MEWBOURNE
COLLEGE OF EARTH & ENERGY
THE UNIVERSITY OF OKLAHOMA

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

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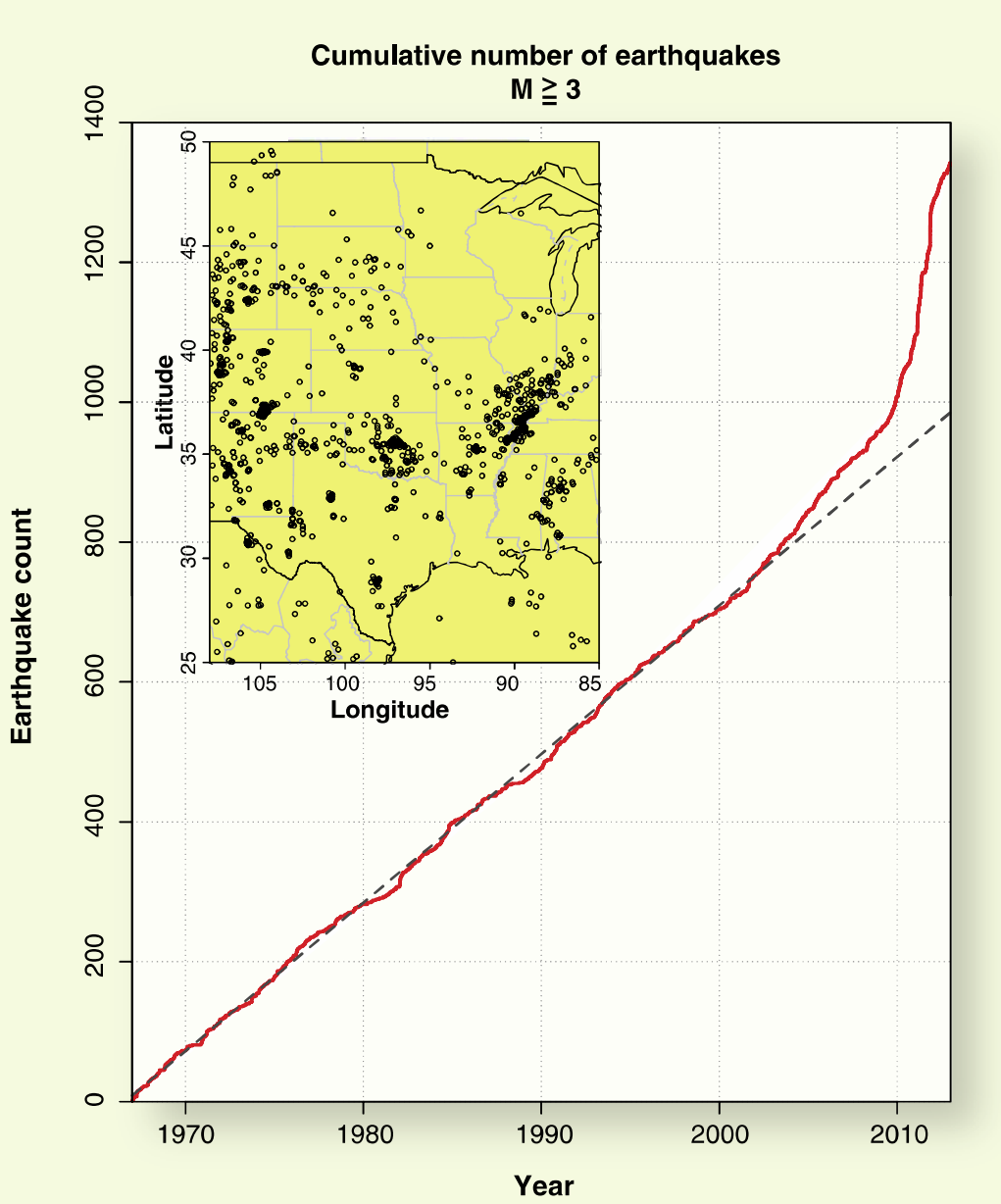
Outline

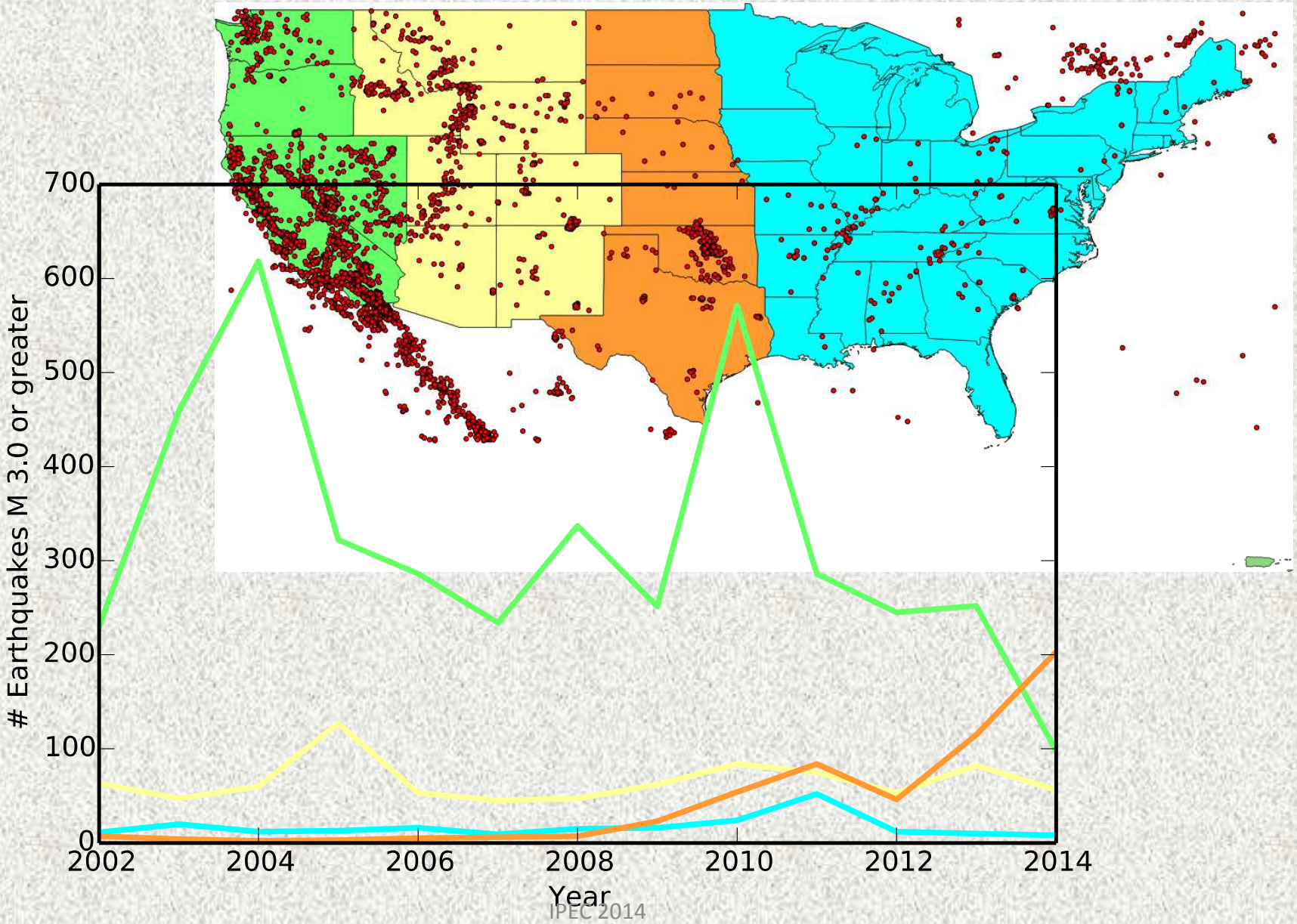
- Seismicity Rates in Mid-continent and Oklahoma
  - Implications of these seismicity rates
- Potential for Induced Seismicity
- Case examples from the mid-continent

Earthquake Rates for the Central and Eastern US

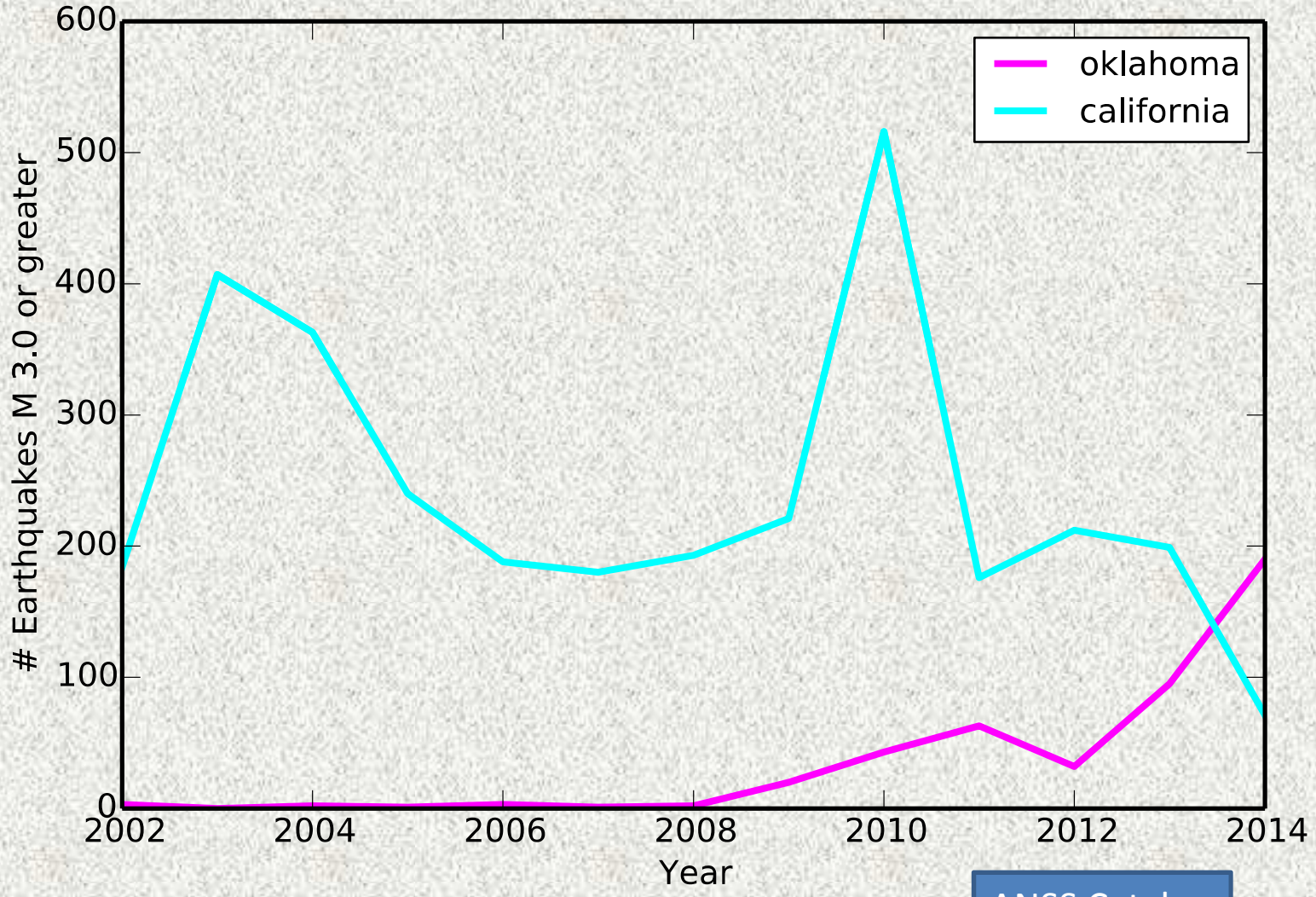


Ellsworth (Science, 2013)

ANSS Earthquakes by Region



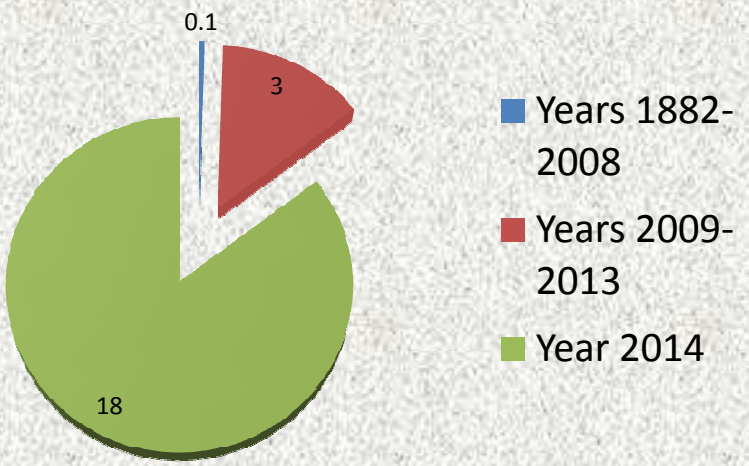
Mid-continent increase primarily in Oklahoma



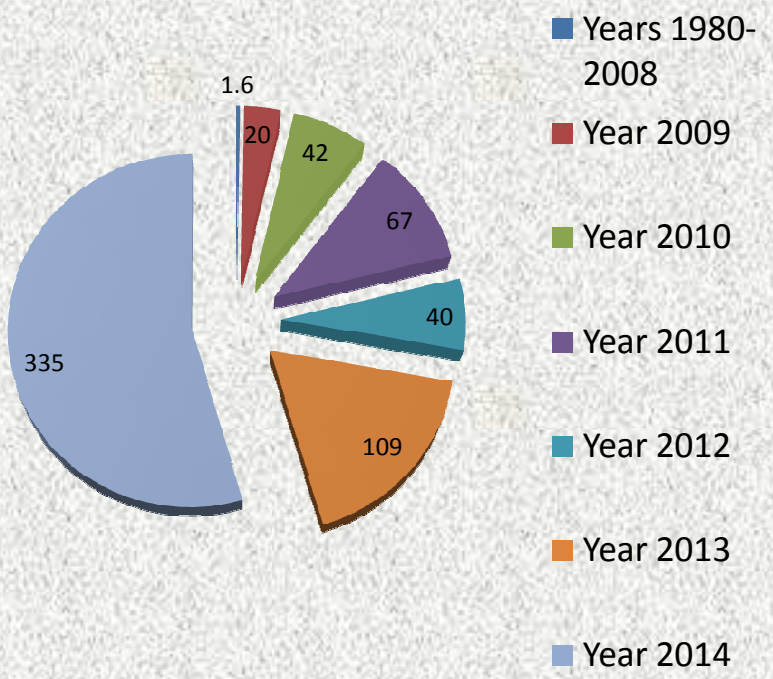
ANSS Catalog

Yearly Earthquake Rates

Magnitude 4 or Greater Earthquakes

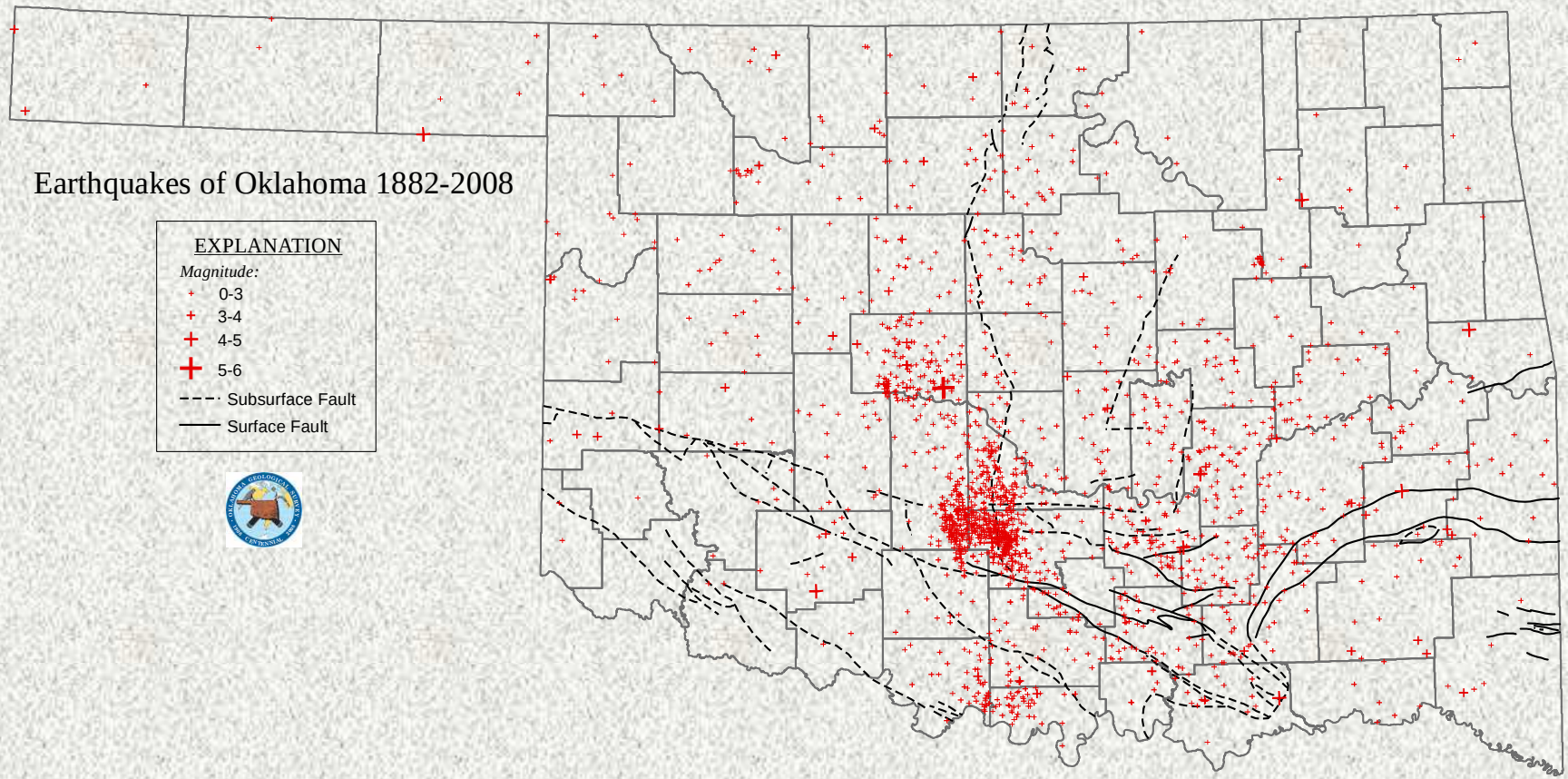


Magnitude 3 or Greater Earthquakes

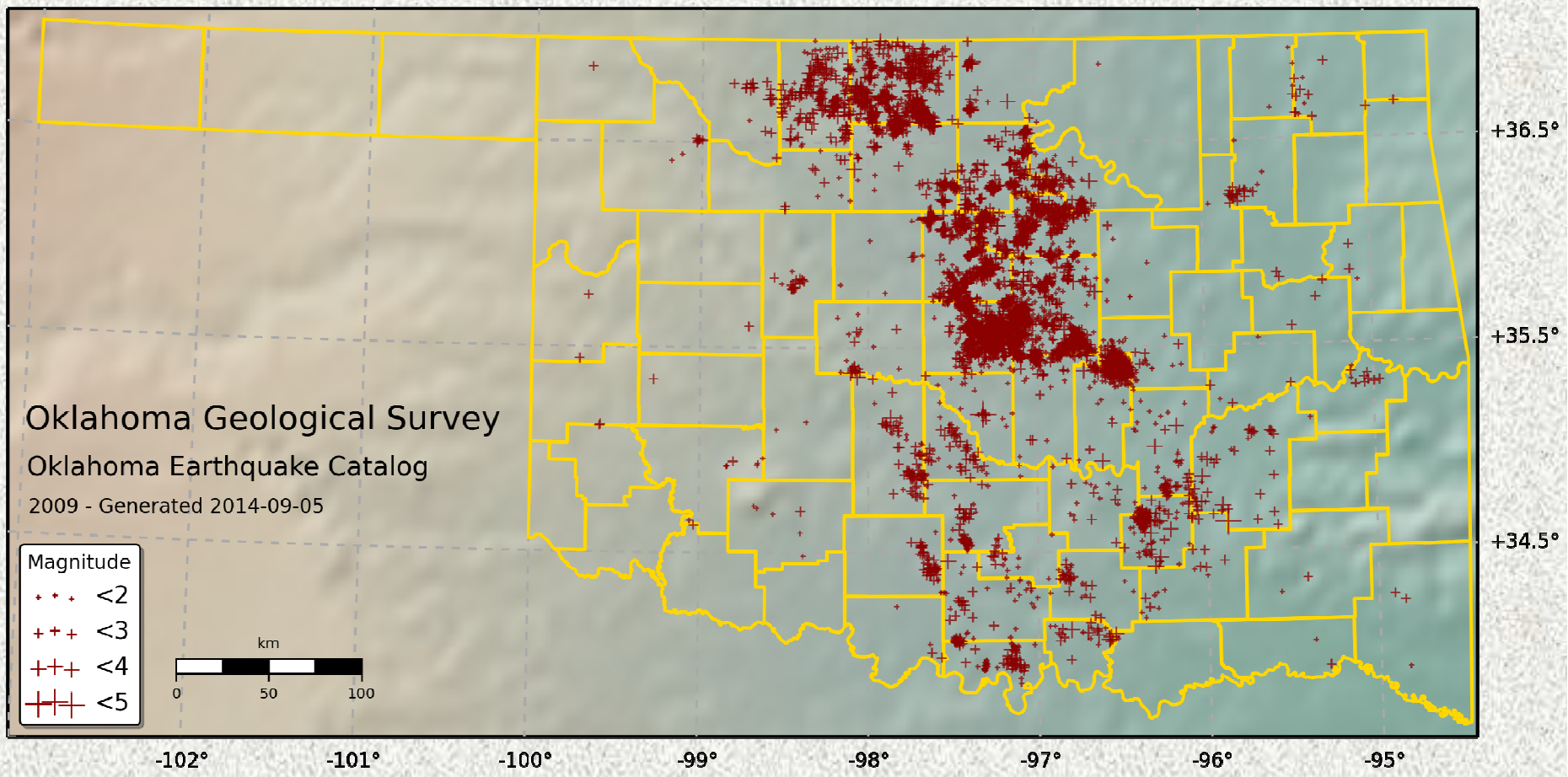


Created Sept. 5, 2014

Earthquakes 1882-2008



Earthquakes 2009-2014



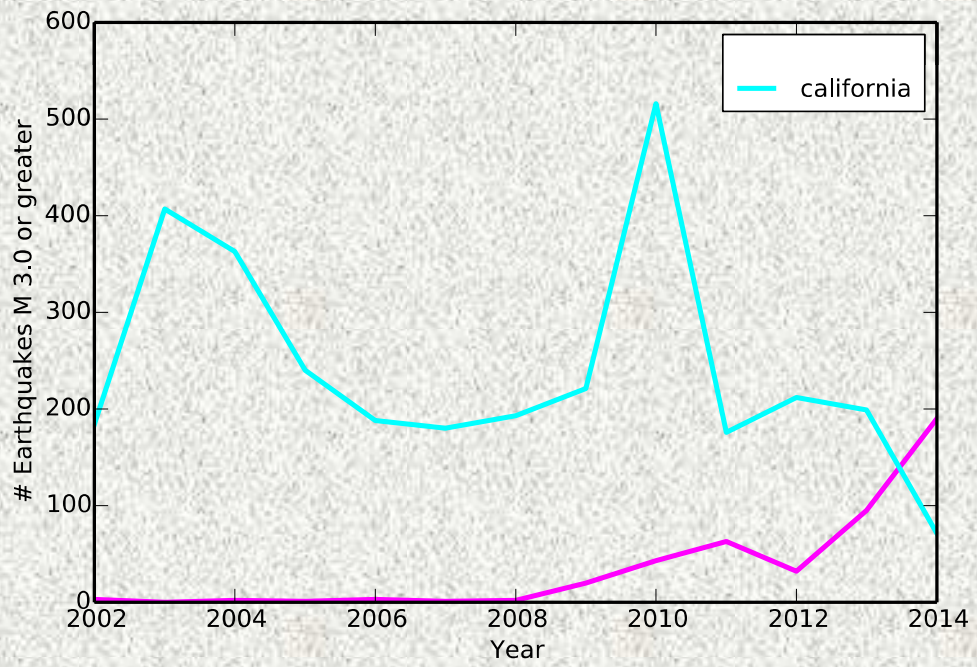
Increase in earthquakes is occurring over about 10,000 square miles

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."

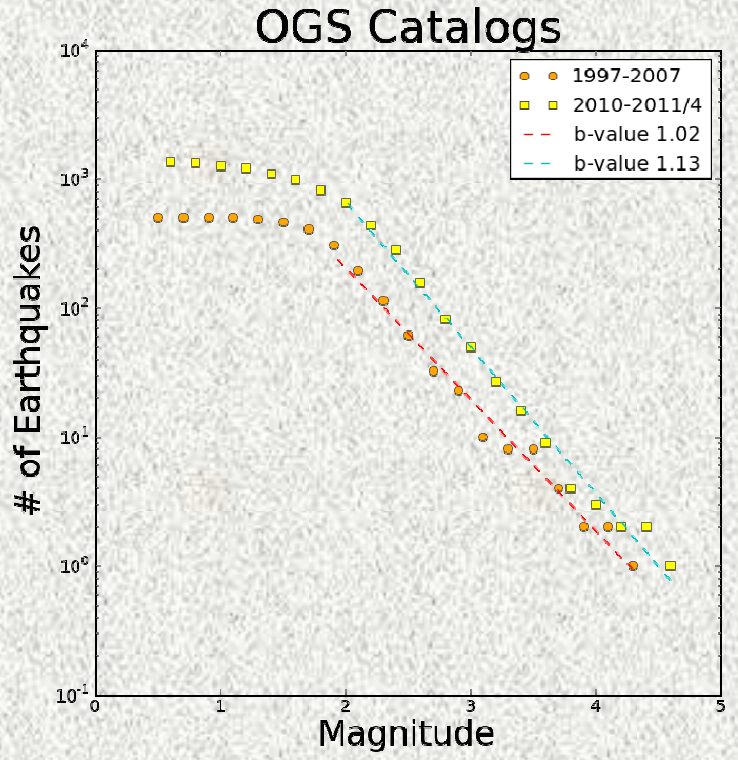
- An increase like this has not been observed in modern seismology in an intra-plate setting
- Modern seismology is young compared to geologic process of 10's to 100's of thousands of years
- Increase is occurring over a large area ~10,000 sq. mi



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?

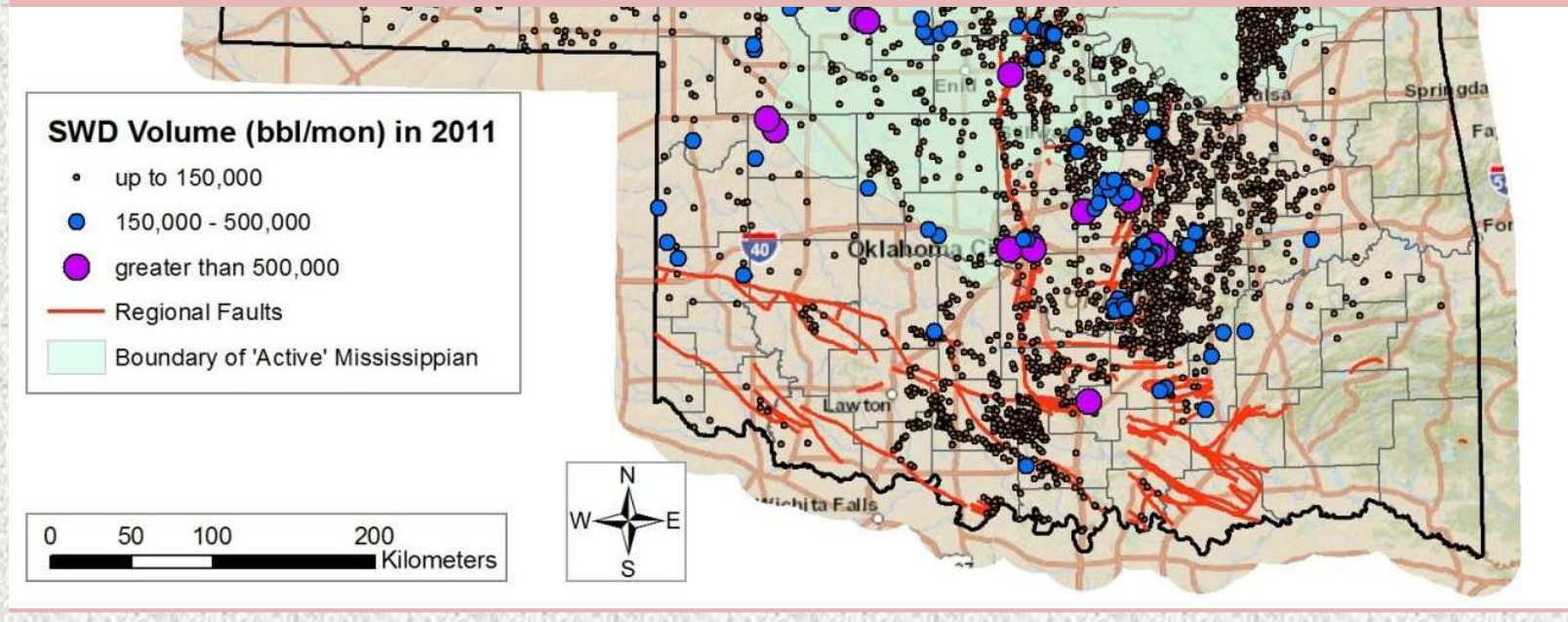
- Great Question!
  - Or better “Why now?”
- Seismic history is not long enough to rule out natural rate
  - may be a combination of factors causing the change
- However, most seismologist believe the drastic rate change is NOT due to natural seismicity
  - Likely contributing factor is the increase 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 pre-Cambrian basement

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
- Long history of oil and gas activity and large number of wells require detailed research projects to identify induced seismicity
  - 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

2011 Di

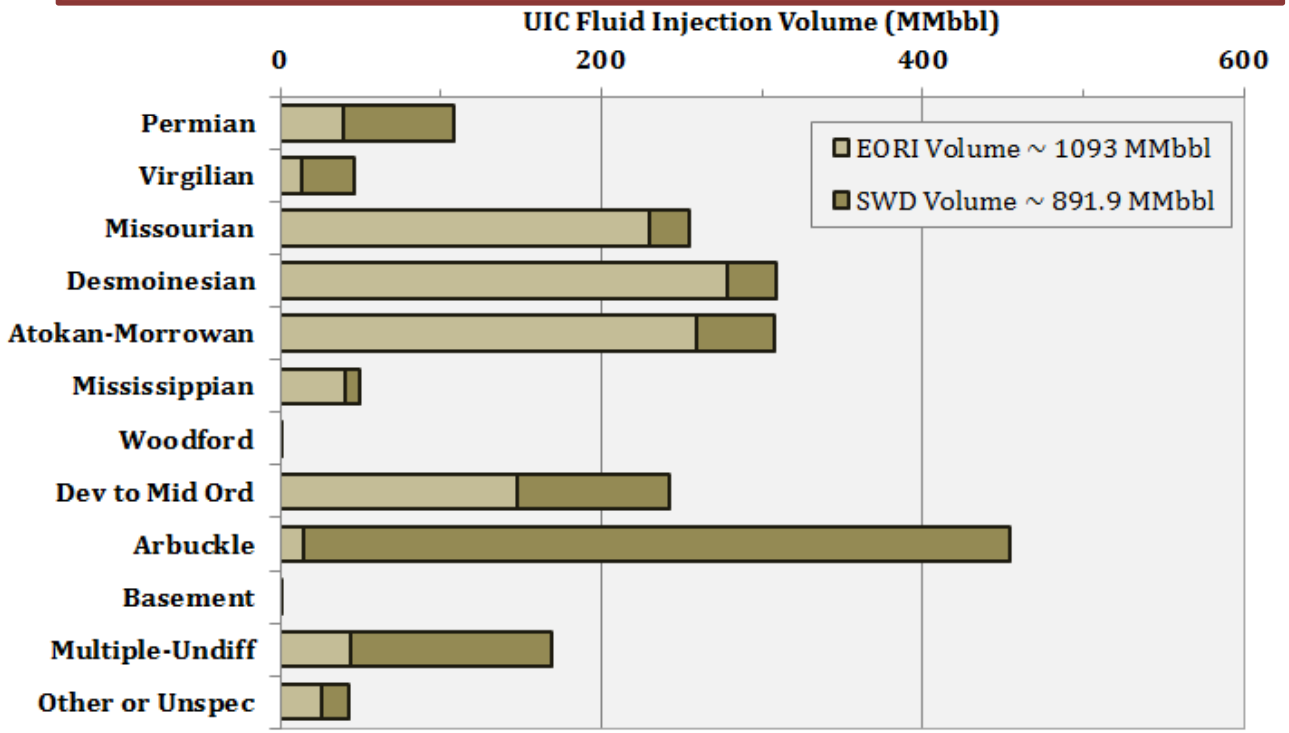
Murray &



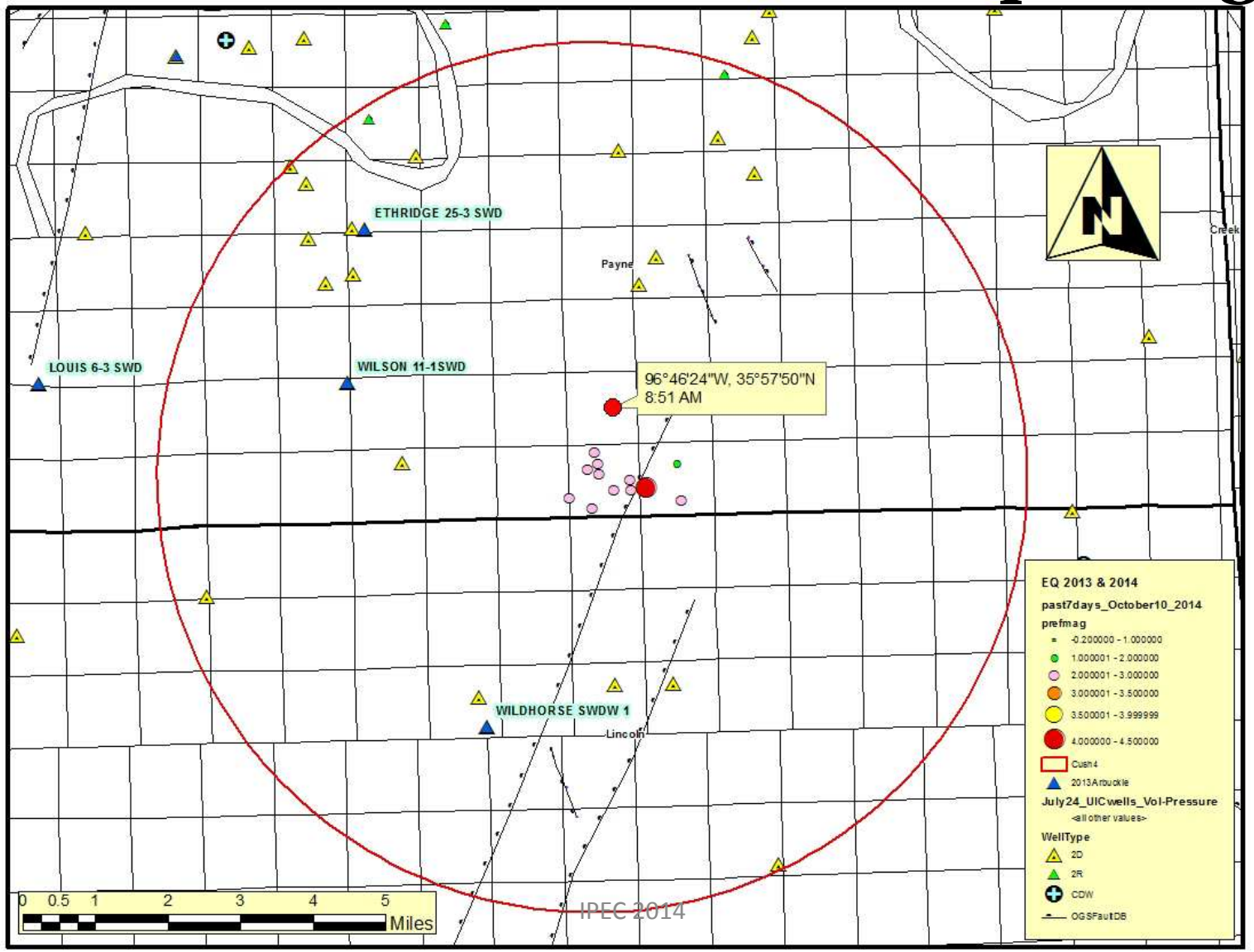
Injection by Formation

Zone	Group	Formation
Permian		Garber
	Chase	Brown Dolomite
	Council Grove	Pontotoc
	Admire	Belveal
Virgilian	Wabaunsee	Cisco Lime
	Shawnee	Pawhuska
		Endicott
	Douglas	Tonkawa
Missourian	Hoxbar	Lansing
		Cottage Grove
		Kansas City
		Hogshooter
		Layton
		Cleveland
Desmoinesian	Marmaton	Oswego
	Cabaniss	Skinner
	Krebs	Red Fork
		Burbank
		Bartlesville
		Hartshorne
Atokan-Morrowan	Atoka	Gilcrease
		Dutcher
	Morrow	Cromwell
	Springer	Wamsley
Mississippian	Chester	Manning
		Caney
	Meramec	Miss Lime
		Miss Chat
		St. Louis
		Mayes
	Osage	Sycamore
	Kinderhook	Kinderhook
Woodford	Upper Devonian	Woodford
Dev to Mid Ord	Middle Devonian	Misener
	Lower Dev - Silurian	Hunton
	Cincinnatian	Sylvan
		Viola
	Simpson	Bromide
		Wilcox
		McLish
		Oil Creek
Arbuckle	Arbuckle Group	West Spring Creek
		Kindblade
		Butterly Dolomite
Basement & Crystalline Rock	Cambrian	Reagan
	Pre-Cambrian	Granite

- Vast majority of disposal by volume is not frac waste-water but produced water (part of producing oil and gas)
- Large number of Arbuckle wells injecting on or near vacuum for years

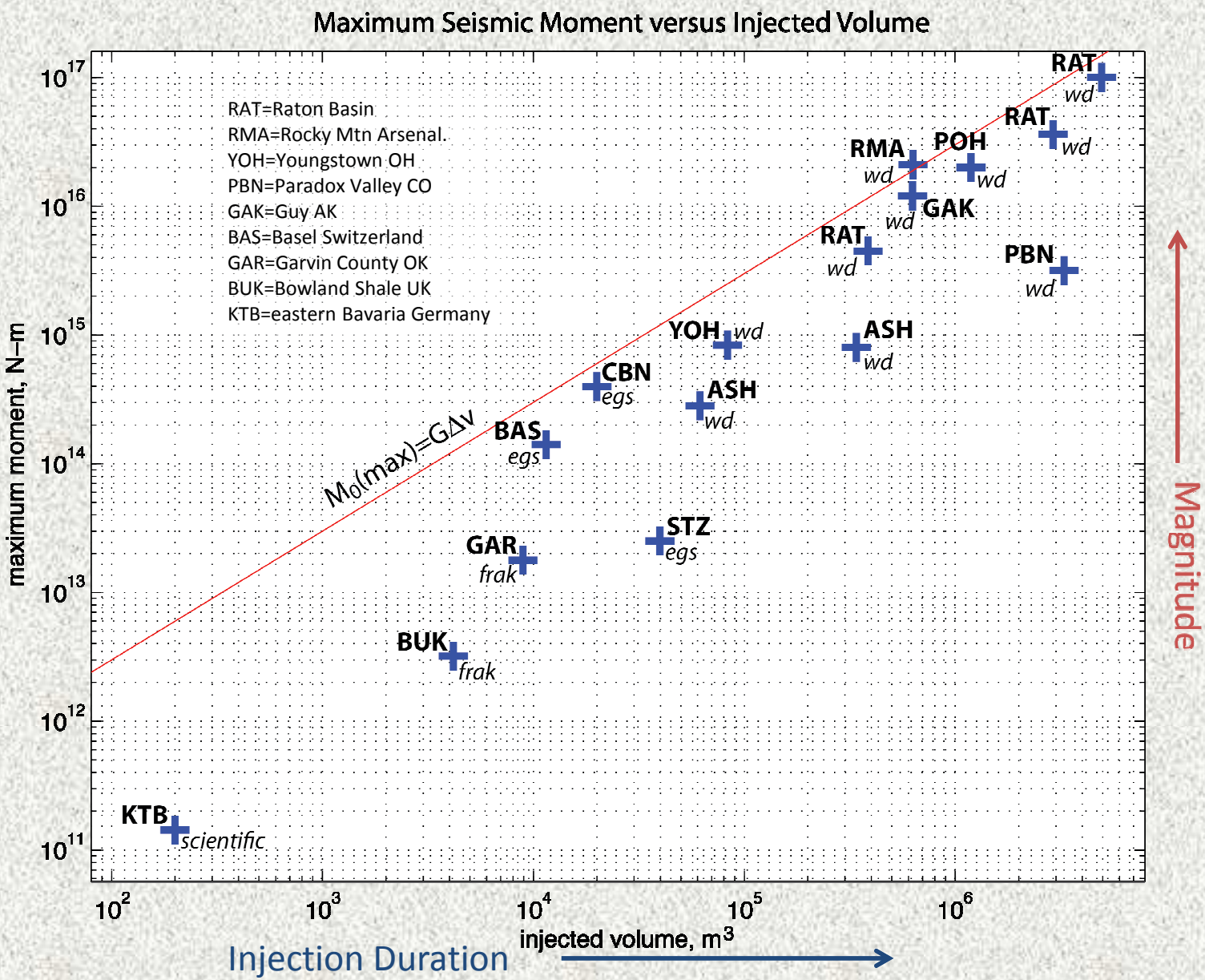


Oklahoma Corporation Commission Areas of Interest Greater Reporting



Earthquakes Triggered by Hydraulic Fracturing

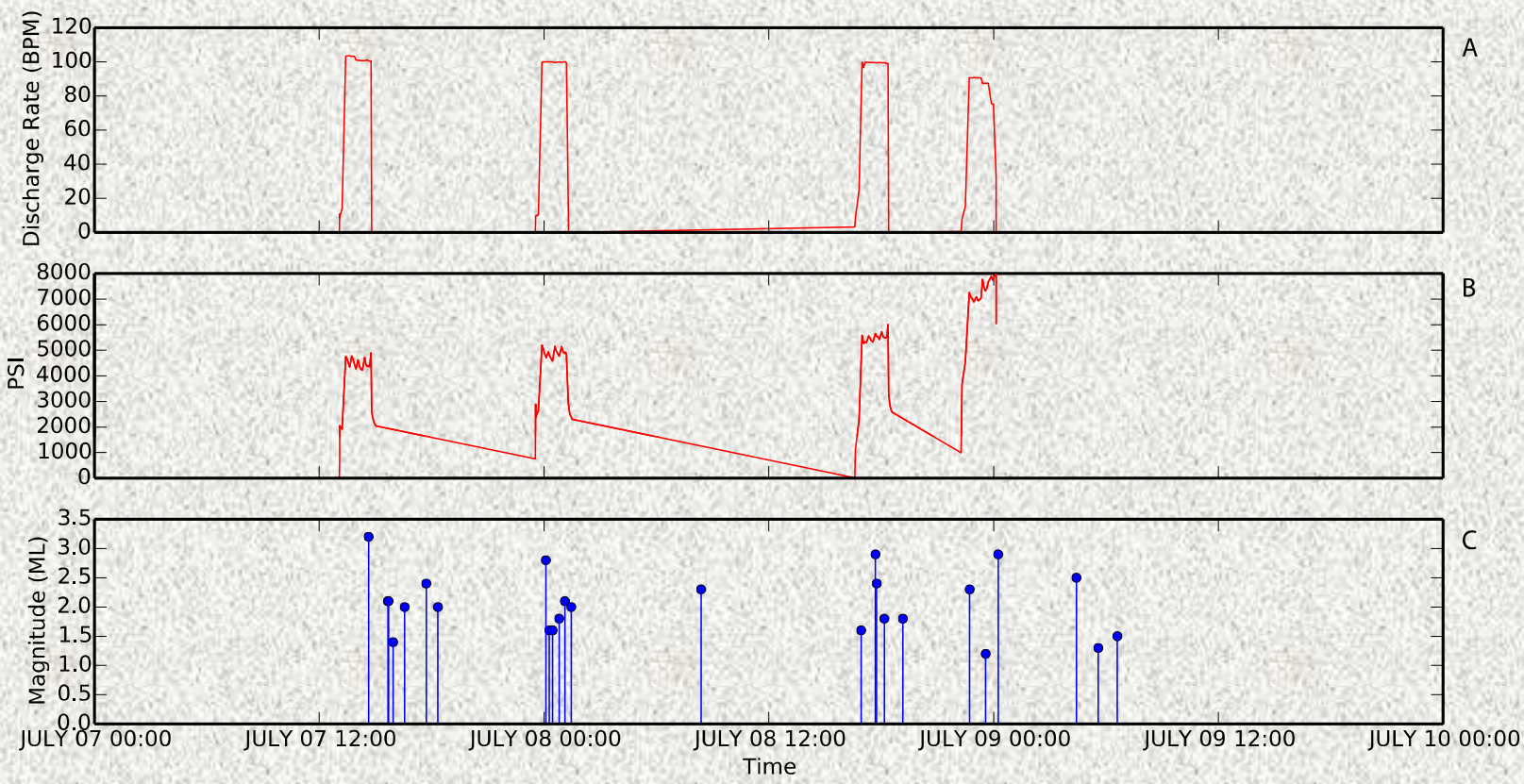
- Growing number of recognized and documented cases
  - UK, Alberta, British Columbia, Ohio, and Oklahoma
- Maximum observed magnitude of 4.2
- Earthquakes are generally limited in time and space
- Easier to detect due to strong correlations in space and time



IPEC 2014

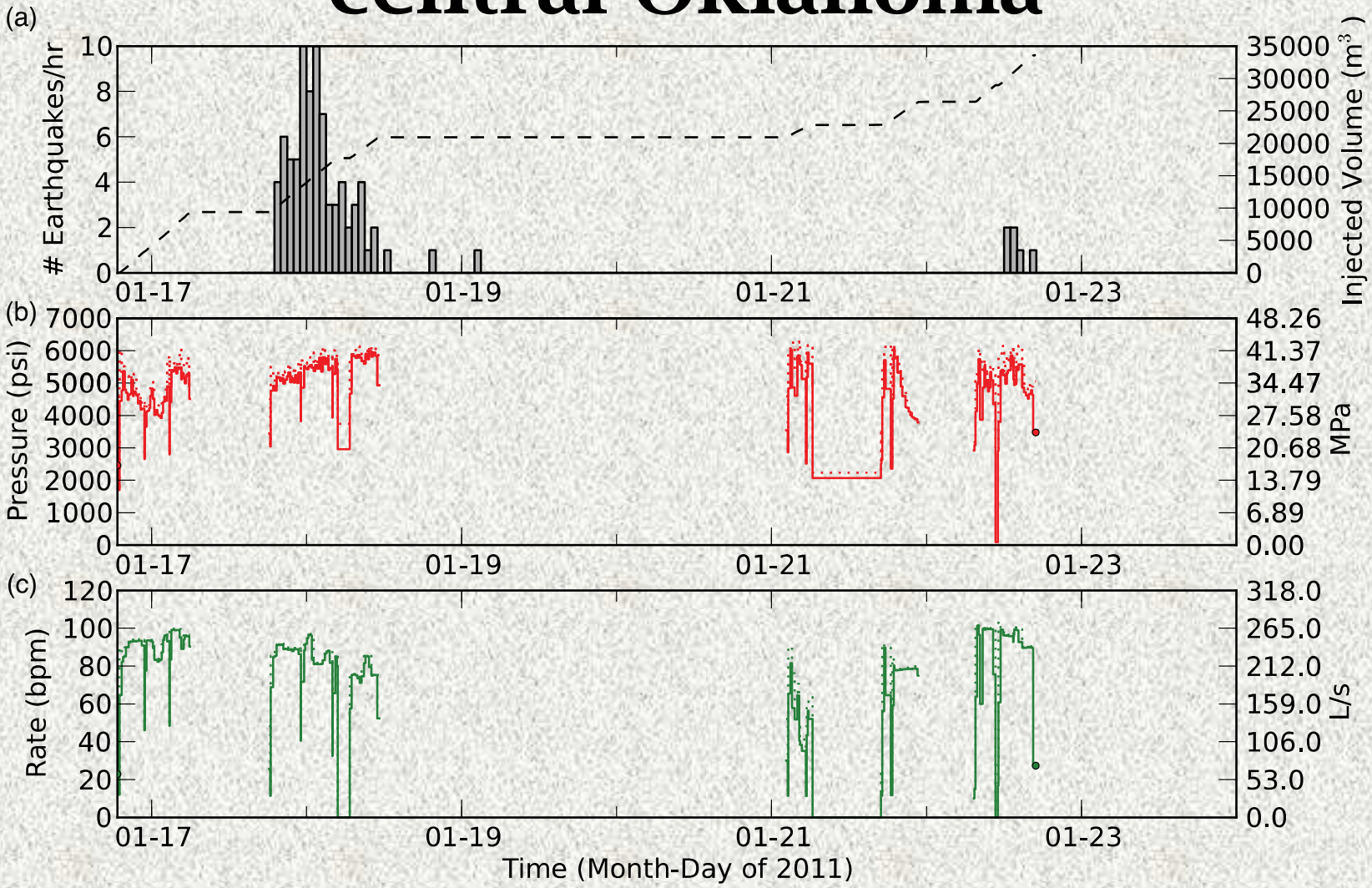
Courtesy of Art McGarr (USGS)

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., 2014, OGS OF1-2014)

Another case from HF in south-central Oklahoma



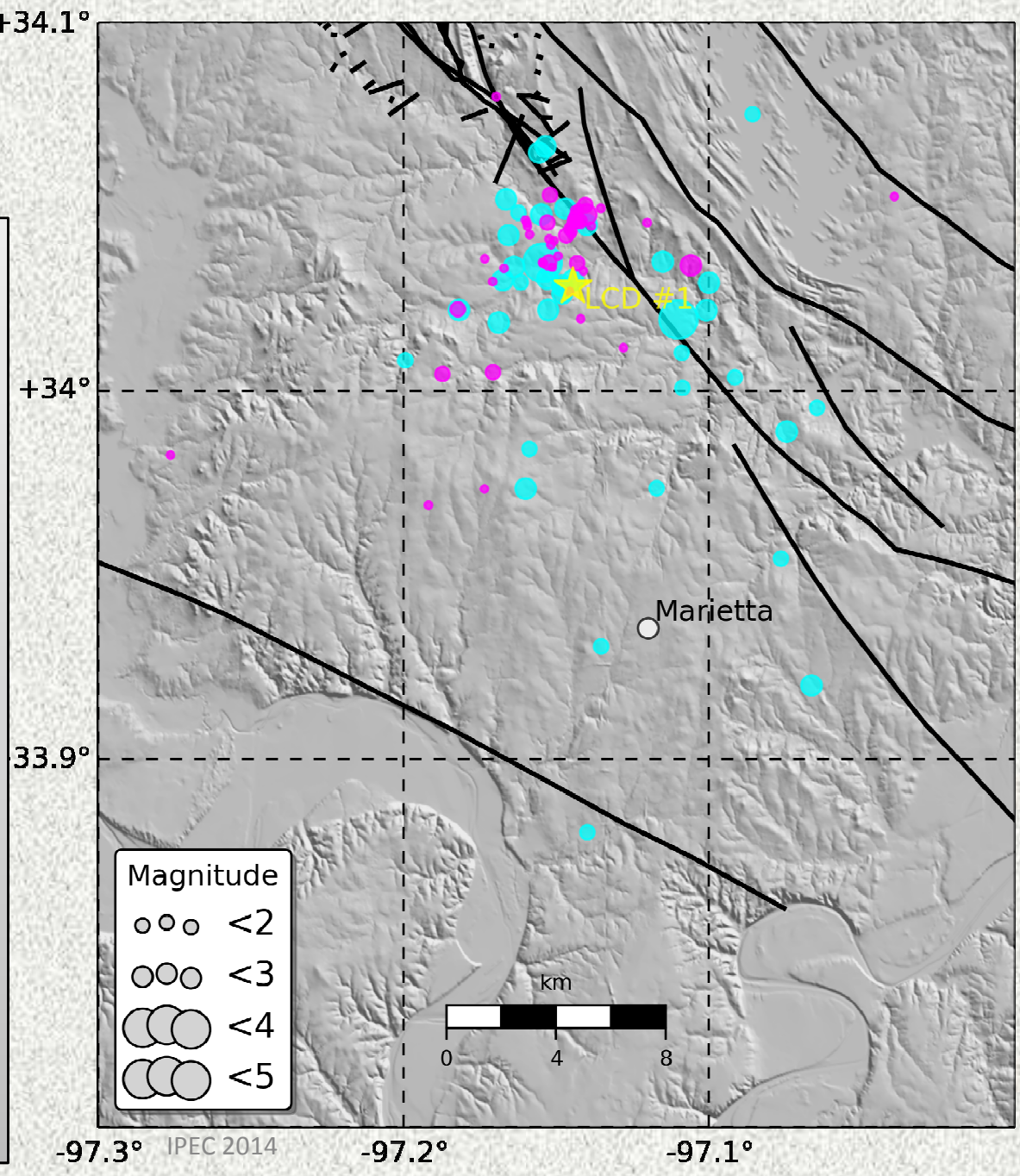
Holland, Bull. Seismol. Soc. Amer. (2013)

Recent potential cases of earthquakes triggered by disposal

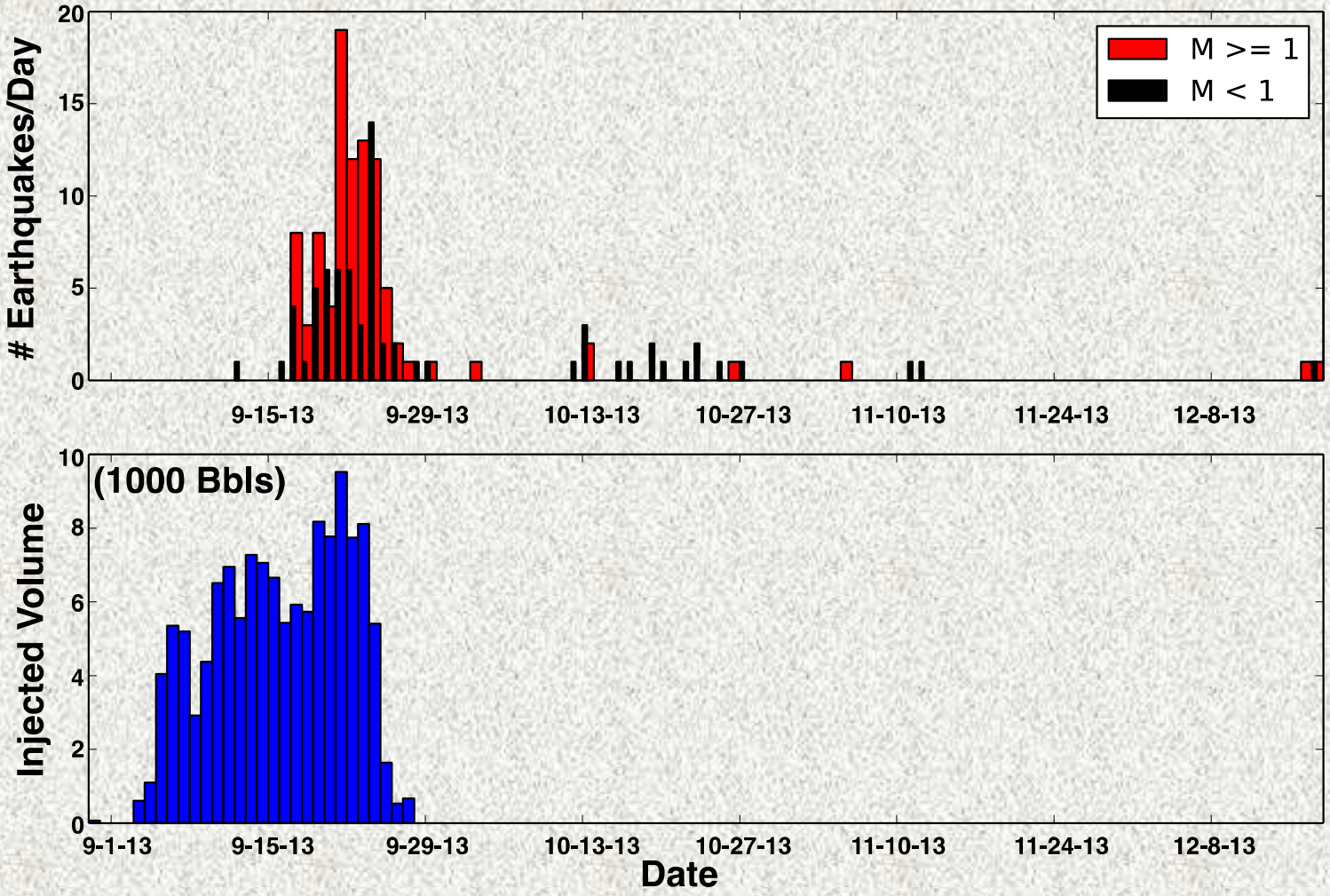
- Arkansas - Guy/Greenbrier
- Texas – DFW, Azzel, Cleburne
- Ohio – Youngstown
- Colorado – Raton
- Oklahoma – Prague, Jones, Hunton dewatering? and Mississippi Lime…

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

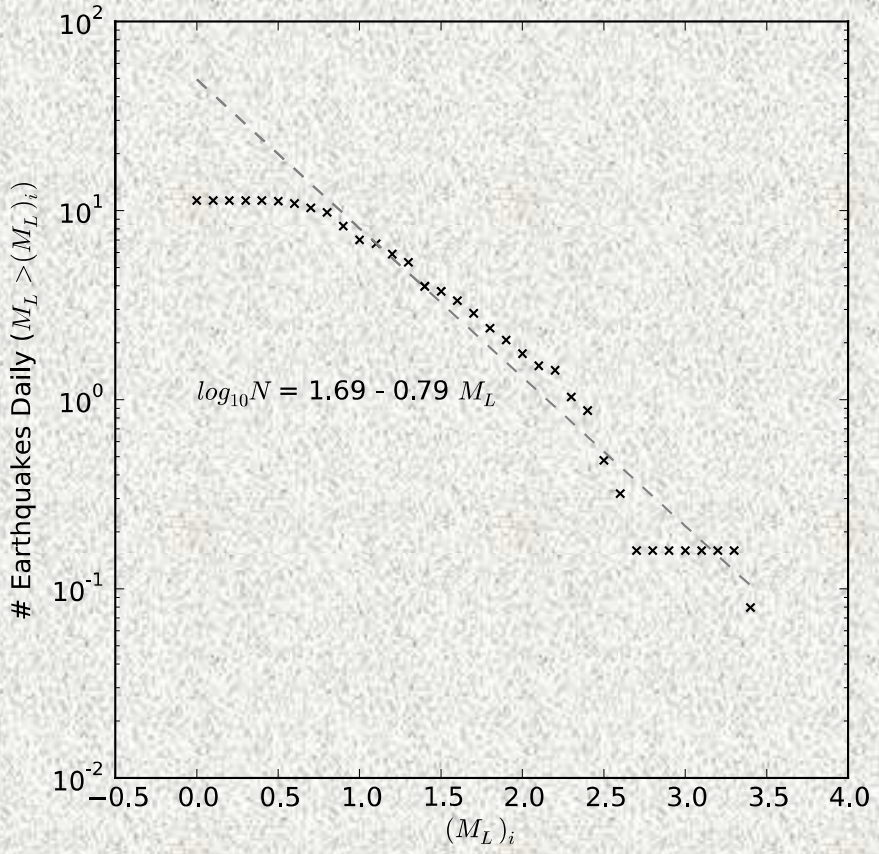


LCD #1 Injection and Earthquakes

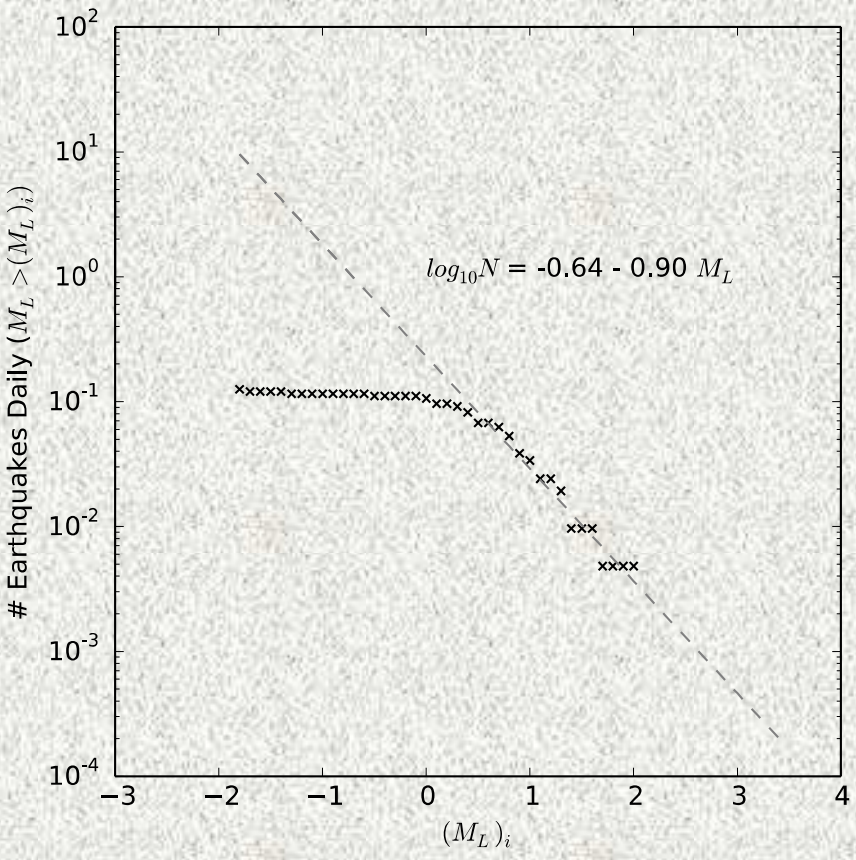


Recurrence and b-values

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

Questions or Comments?

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Abstract

Currently Oklahoma and the mid-continent are experiencing more magnitude three and greater earthquakes than the western United States. While few of these earthquakes have been damaging or strong these earthquakes raise many concerns from earthquake seismologist to local residents. The significance of the rate increase will be 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 waste-water disposal through injection poses the greatest chance of generating significant seismicity. Throughout the mid-continent a number of potential cases of induced seismicity from disposal wells exist. These cases will be summarized and then we will 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.