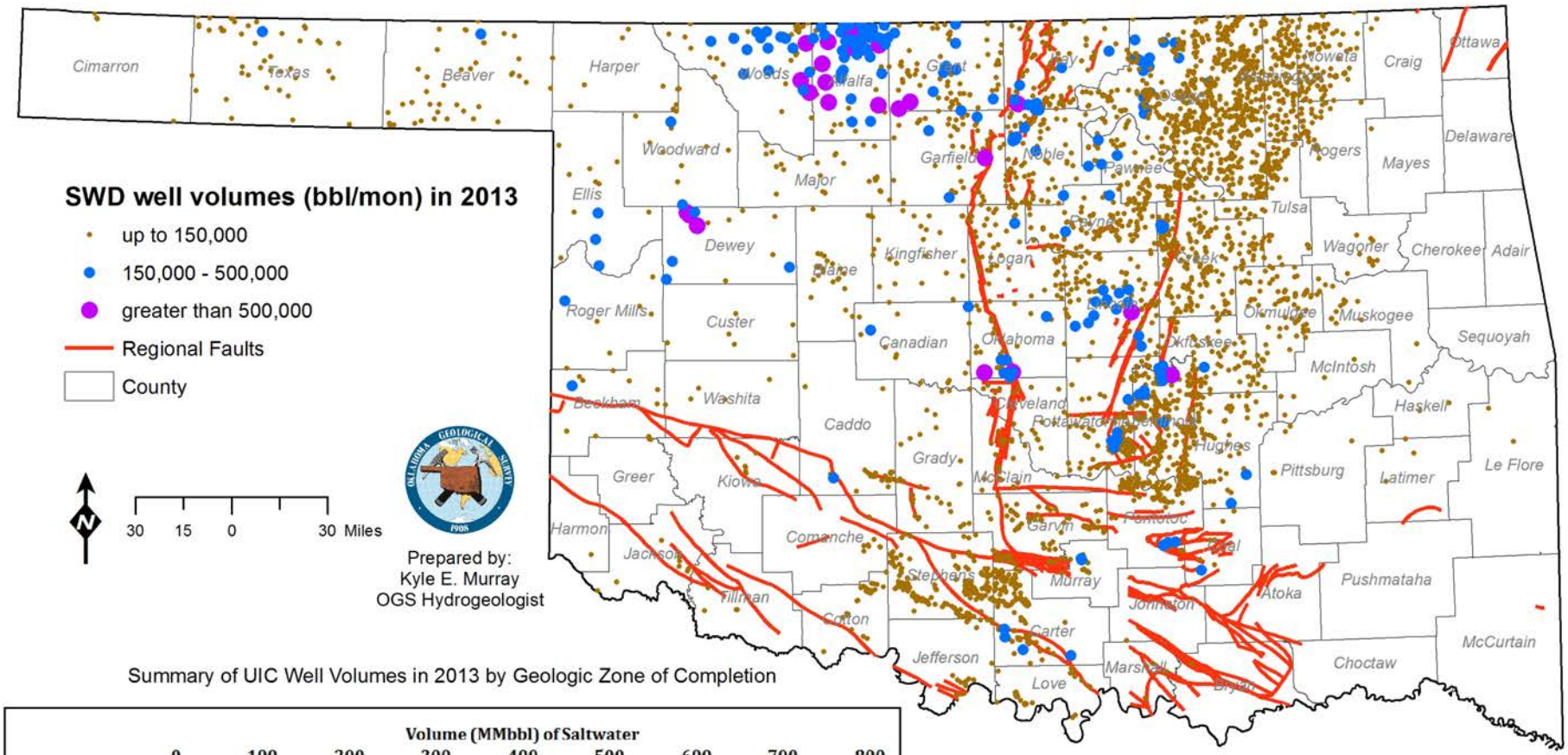


Area of greatest increase is about 15% of Oklahoma.
Captures areas of significant waste-water disposal wells

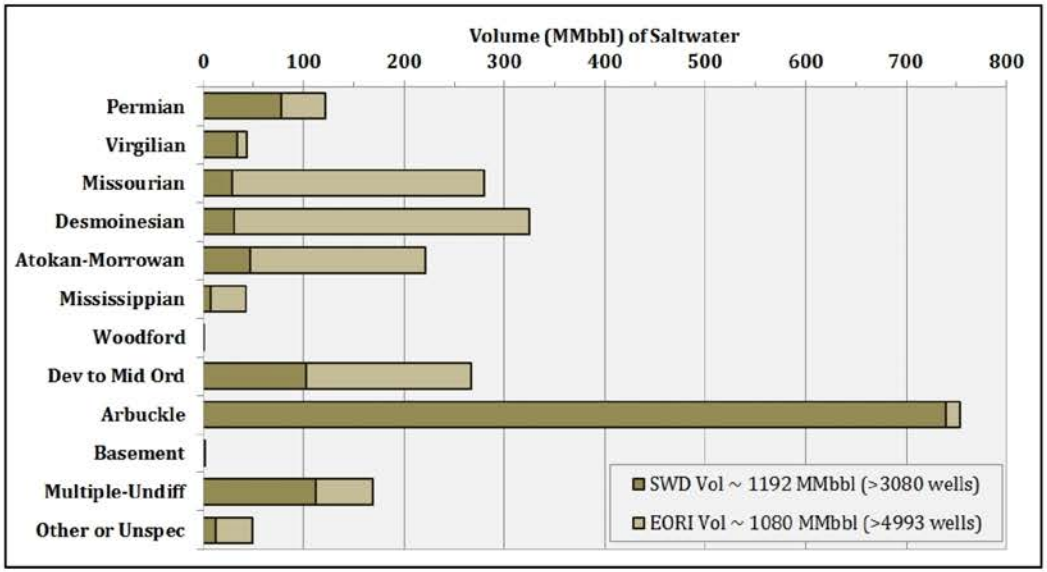
Cumulative Seismicity in Oklahoma



Oklahoma Geol. Survey www.okgeosurvey1.gov/pages/earthquakes/catalogs.php



Summary of UIC Well Volumes in 2013 by Geologic Zone of Completion

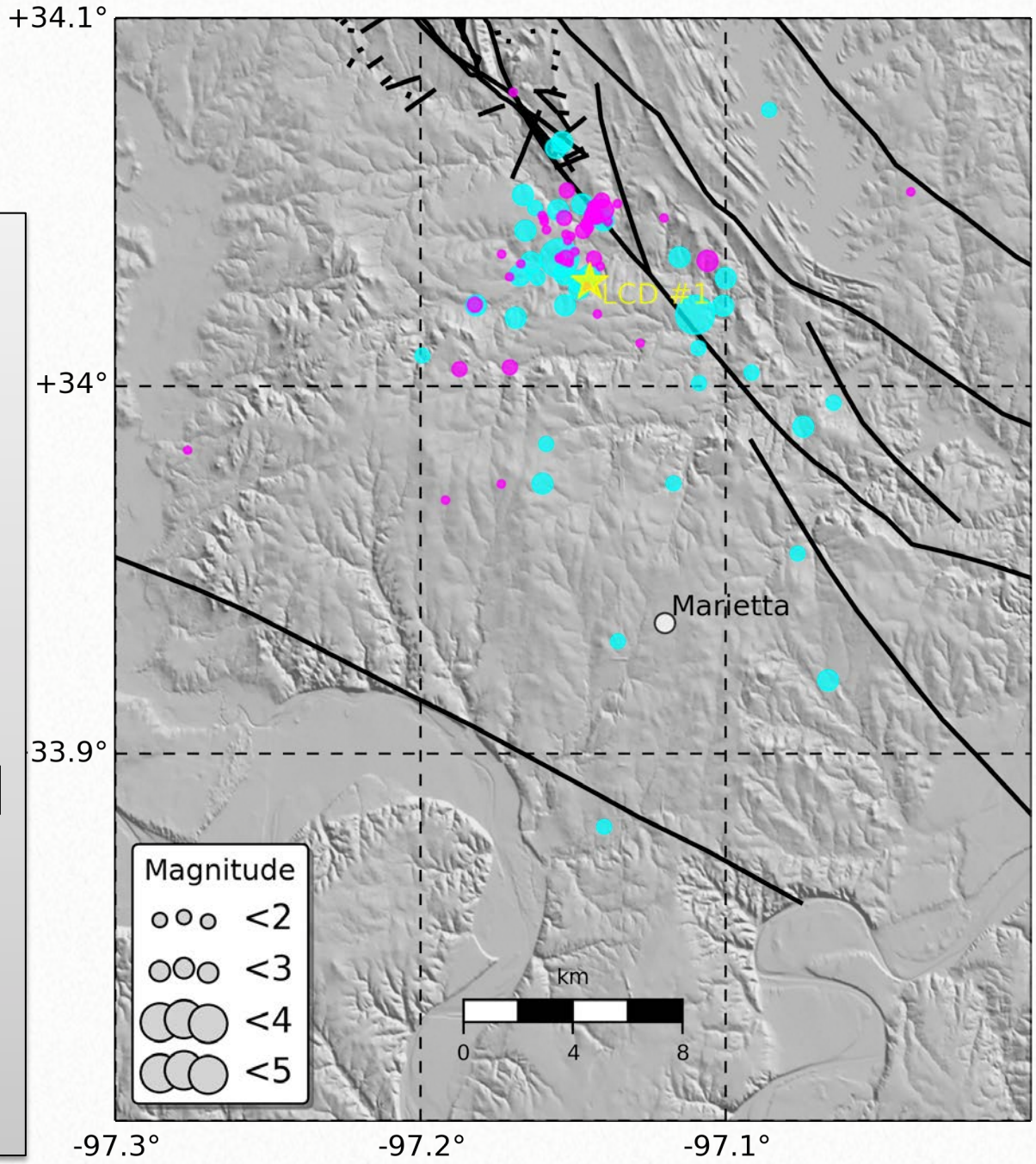


Murray 2014, OGS OF1-2014

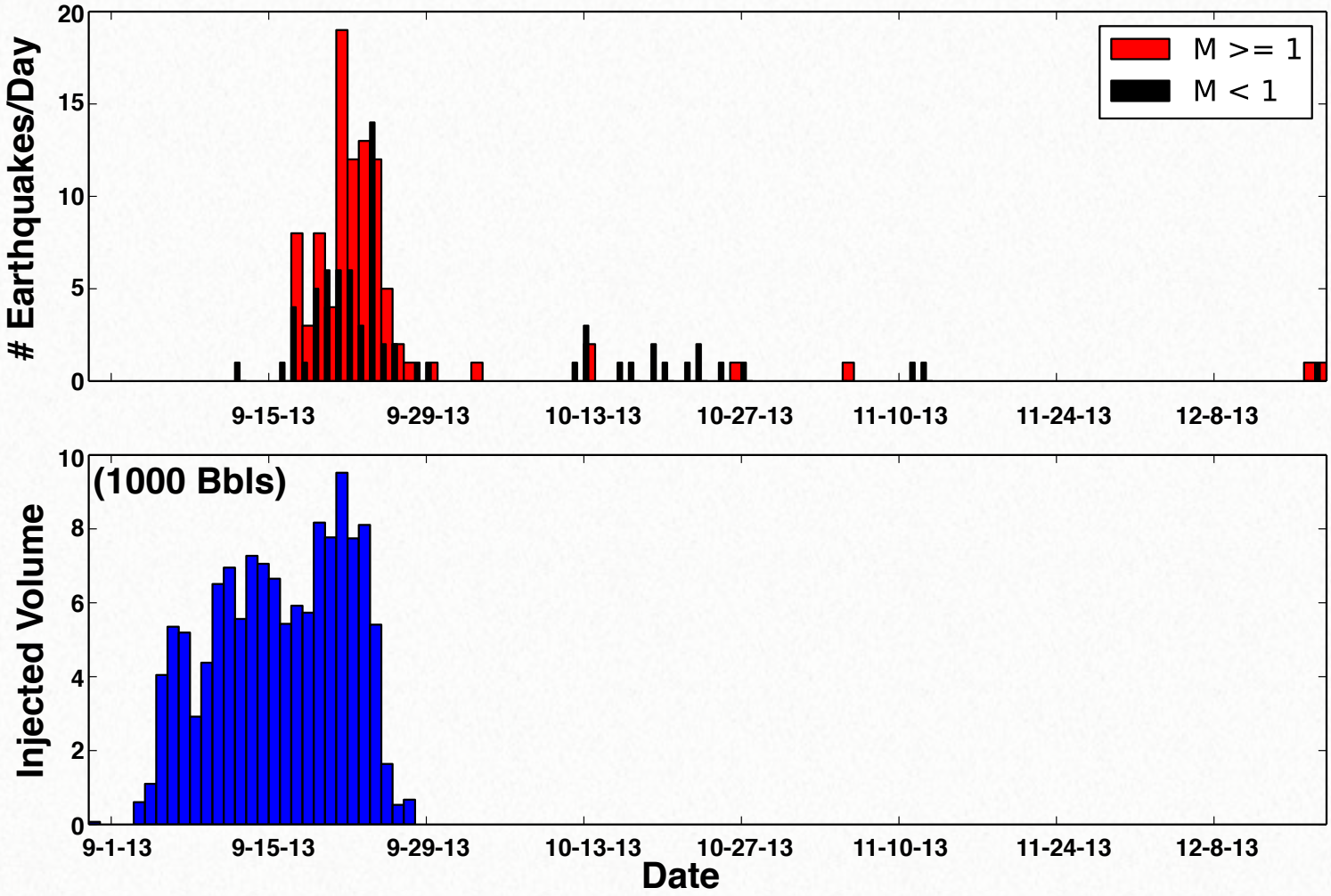
Index Location Map for Oklahoma

LCD #1 Disposal

- prior to local network
- with local net
- Avg depth ~2 km
- M3.4 did damage to local residences
- Feeling M1.8 earthquakes

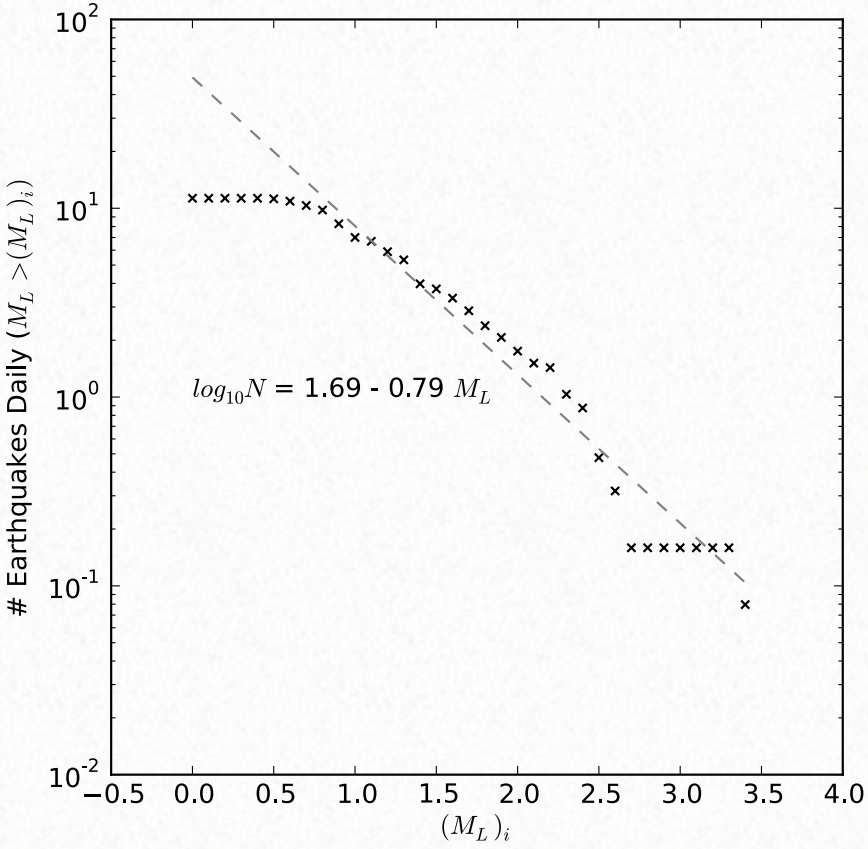


LCD #1 Injection and Earthquakes

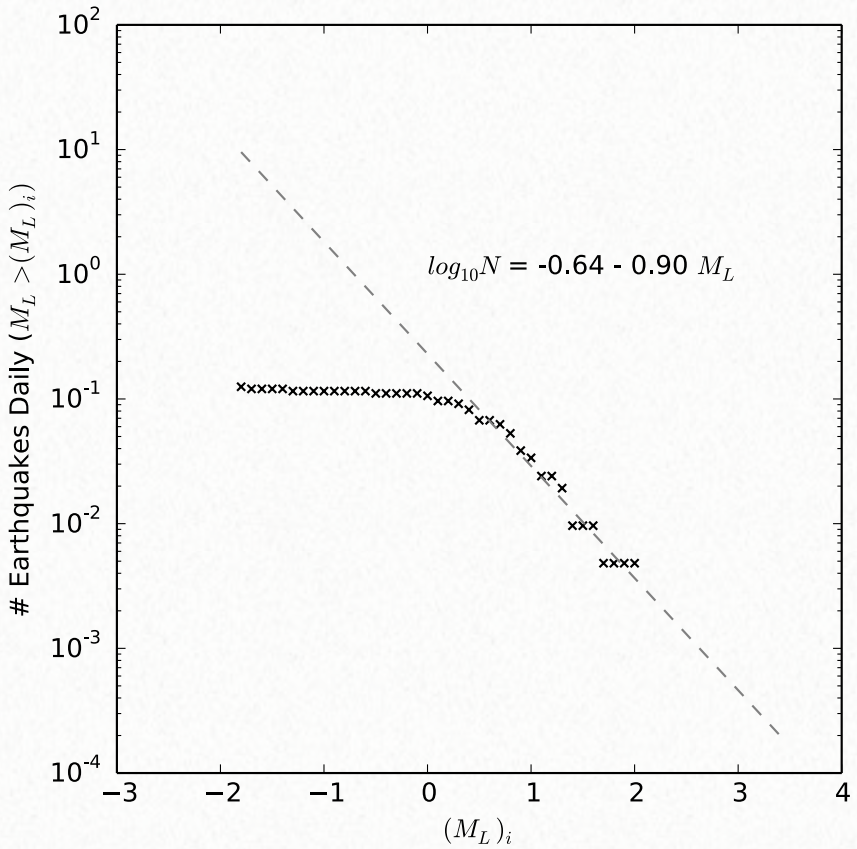


Recurrence and b-values

WMOK Cross Correlations
Events from: 9/16 - 9/29/13
Magnitude of Completeness: Mc~1.0

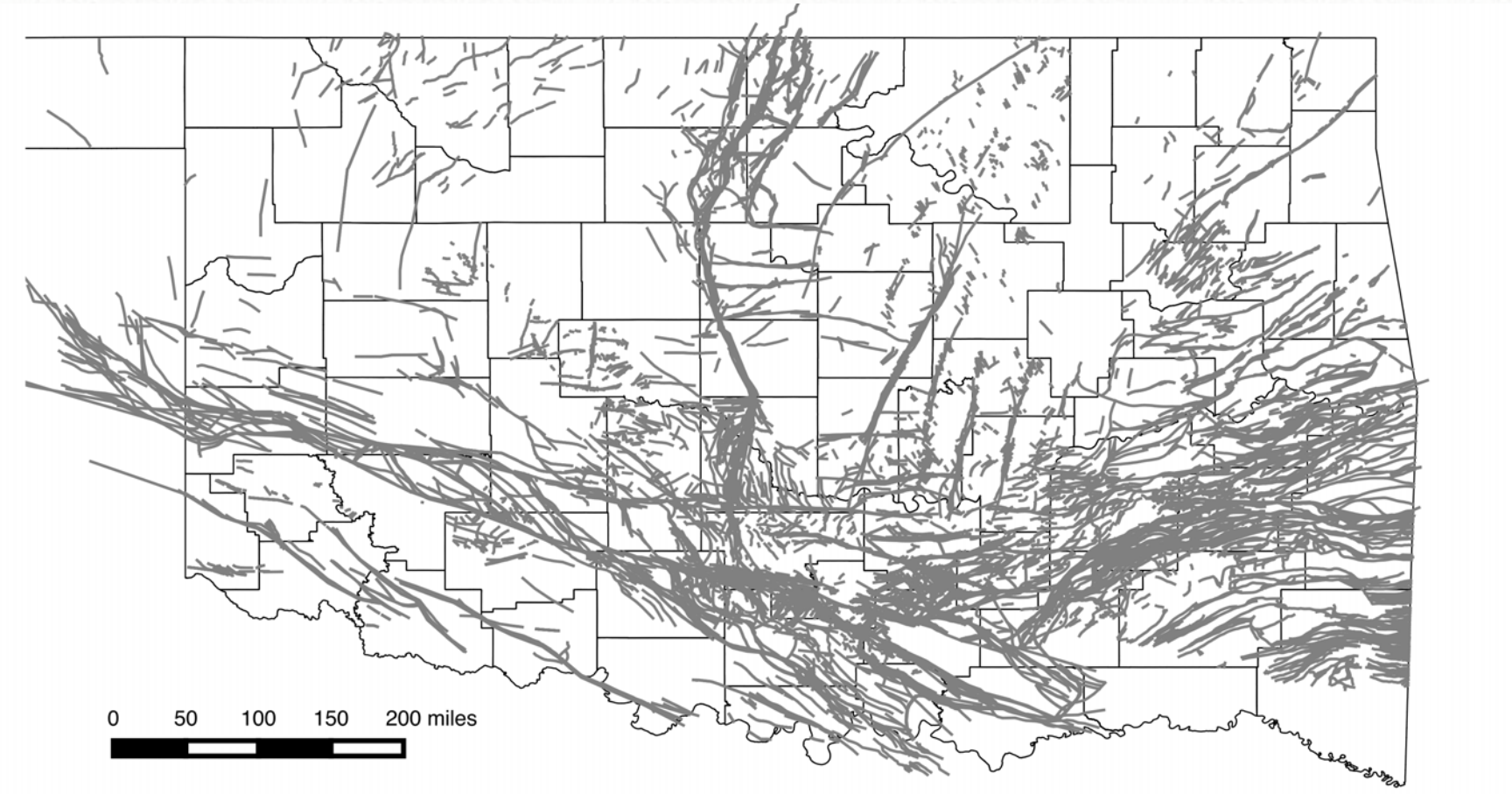


Earthquakes located using local network
Events from: 9/29 - 4/25/14
Magnitude of Completeness: Mc~0.5



Rate of earthquakes much greater during injection

Mapped Faults in Oklahoma

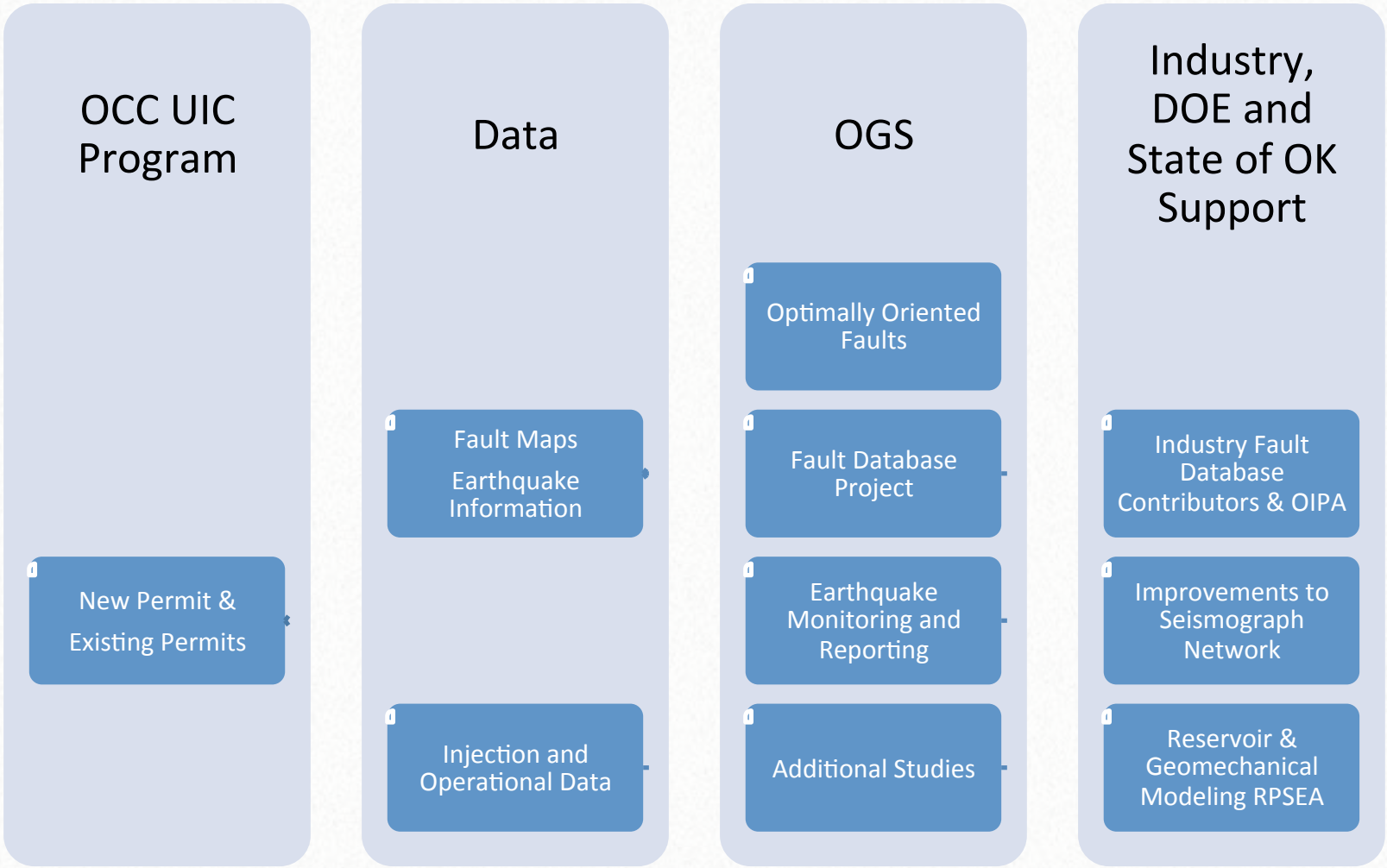


Faults are compiled from industry contributions and published literature

Steps the Industry Can Take

- Treat waste-water disposal as an integral part of production and not simply a cost
  - Greater attention to siting of disposal wells
    - Avoid favorably oriented faults and highly fractured and faulted areas
    - When possible, site in formations with permeability barriers between injection formation and crystalline basement
    - Avoid injecting into crystalline basement
  - Greater data at completion and throughout operation
    - Regular formation pressure measurements may be key
- Cannot go back in time to collect key data (Draft Best Practices are Available)

Interagency Cooperation



Questions or Comments?

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