MEWBOURNE
COLLEGE OF EARTH & ENERGY
THE UNIVERSITY OF OKLAHOMA

Recent Earthquakes: Town Hall Meeting, June 26, 2014

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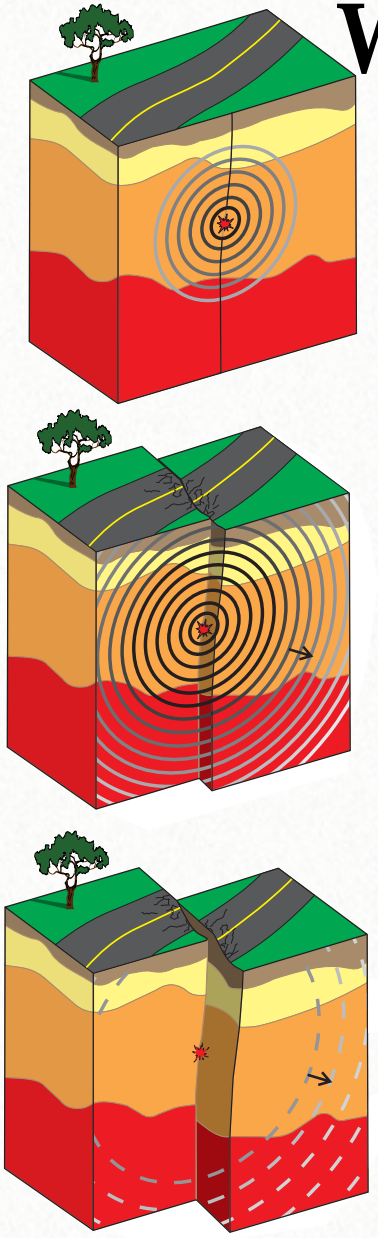
Outline

- Briefly address Induced Seismicity
- Earthquakes, global/regional and local seismicity
- Increased hazards and earthquake preparedness
- EQ triggering: What we know and what we can say
- Oil and Gas Technologies (OCC)
  - Response to potential induced seismicity
- Triggered/Induced seismicity by hydraulic fracturing and injection wells
- Ongoing research and projects at the OGS
- Recent earthquake swarms

Summary for potential induced seismicity

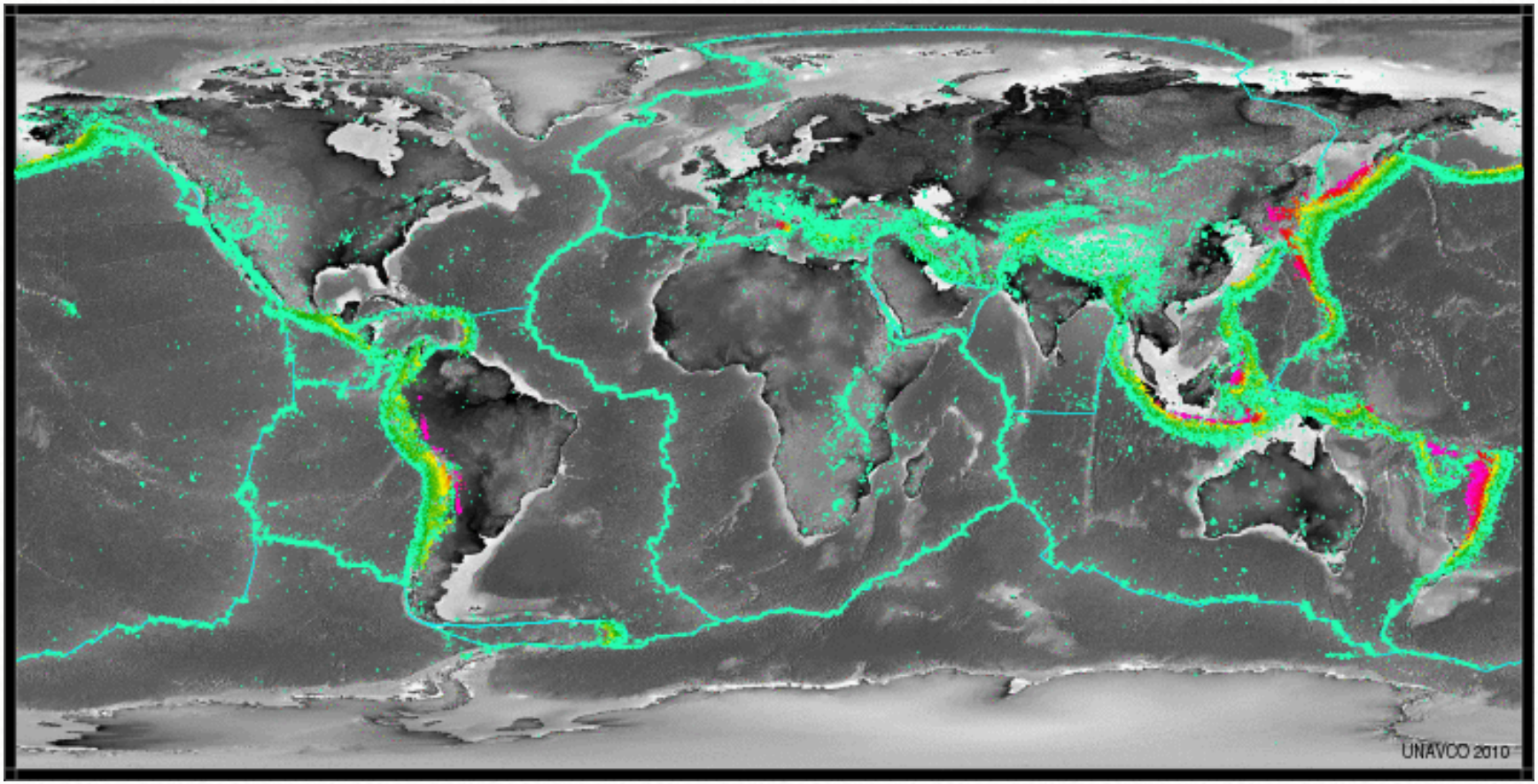
- No documented cases of induced seismicity have ever come close to the current earthquake rates or the area over which the earthquakes are occurring
- Long history of oil and gas activity and large number of wells require detailed research projects to identify induced seismicity
  - The usual simple 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

What is an Earthquake?

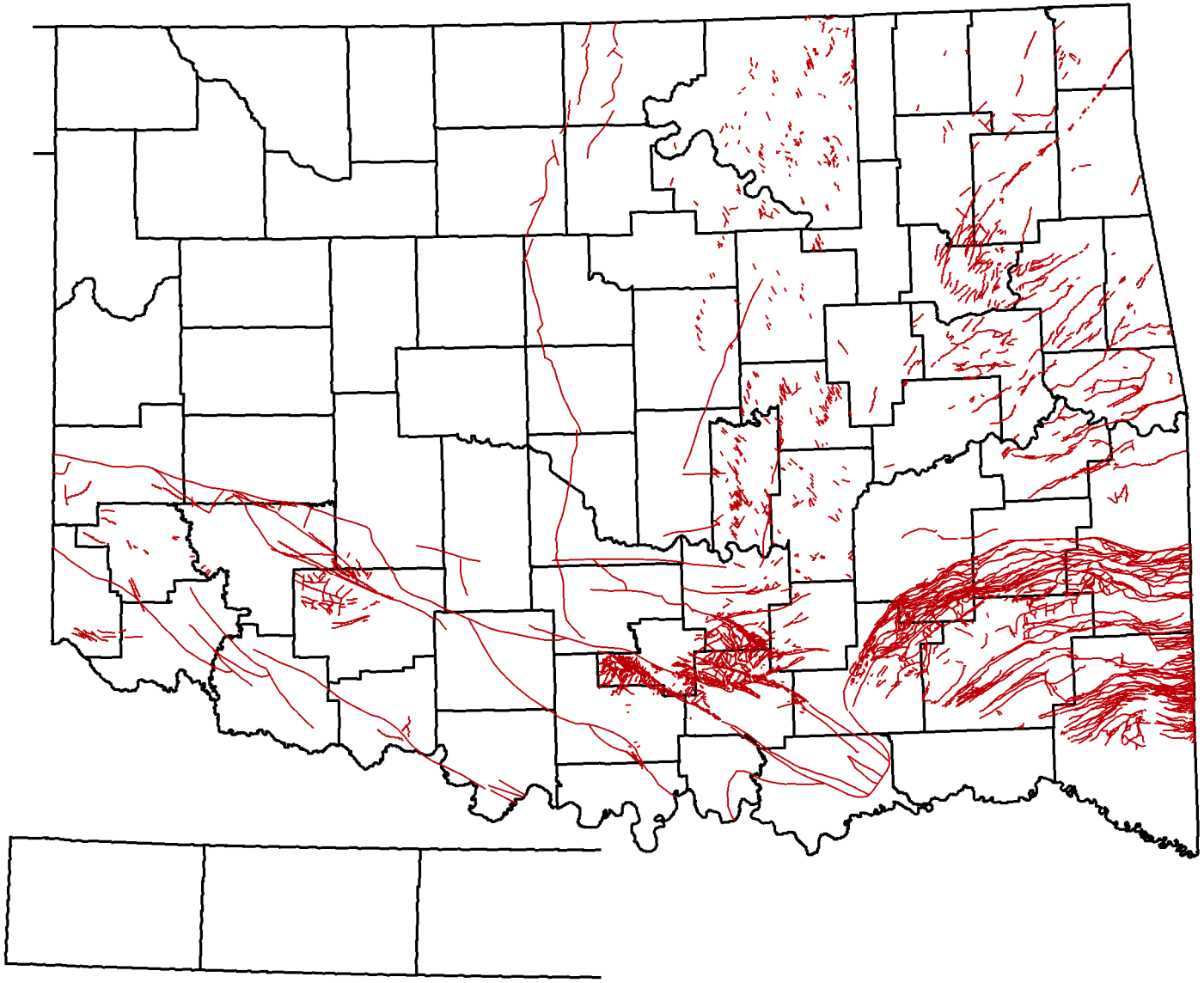


- When one body of rock slides past another
- When this occurs seismic waves "sound" is generated
- This sound radiates out in all directions and is what is measured at a seismic station
  - The recording is a seismogram
  - Waves are used locate and determine the size of the earthquake (magnitude)
  - Contain much more information
- In most earthquakes people feel the seismic wave

Earthquakes Worldwide



Mapped Faults in Oklahoma



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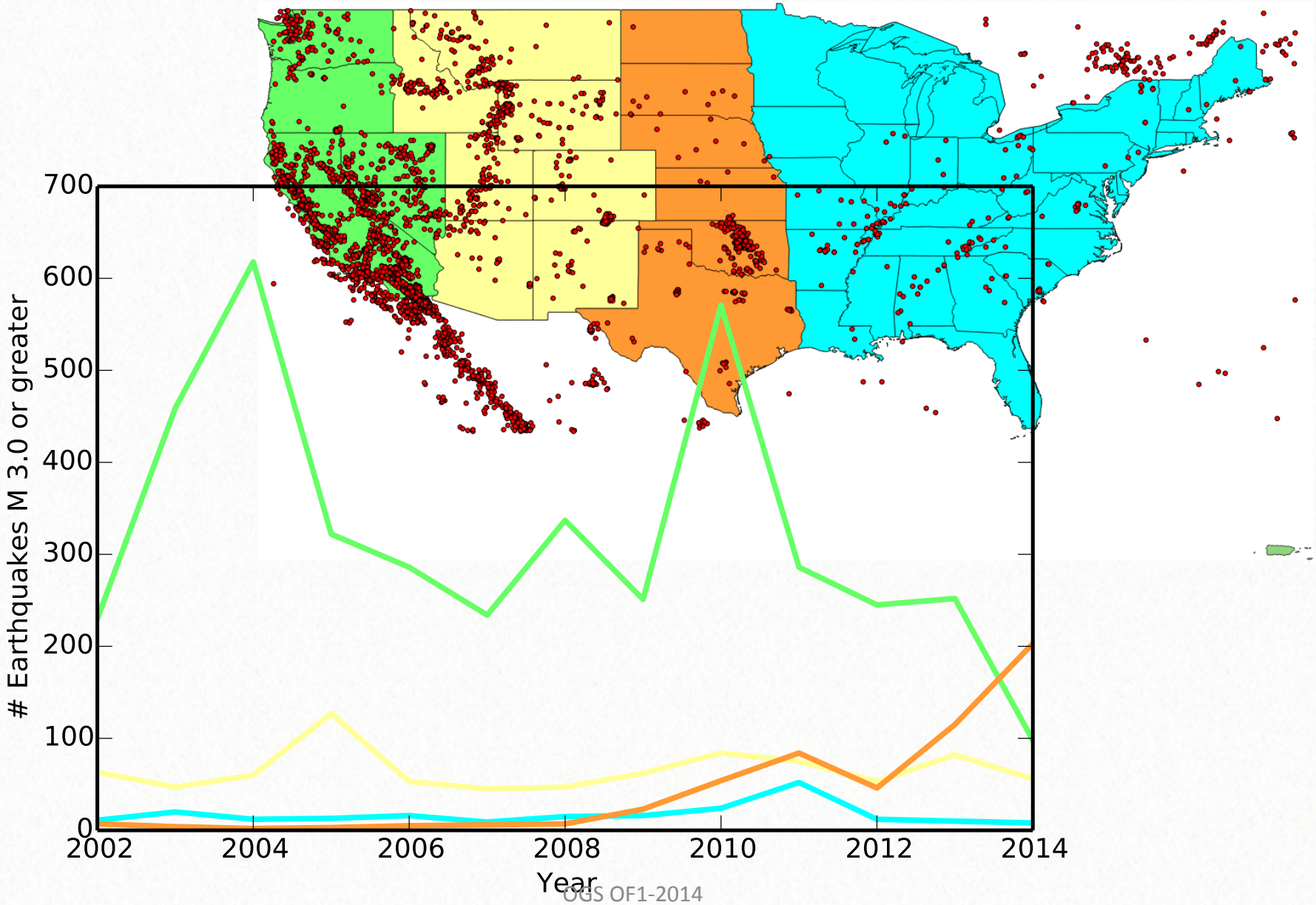
ANSS Earthquakes by Region



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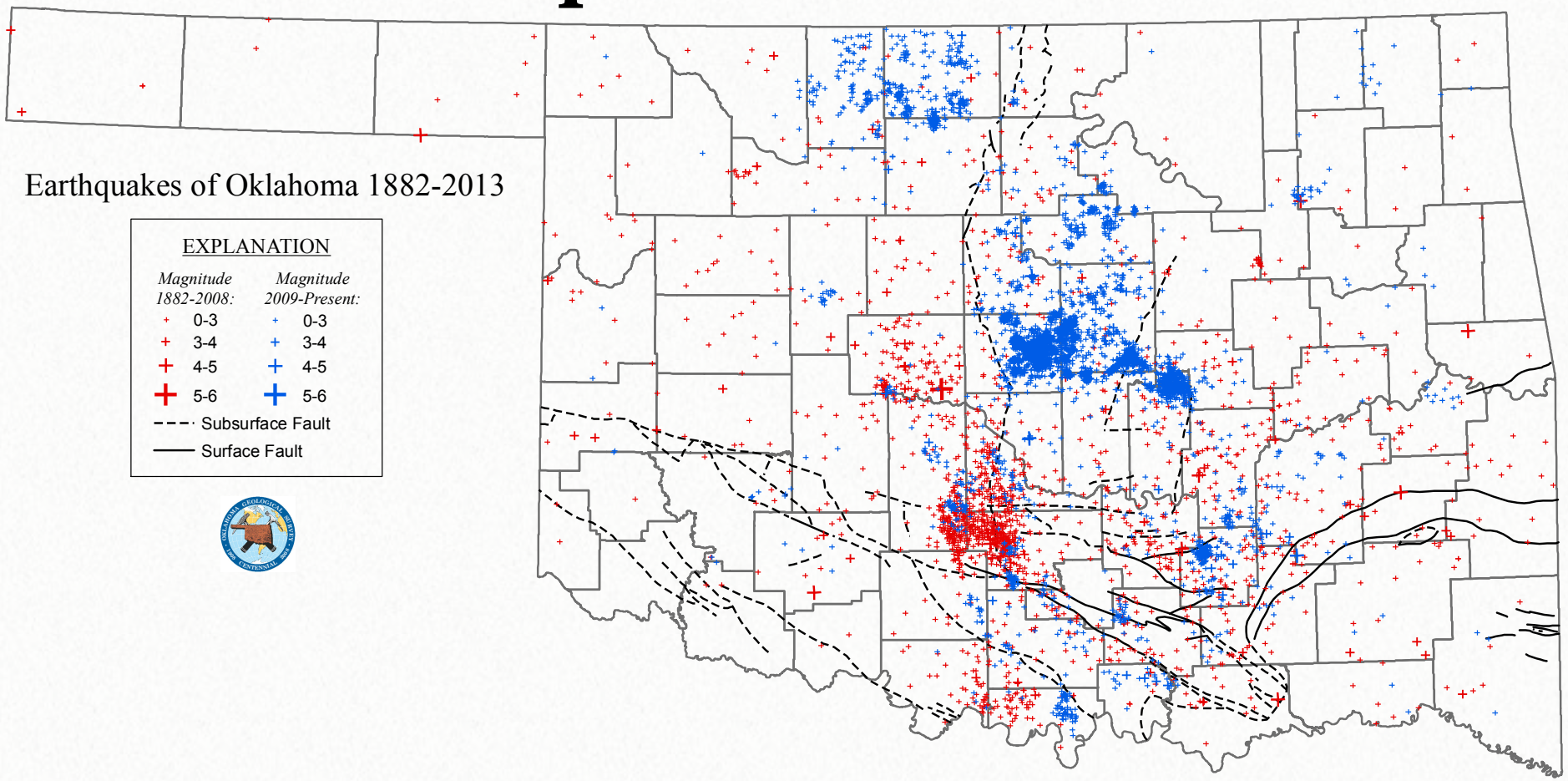
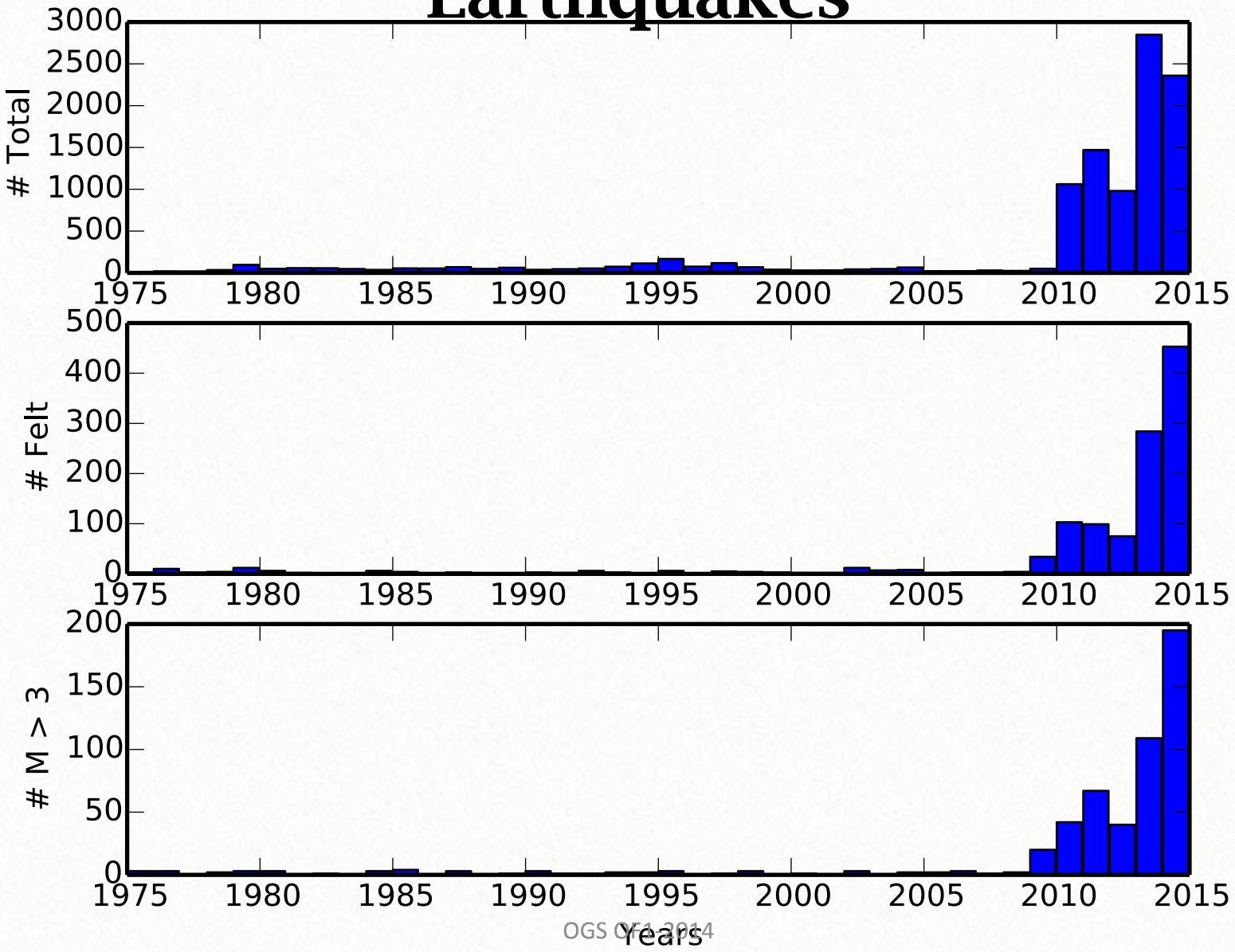
Earthquakes 1882-2013



Dramatic Increase in Oklahoma Earthquakes



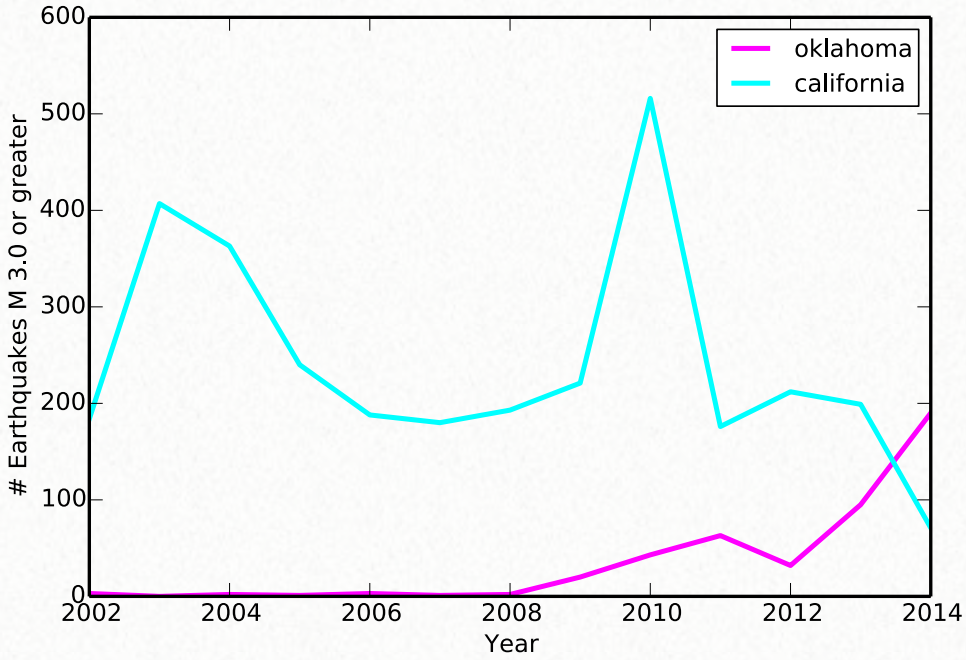
Increased Seismic Hazard

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 very large area ~25,000 km^2



Damaging Earthquakes in Oklahoma

- The chances of a large damaging earthquake in Oklahoma are quite small
- We can't know when or where the earthquakes will occur or stop them
- What we can do is prepare and understand what would be likely to occur in a damaging earthquake
- Most earthquake damage is comprised mostly of damage to unreinforced masonry

Earthquake Preparedness and Response

- Red Dirt Ready
- http://www.ready.gov/earthquakes
- http://shakeout.org/centralus/
- http://www.dropcoverholdon.org/
- http://www.earthquakecountry.info/roots/index.php

- http://www.okgeosurvey1.gov/pages/prepare.php

What to do and not do in an Earthquake

Don't

- Panic
- Run from (exit) a building
  - Most damage occurs to unreinforced masonry (brick and stone façade, chimneys)
  - Wholesale building collapse is less likely
- Get in a doorway
  - Swinging doors can cause injuries

Earthquake Triggering and Induced Seismicity

Natural Causes

- Dynamically by the passage of seismic waves
- Remote Triggering
- Statically by local stress changes from previous earthquakes
  - Small amounts of stress changes have been shown to trigger earthquakes
  - as little as 2-7 psi
- Natural fluid movement
  - May be the cause of many aftershocks
- Hydrologic loads

Anthropogenic

- Reservoir Impoundment
- Mining and Oil Production (Mass Removal)
- Fluid Injection
- Hydraulic fracturing
- Geothermal Production

- Physics of earthquake triggering and induced seismicity are well understood.
- What is not well understood are the physical properties within the Earth that control when and where IS occurs.

Numbers of Documented Induced Seismicity Cases

Energy technology	Number of projects	Number of felt-induced events	Maximum magnitude of felt event	Number of events M > 4.0 [c]	Net reservoir pressure change	Mechanism for induced seismicity
Secondary oil and gas recovery (waterflooding)	~108,000 (wells)	One or more felt events at 18 sites across the country	4.9	3	Attempt to maintain balance	Pore pressure increase
Tertiary oil and gas recovery (EOR)	~13,000	None known	None known	0	Attempt to maintain balance	Pore pressure increase (likely mechanism)
Hydraulic fracturing for shale gas production	~35,000 wells total	1	2.8	0	Initial positive; then withdraw	Pore pressure increase
Hydrocarbon with-drawal	~6,000 fields	20 sites	6.5	5	Withdrawal	Pore pressure decrease
Wastewater disposal wells	~30,000	8	4.8 [b]	7	Addition	Pore pressure increase

Shemeta et al. TLE (2012) taken from:
National Research Council - Induced Seismicity Potential in Energy Technologies

Matt Skinner
Oklahoma Corporation Commission

Earthquakes Triggered by Hydraulic Fracturing

- More readily identifiable than IS from long term injection
  - At most 2% of wells and 10% of earthquakes
  - Cannot explain most of the ongoing earthquake sequences
- Cases have been documented in Ohio, Oklahoma, UK, British Columbia
  - Mmax ~ 3.8
  - Not expected to contribute to large numbers or large magnitudes of earthquakes
- Opportunities for research
  - May provide insight into state of stresses, properties, and processes within the Earth
  - Increase in microseismic monitoring may help improve our understanding
  - Much more geotechnical data possibly available

Earthquakes Triggered by Fluid Injection

Challenges

- Earthquake rate changes over such a large area would be unprecedented (~25,000 km^2)
- Why now?
  - Same technologies used for 60 years
- More difficult to identify
  - Not observing some of the typical behaviors of IS
- Likely many cases of induced seismicity
  - How do we sort out the cases that have the potential to advance our understanding?

Opportunities

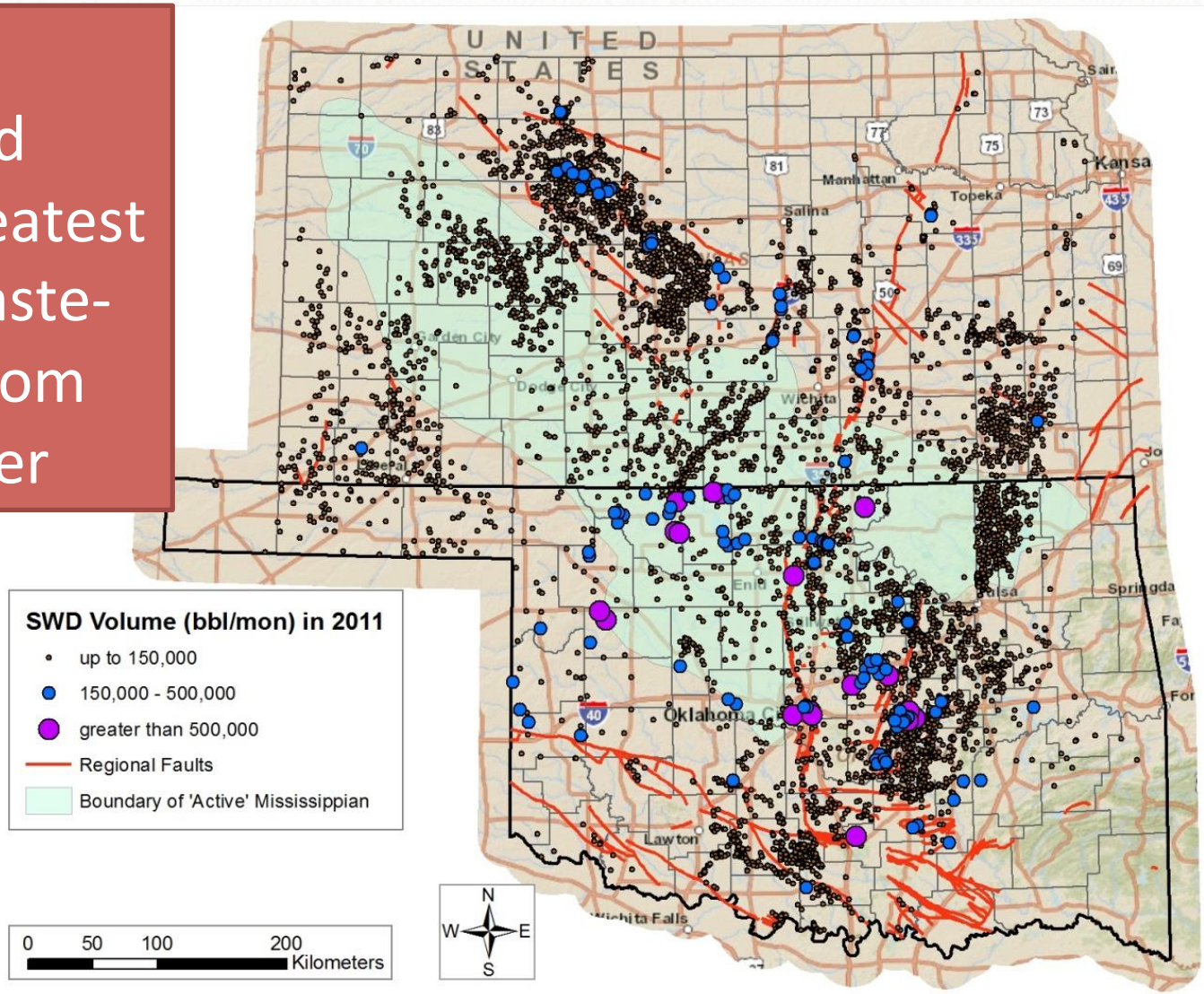
- With proper study triggered seismicity might be mitigated
- Identifying critically stressed faults
- New opportunities for research
  - Multiyear multi-disciplinary collaborative project at OU
- Much more geotechnical data possibly available

Triggered Seismicity from UIC Class II Wells

- Disposal wells are recognized as the the greatest hazard
  - Longer durations of injection
  - Greater volumes -> greater magnitude?
- EOR wells may be less of an issue because of the balance of volumes and pressures
- Much more difficult to identify
  - Large number of wells (Oklahoma)
    - >4,000 disposal wells
    - >5,000 EOR wells
  - Injection occurs for a significant amount of time
  - Less geotechnical information available vs production wells
  - Globally, cases that have been identified generally involve individual wells
  - The interaction of wells is unclear and requires further research

Disposal Wells

In Texas, Oklahoma, and Kansas the greatest volumes of waste-water come from produced water



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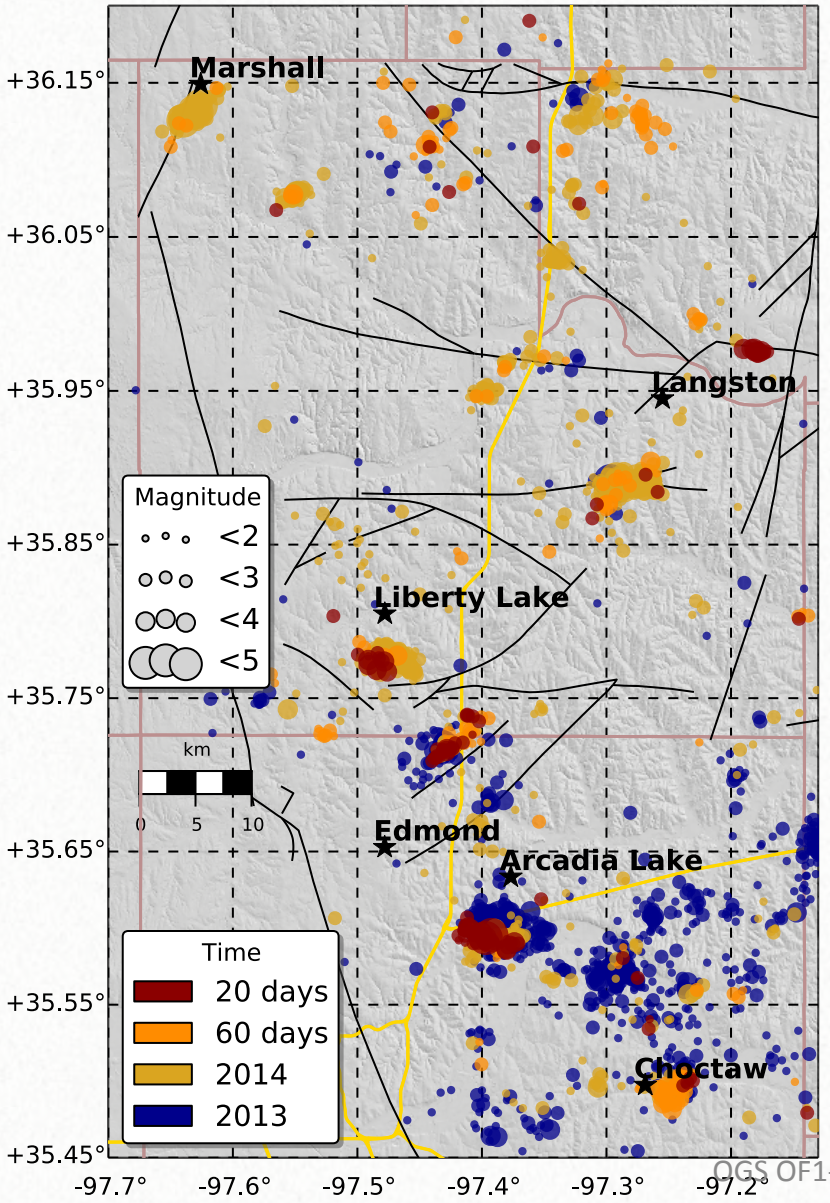
Current Efforts

- Multiyear multi-disciplinary collaborative DoE funded project at OU ($1.8 million including cost sharing from industry and state agencies)
  - Adding permanent and temporary seismic stations to the regional network
  - Risk mitigation and management
- Working with industry and other researchers to improve our understanding of
  - Faults in Oklahoma
  - Stress in the subsurface
- Test whether the ”Traffic Light System” and other methods can work to manage/mitigate risk
- Increased public outreach and education
- OGS Resources
  - http://www.okgeosurvey1.gov/pages/research.php
  - http://www.okgeosurvey1.gov/pages/earthquakes/induced-seismicity.php

Logan and Northern Oklahoma County Seismicity



2013-2014
Earthquake sequences
(south to north):

- Choctaw
- Southern Arcadia Lake
- Waterloo Road
- Liberty Lake
- Langston
- Marshall

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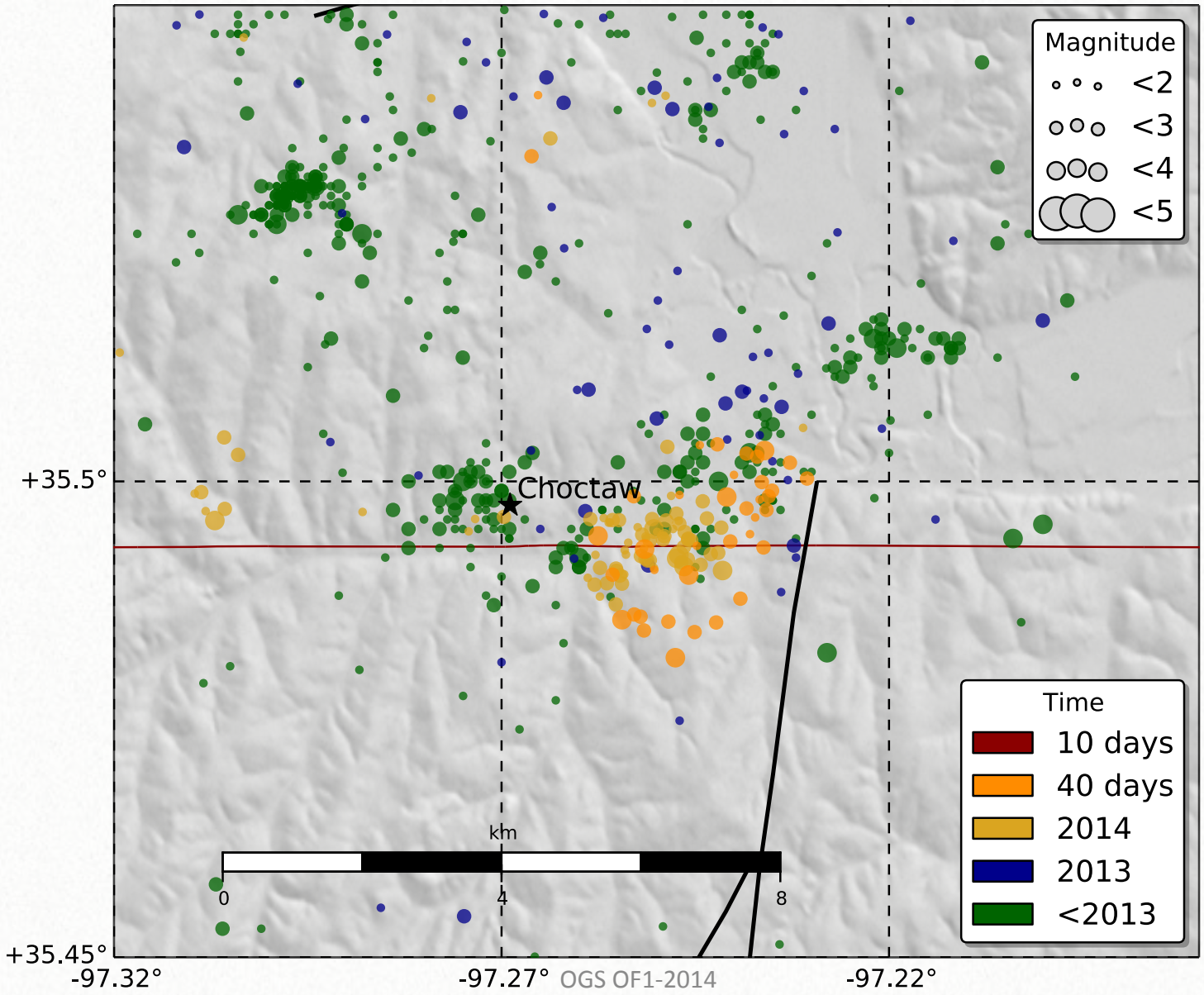
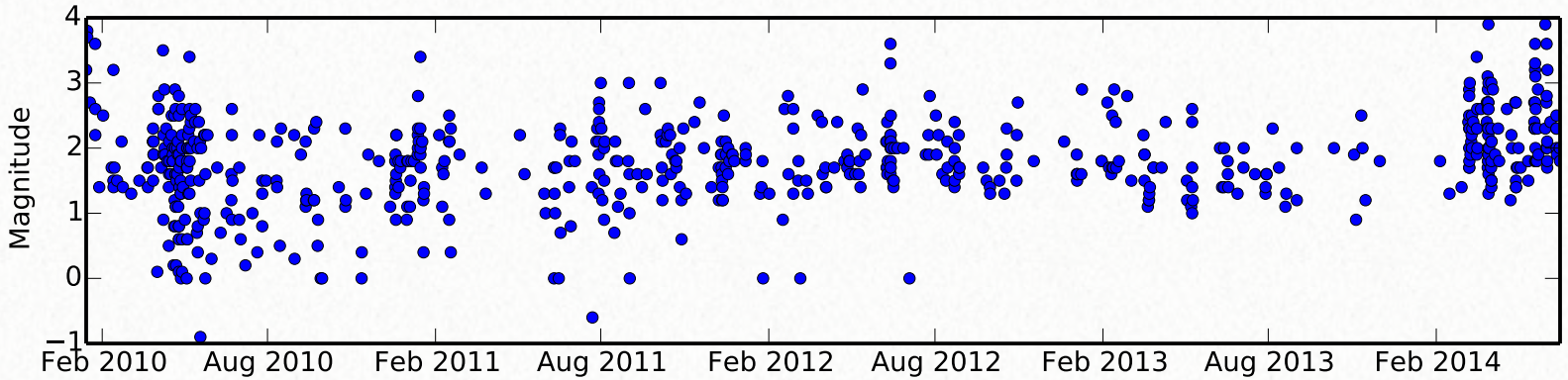
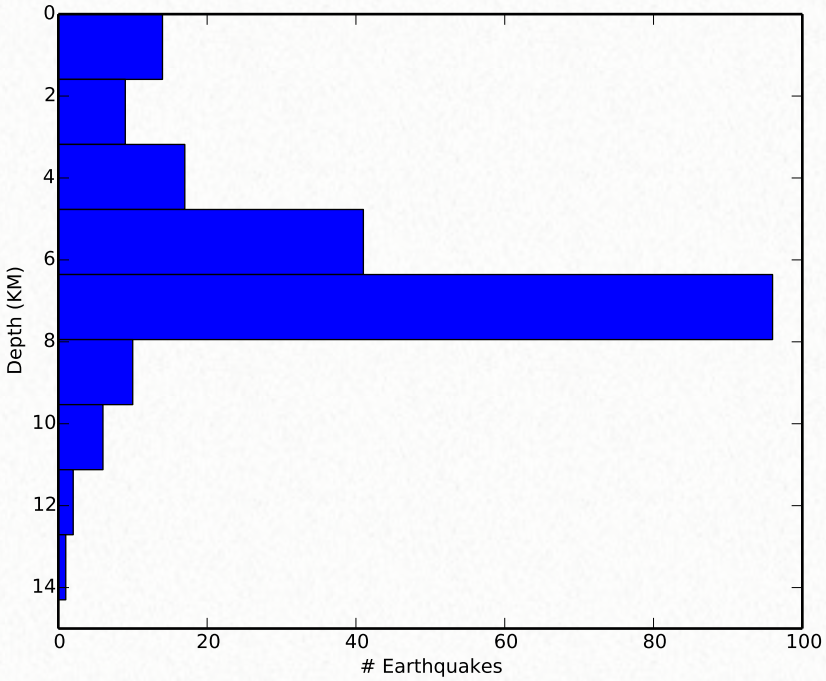
Choctaw Sequence



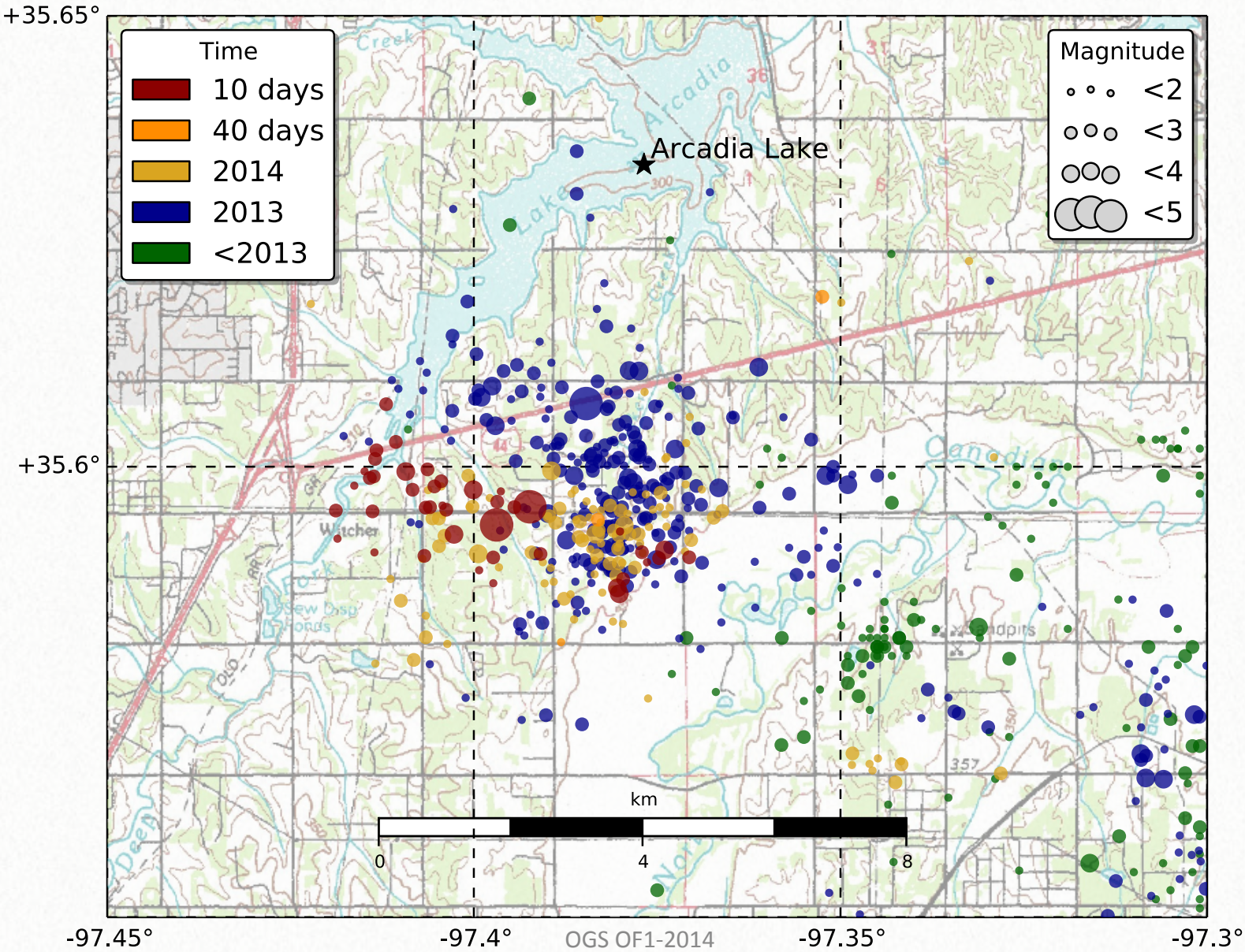


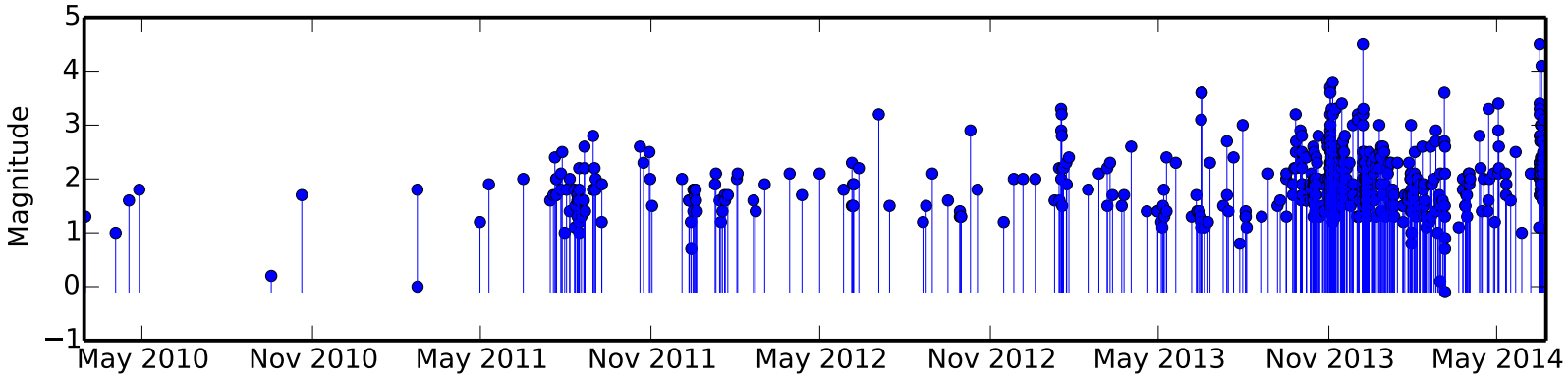
Choctaw Sequence (2010-present)

- 636 earthquakes located to date
- 26 events >= M3.0
- 92 events felt
- Median depth of events are 6.8km or 4.2mi



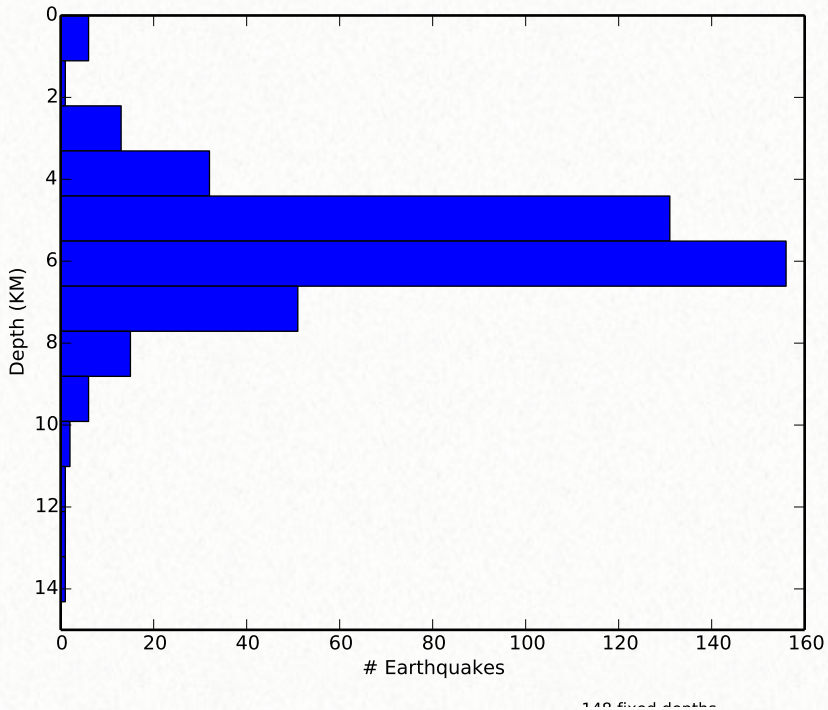
Southern Arcadia Lake Swarm



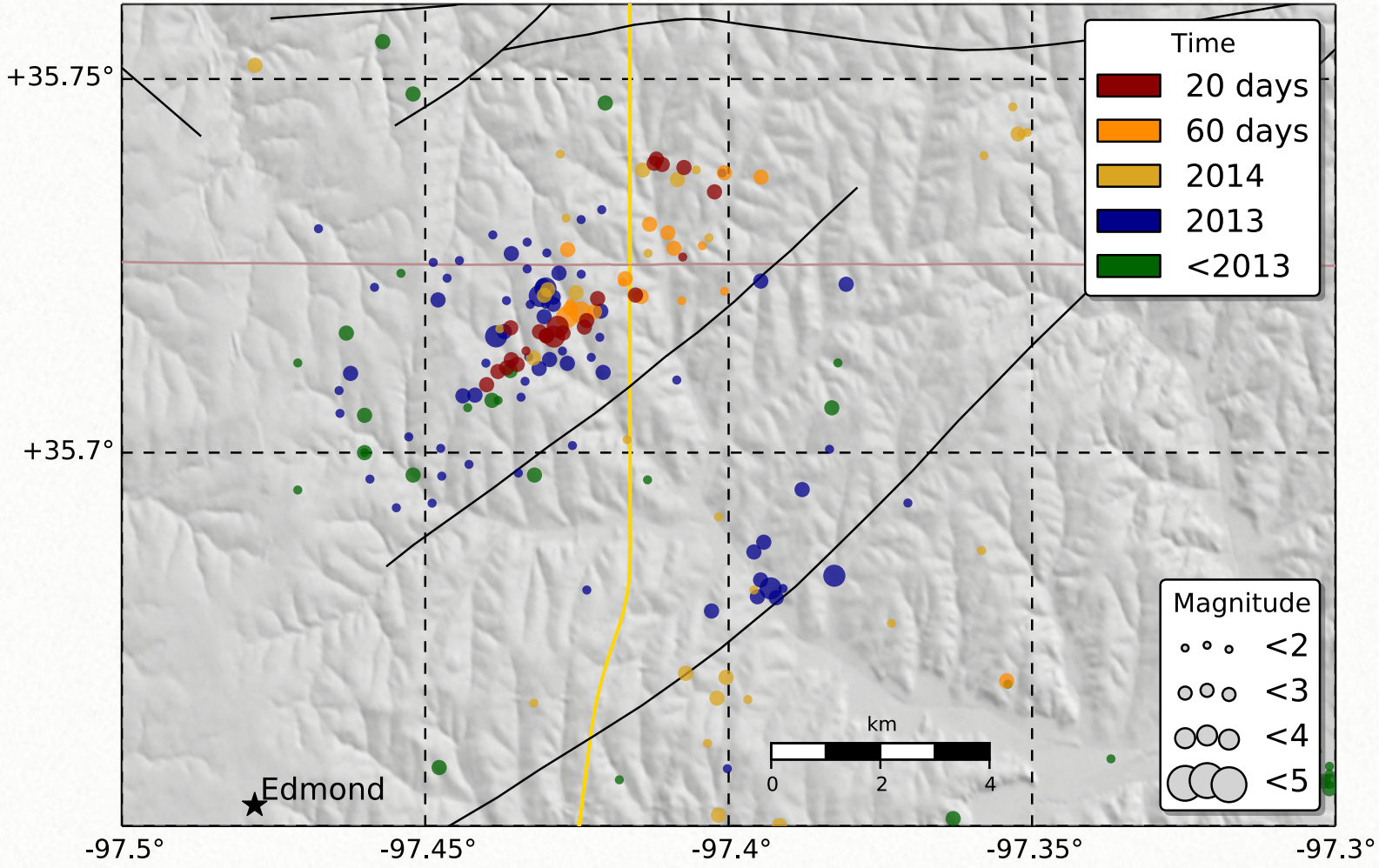


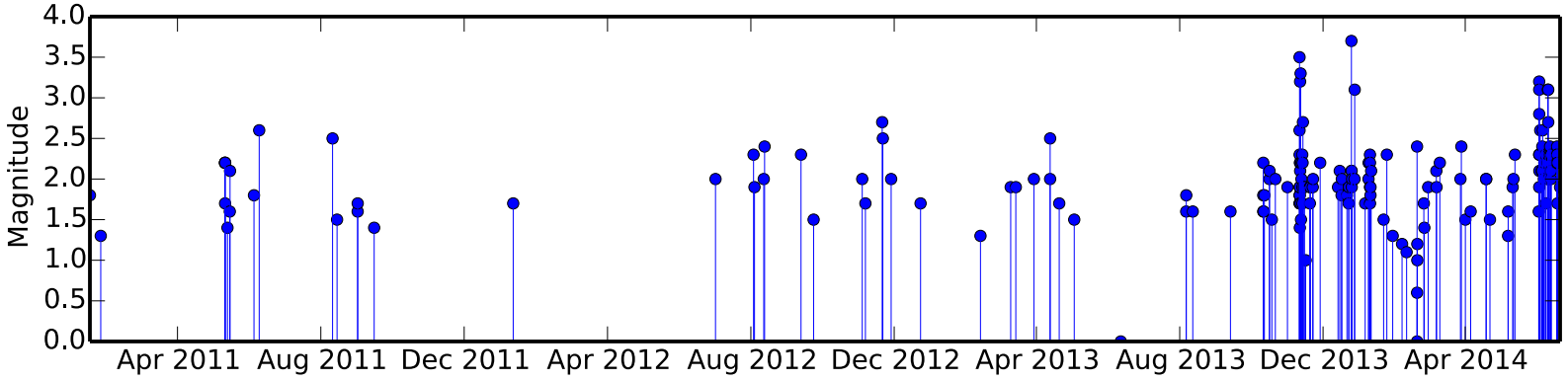
Southern Arcadia Lake Swarm (2010-present)

- 565 earthquakes located to date
- 38 events >= M3.0
- 100 events felt
- Median depth of events are 5.66km or 3.5mi



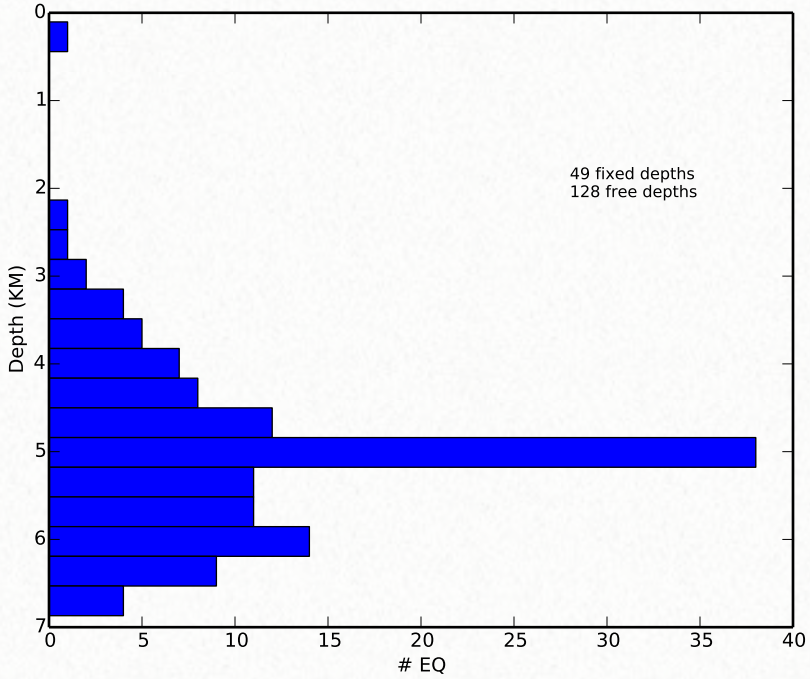
Waterloo Road Sequence



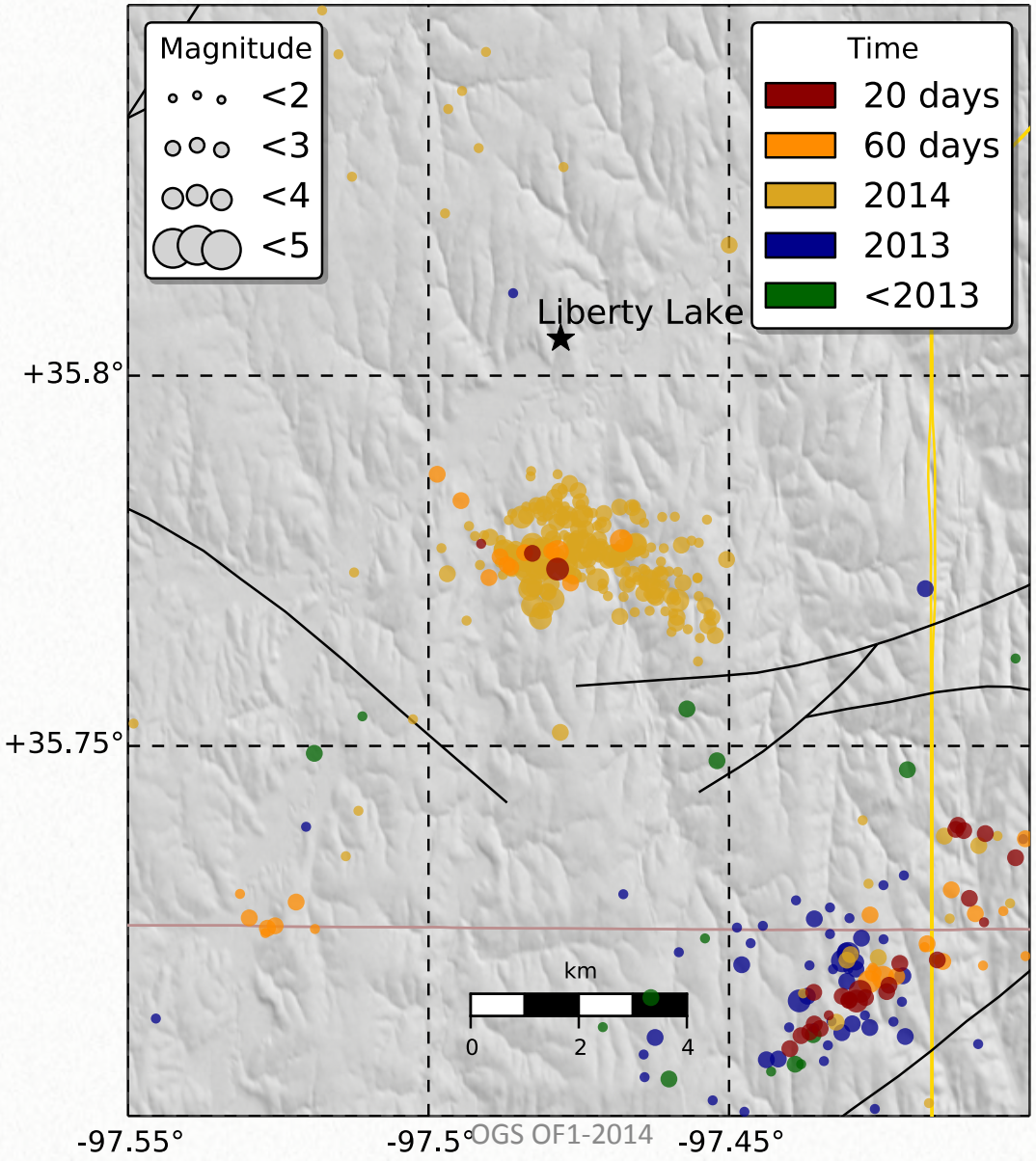


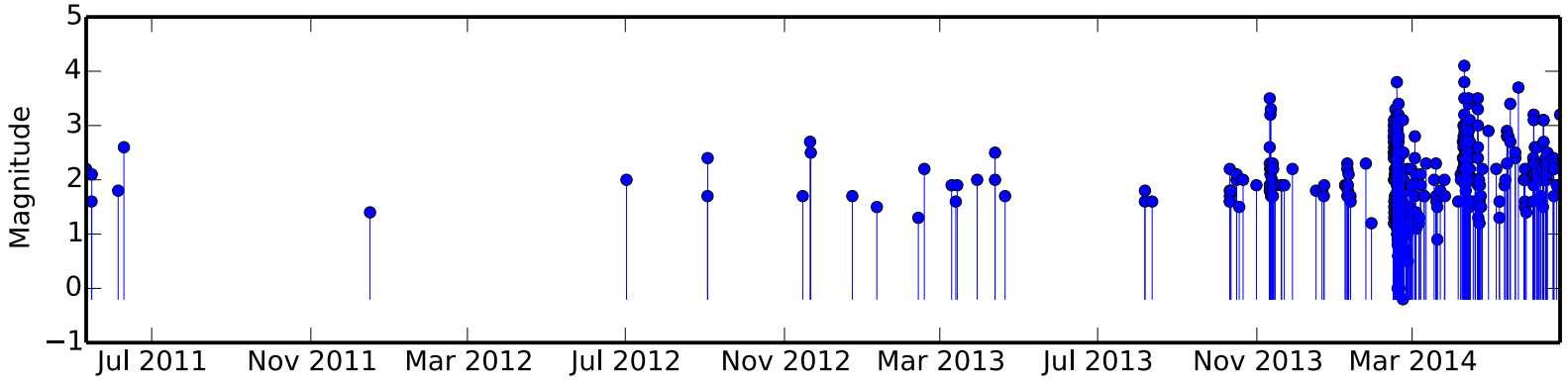
Waterloo Road Sequence (2010-present)

- 177 earthquakes located to date
- 9 events >= M3.0
- 50 events felt
- Median depth of events are 5.0km or 3.1mi



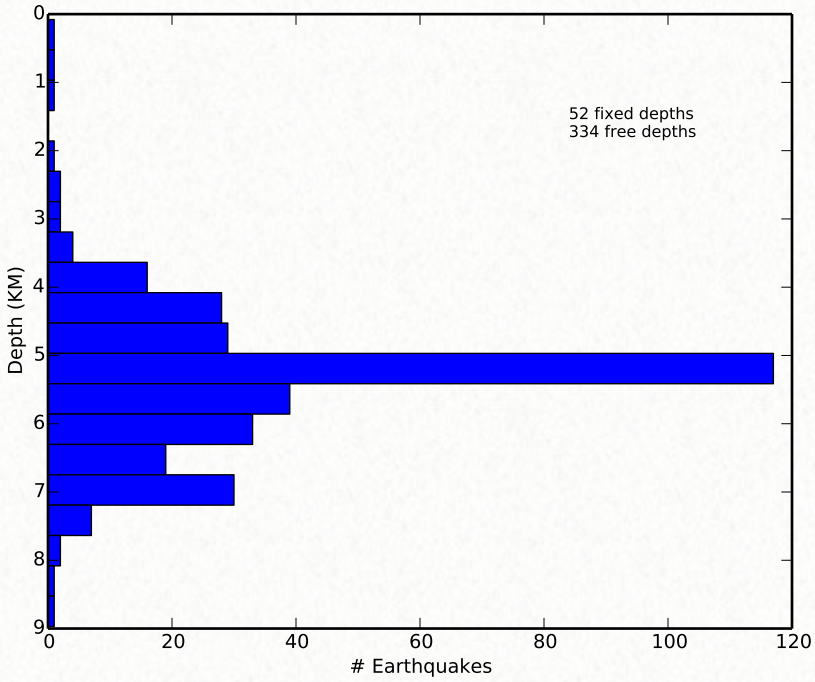
Liberty Lake Sequence



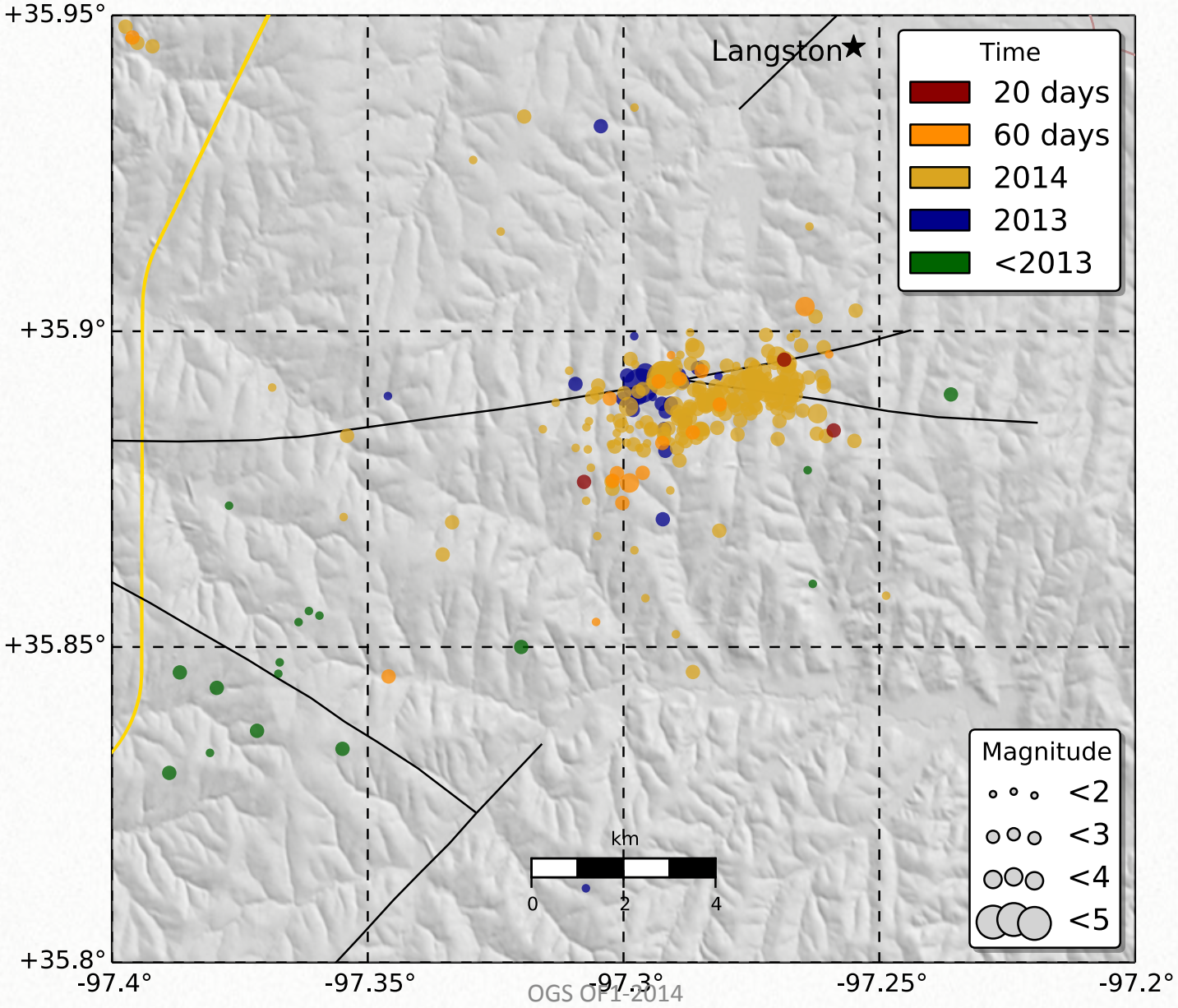


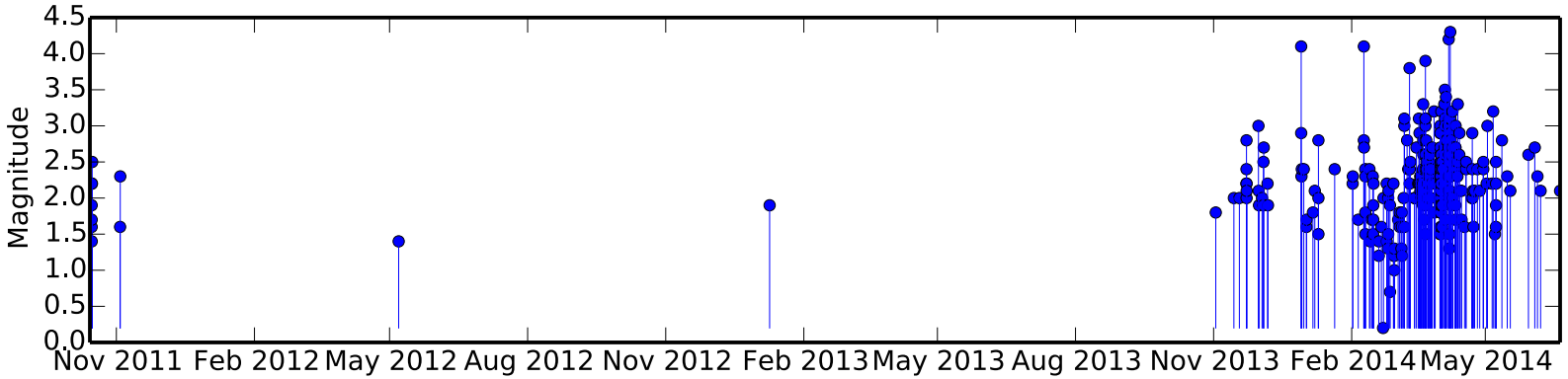
Liberty Lake Sequence (2010-present)

- 386 earthquakes located to date
- 34 events >= M3.0
- 113 events felt
- Median depths of events are 5.0km or 3.1mi



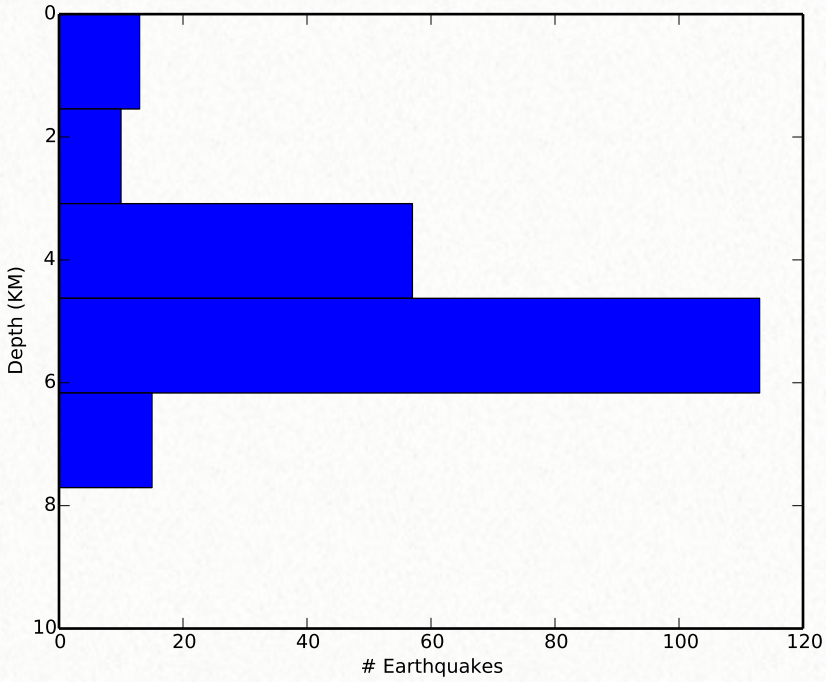
Langston Sequence



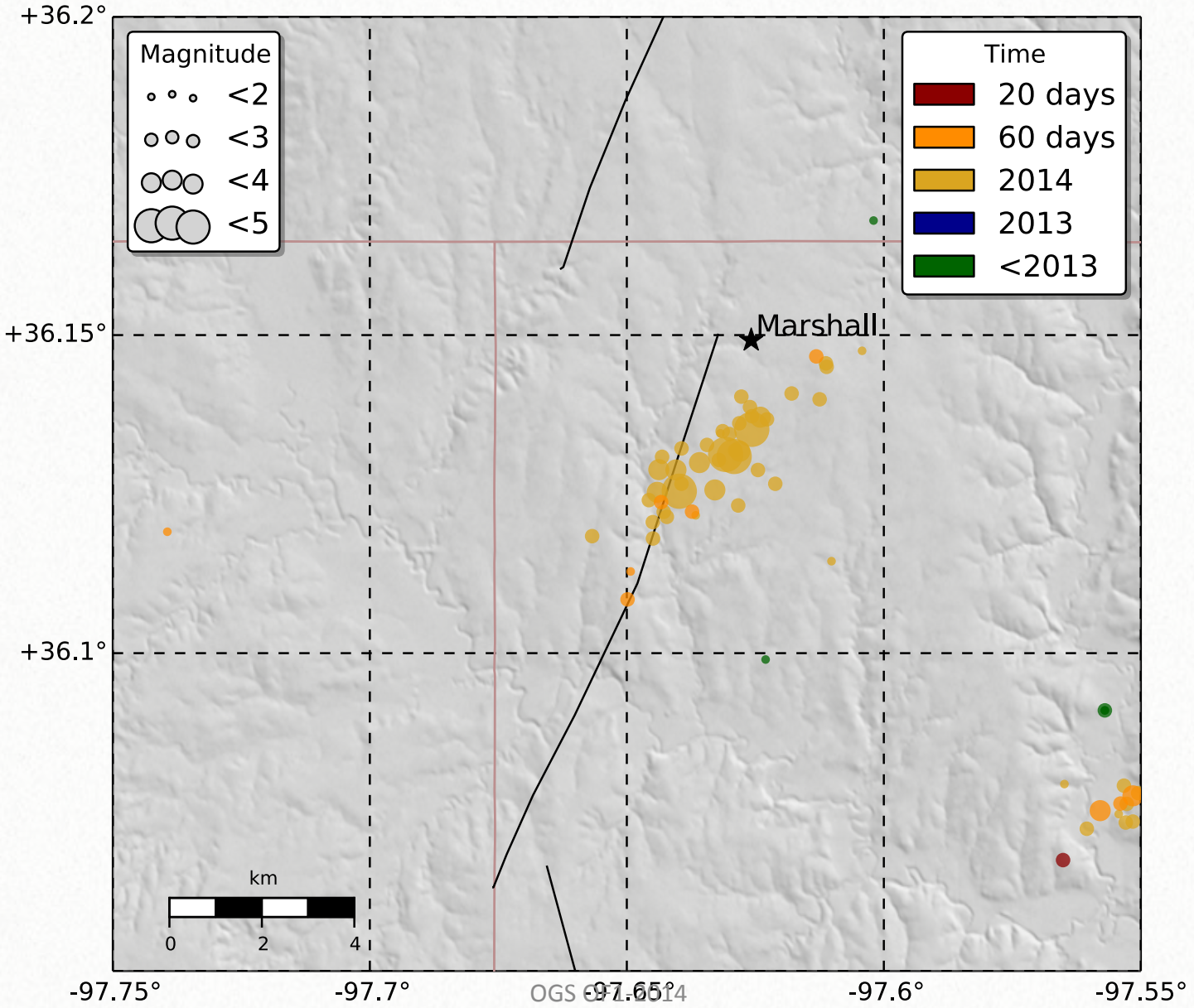


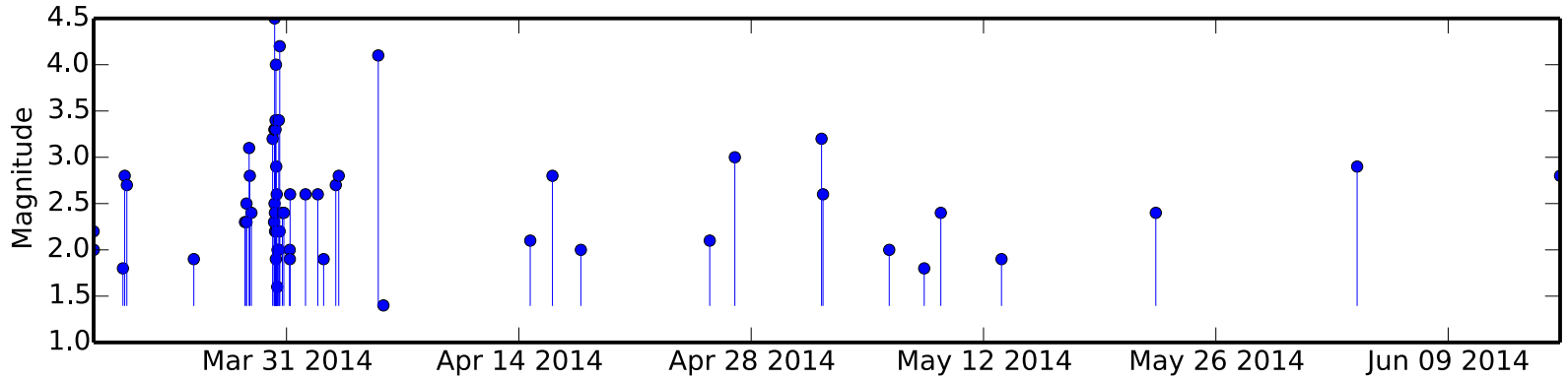
Langston Sequence (2010-present)

- 282 earthquakes located to date
- 30 events >= M3.0
- 52 events felt
- Median depths of events are 5.0km or 3.1mi



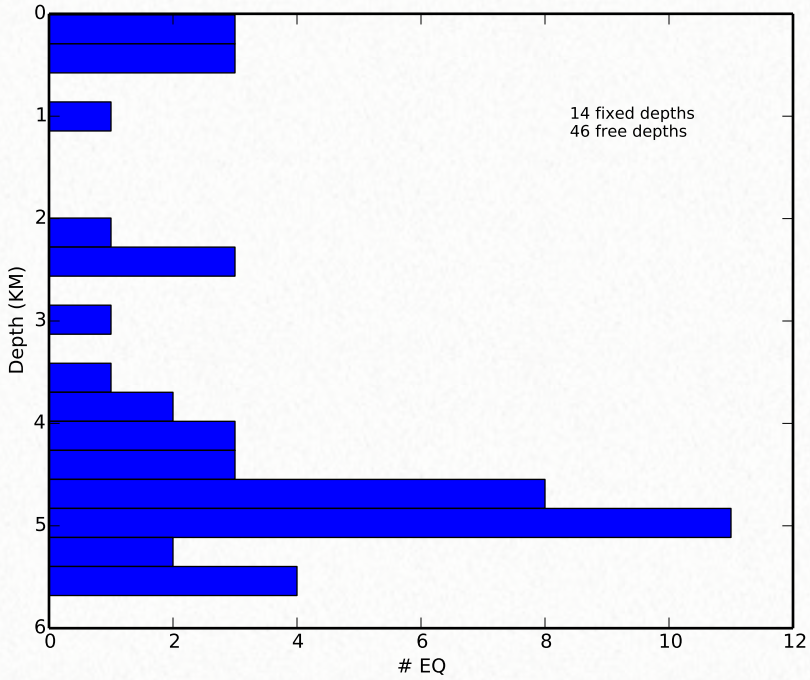
Marshall Sequence

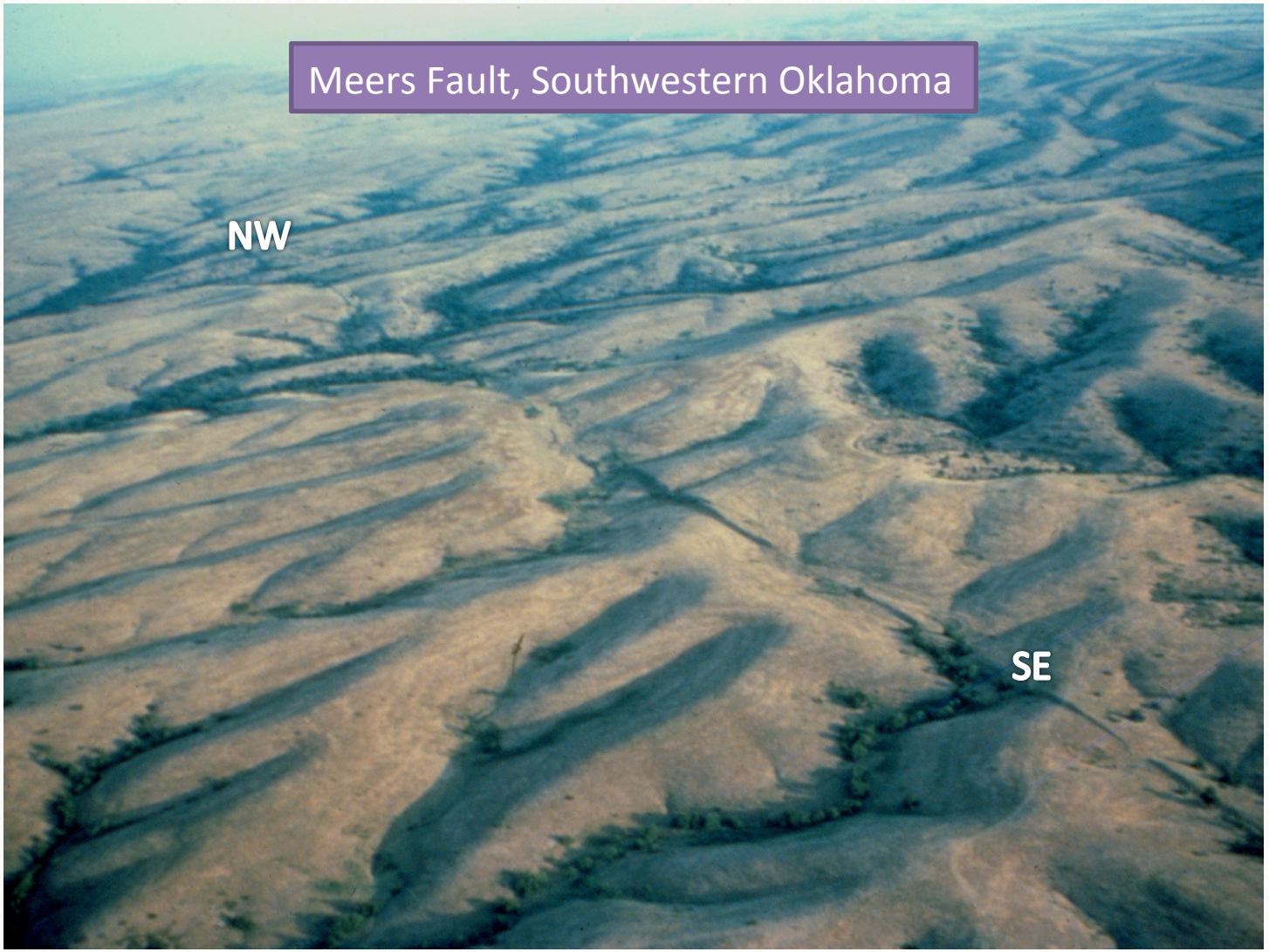




Marshall Sequence (2010-present)

- 60 earthquakes located to date
- 13 events >= M3.0
- 17 events felt
- Median depth of events are 4.6km or 2.85mi



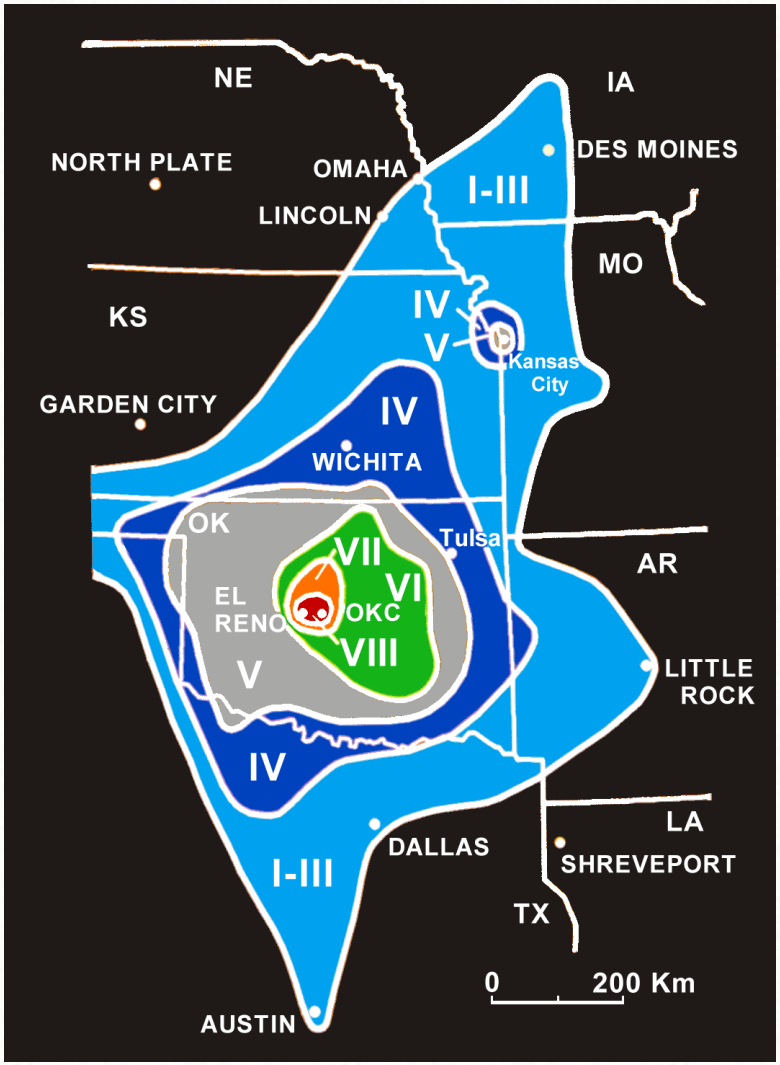


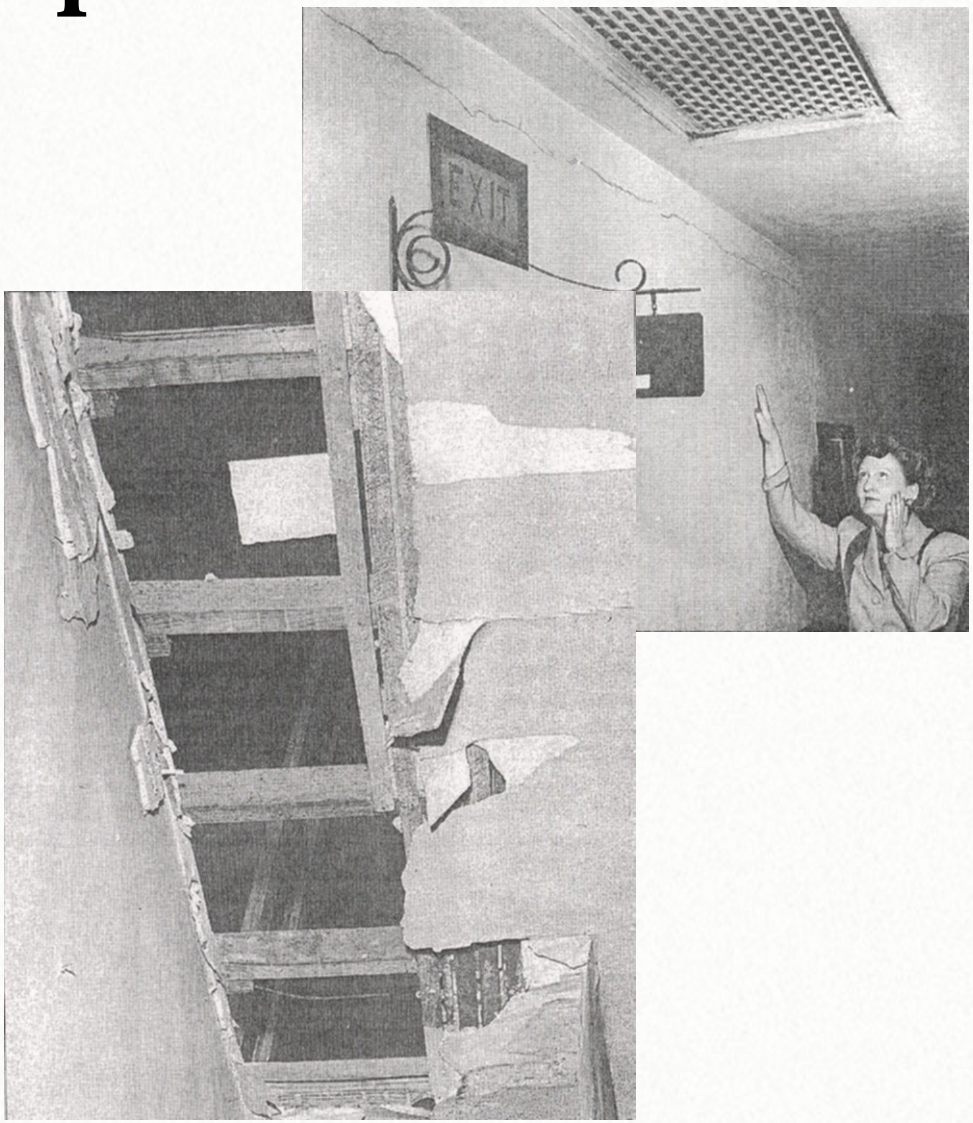
Questions?

www.okgeosurvey1.gov

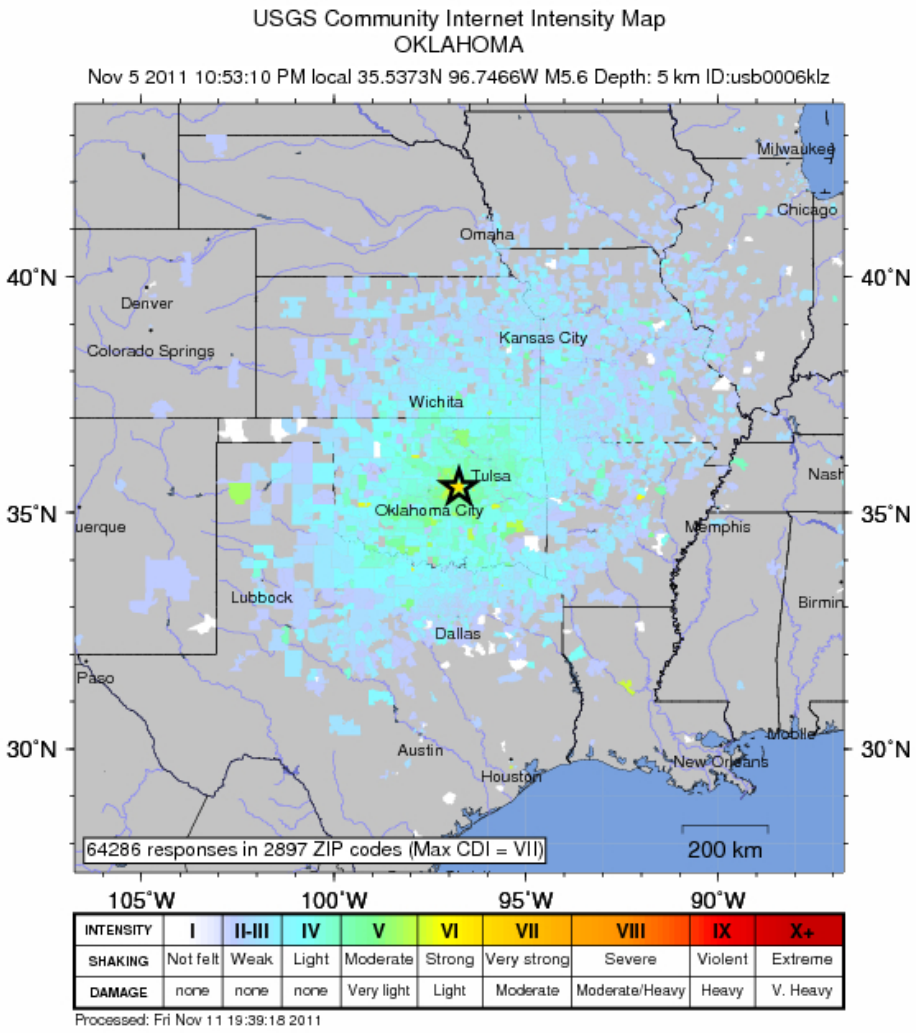
OGS Open File Report OF1-2014

El Reno, April 9 1952



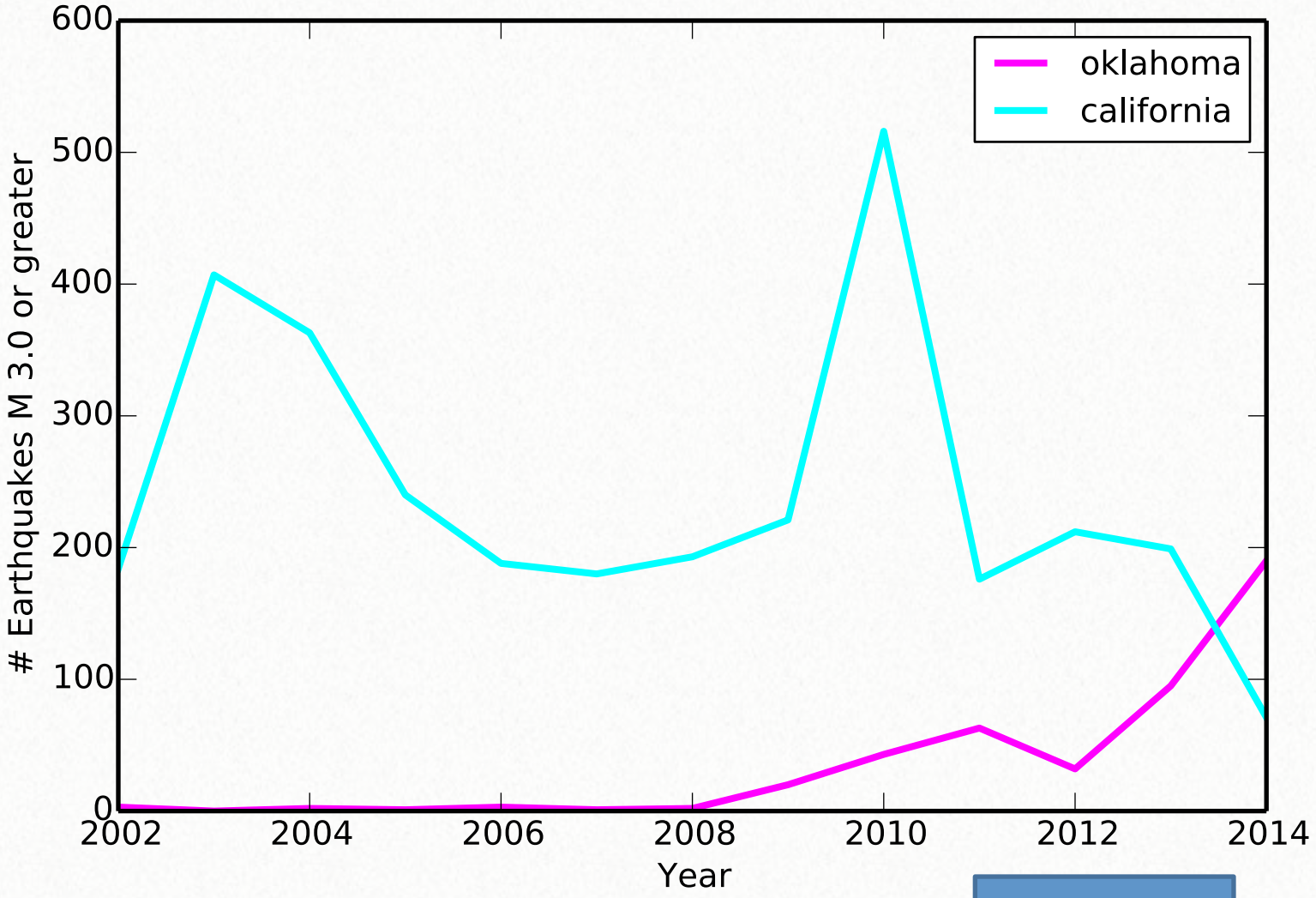


November 2011, Prague Earthquakes



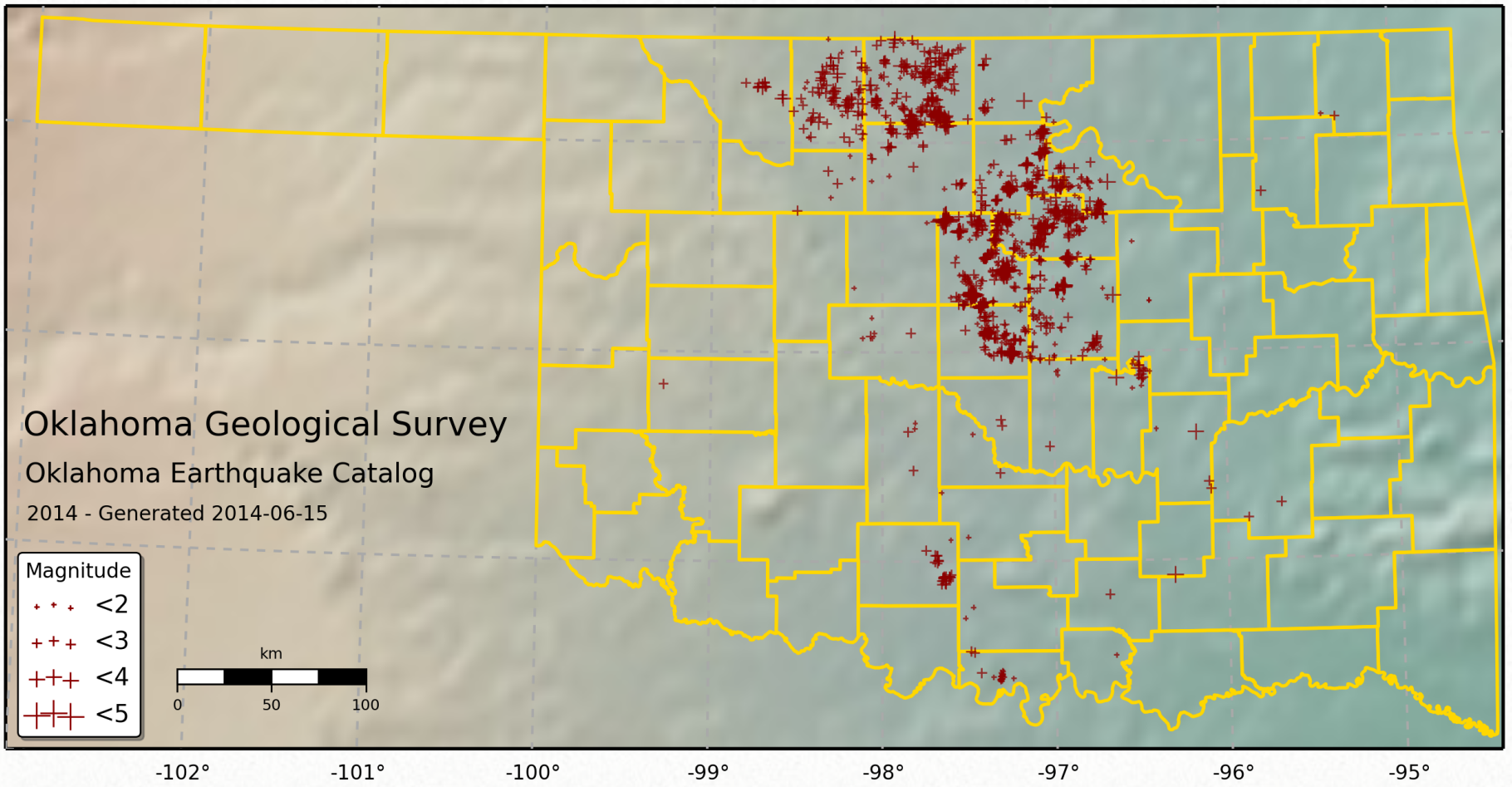
Damage to unreinforced masonry

Mid-continent increase primarily in Oklahoma

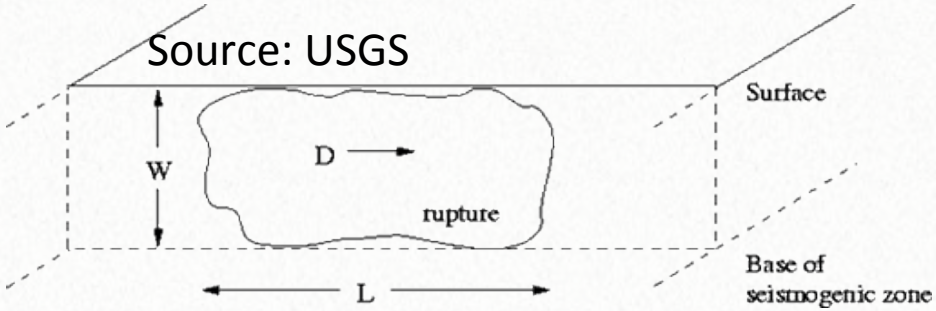


ANSS Catalog

Earthquakes 2014

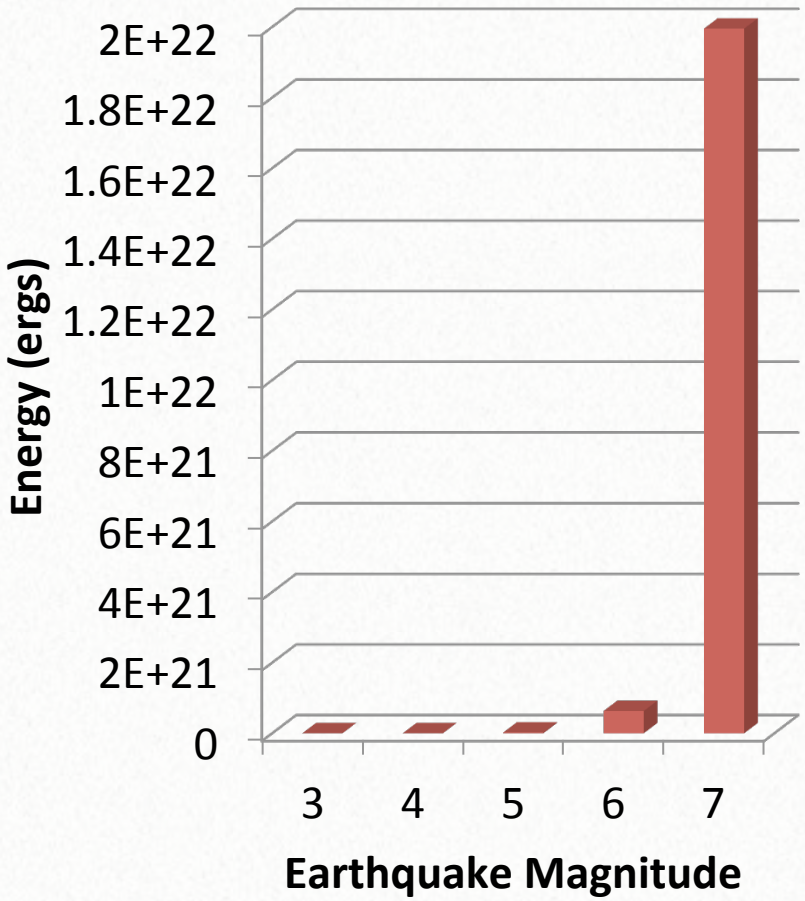


Measuring an Earthquake: Magnitude



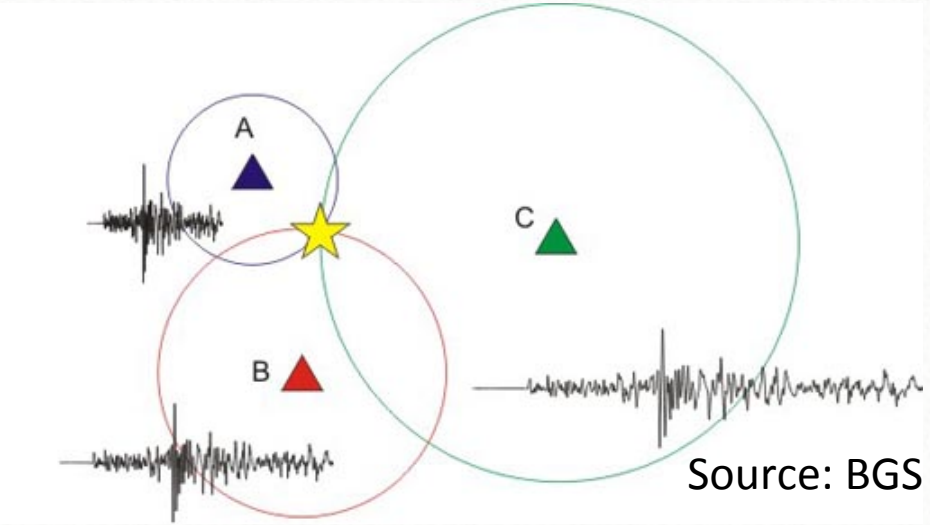
$$M_o \propto WLD$$

- Magnitude is proportional to rupture area and slip on fault
  - Log measure of the energy released as seismic waves
  - 1 Magnitude unit is ~32 times more energy release
- Cannot be directly measured inferred from measurements at surface



Earthquake Locations

- Earthquake locations contain uncertainty
  - Some more than others
- Factors controlling location accuracy
  - Station very near earthquake (depth)
  - How many stations are close to earthquake
  - Understanding of velocity distributions within the Earth



Oklahoma has a good regional network (may not be adequate to assess specific cases of IS)

- Horizontal uncertainties are about 8 km with uncertainties .1 to 15 km
- Vertical uncertainties .1 to unconstrained

Earthquake Triggering

How?

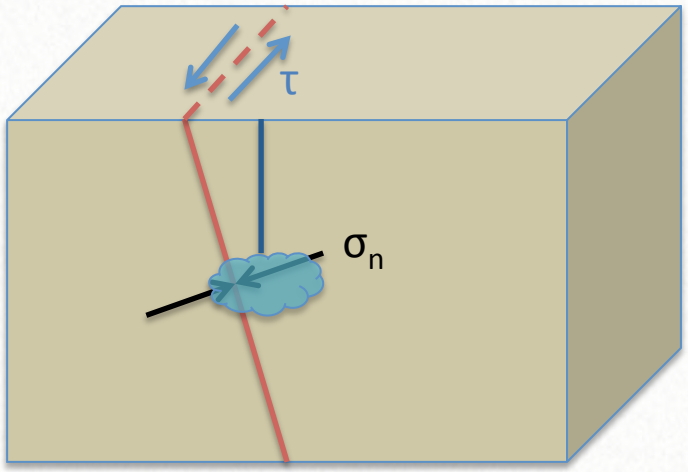
- Increase in shear stress
  - Mass changes
  - Permeability barriers
  - Thermal changes
- Increase in pore pressure
  - Fluid injected under pressure
  - Fluid injected under little or no pressure can generate a hydraulic head (100 m head ~ 1 MPa)

General Observations

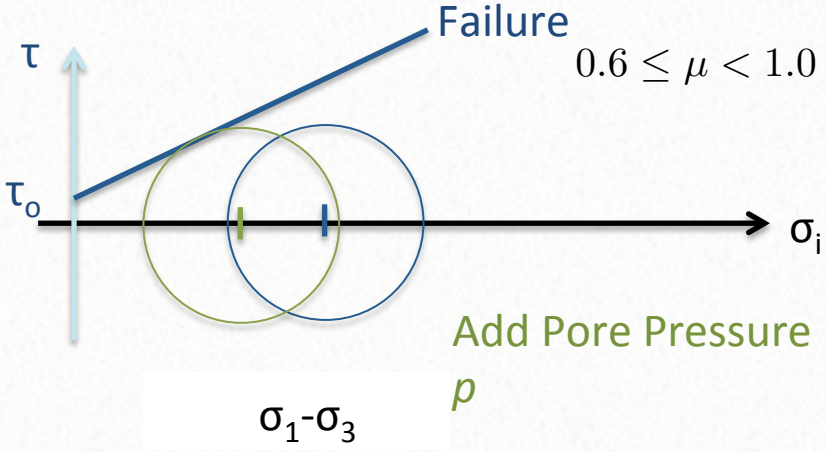
- Most of the Earth's crust is near failure
- Magnitudes tend to increase with time or injected volume
- Earthquakes may start close to a well and migrate outward
- Earthquakes may show temporal correlation to injection

Induced Seismicity from Fluid Injection

- Increased pore pressure from fluid injection effectively reduces friction on fault
  - Or in Mohr-Coulomb space moves the circle towards failure
- Pore pressure can be increased even injecting on vacuum
  - Hydraulic head

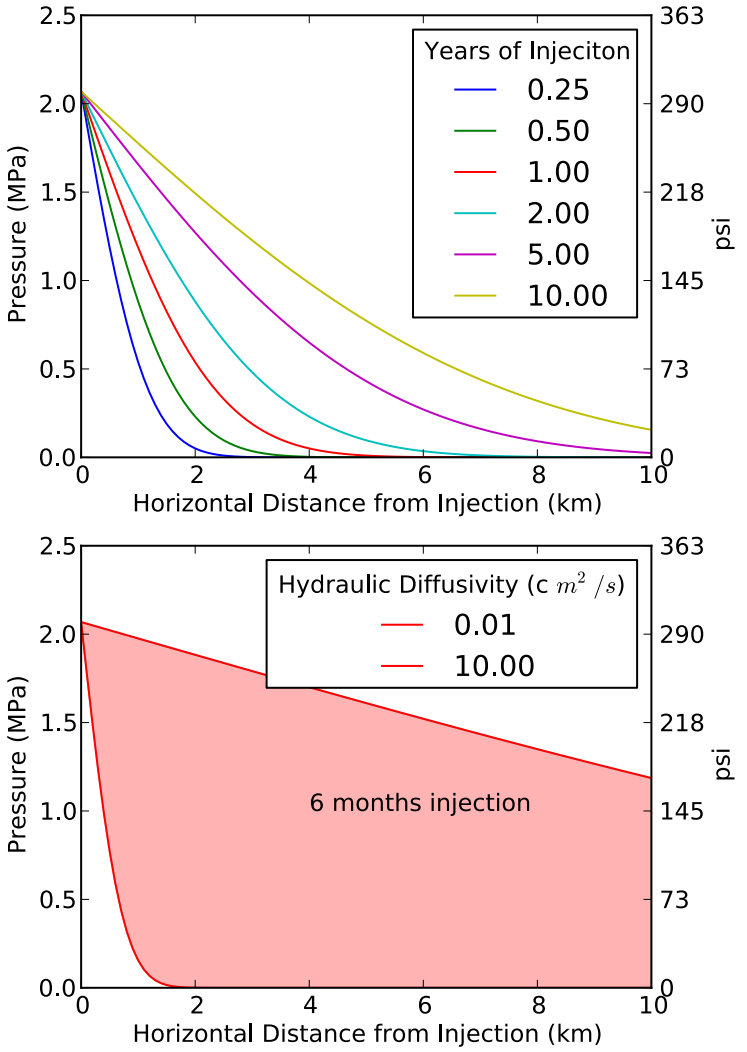


$$\tau_{crit} = \tau_o + \mu(\sigma_n - p)$$



Pressure Diffuses Within the Earth

- Pressure increase is not due to actual fluid flow
  - Can be much more rapid
  - Because water is fairly incompressible it is similar to an elastic response although slower
  - Diffusivity constant is
    $$c = T/S$$
    - T = transmissivity
    - S = storativity
  - Proportional to permeability
- Pressure increases over time

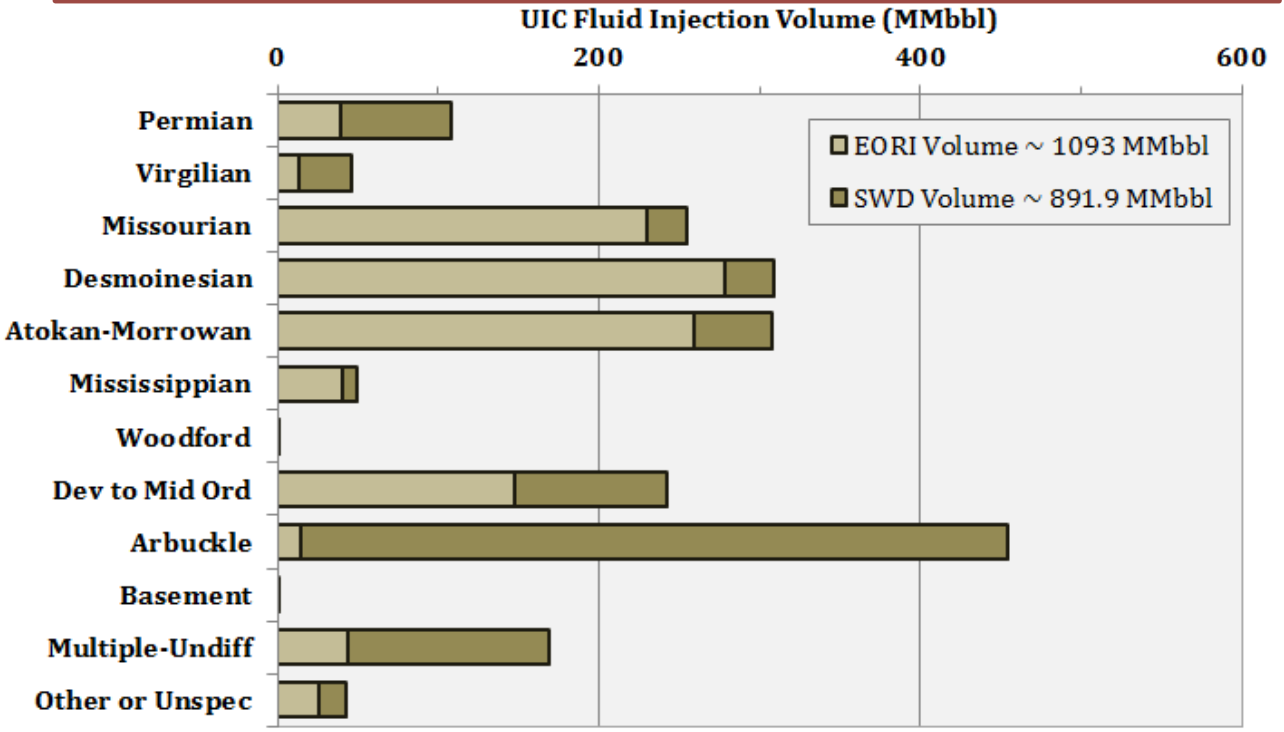


Talwani et al. (2007) J. Geophys Res.

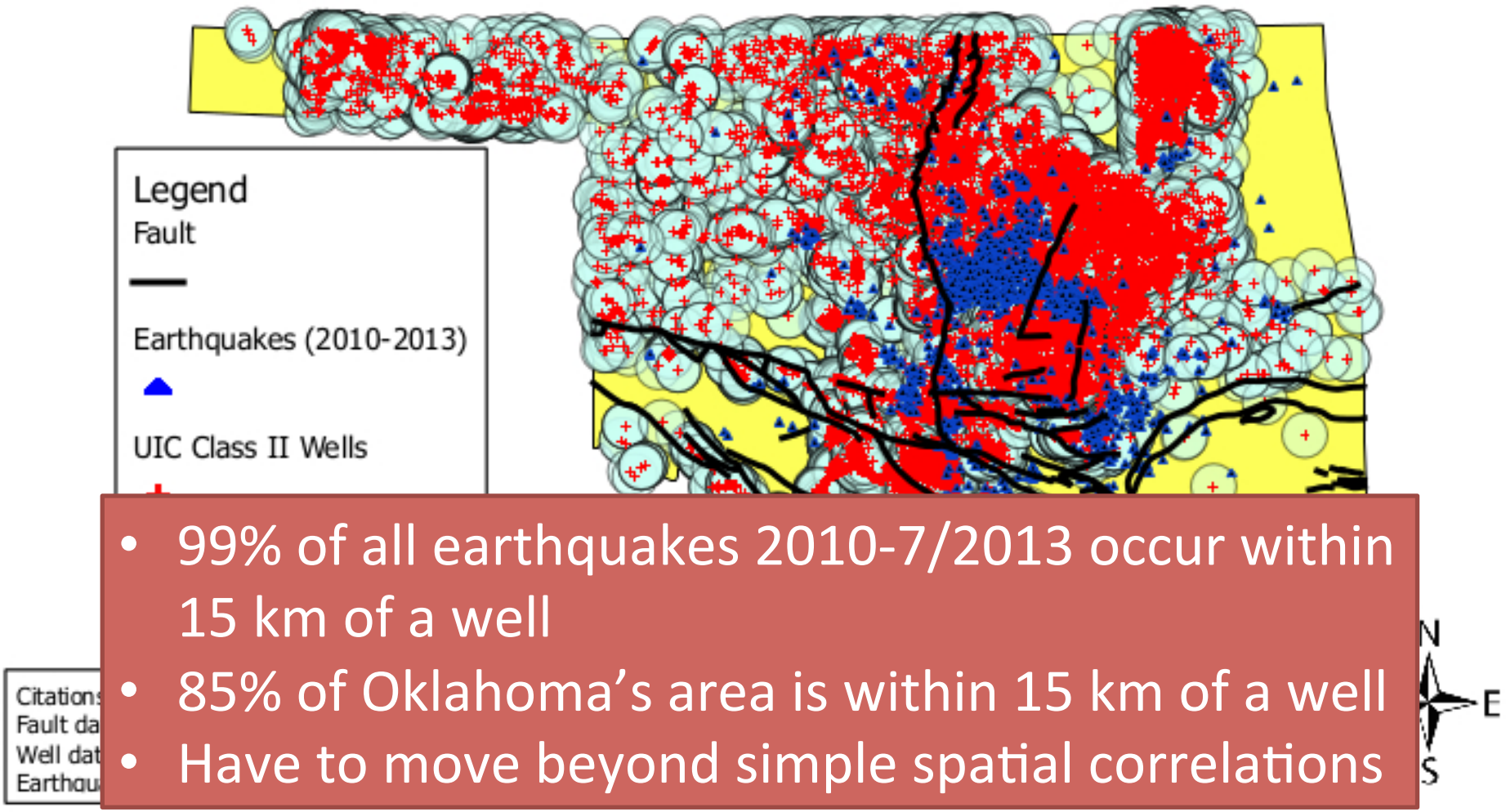
Injection by Formation

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 vacuum for years



All UIC Class II Wells



- 99% of all earthquakes 2010-7/2013 occur within 15 km of a well
- 85% of Oklahoma's area is within 15 km of a well
- Have to move beyond simple spatial correlations