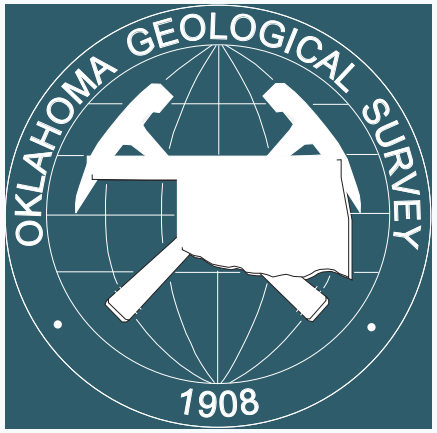

Oklahoma Earthquakes

July 2014

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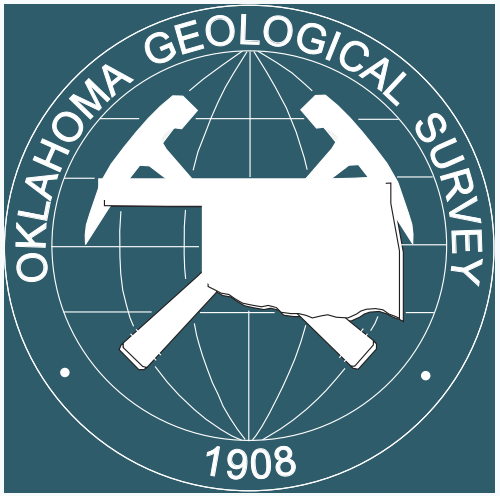


MEWBOURNE
COLLEGE OF EARTH&ENERGY
THE UNIVERSITY OF OKLAHOMA

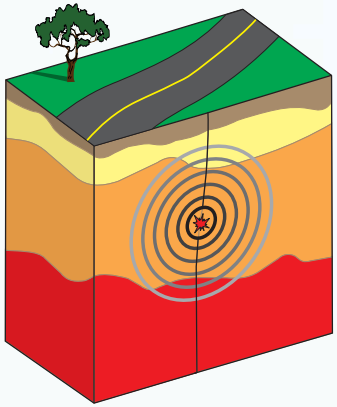
The Oklahoma Geological Survey is a state agency for research and public service located on the Norman Campus of the University of Oklahoma and affiliated with the OU College of Earth and Energy. The Survey is chartered in the Oklahoma Constitution and is charged with investigating the state's land,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

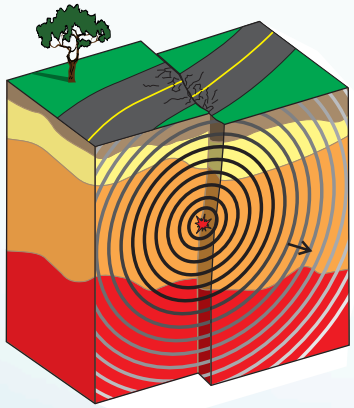
We are not a regulatory authority

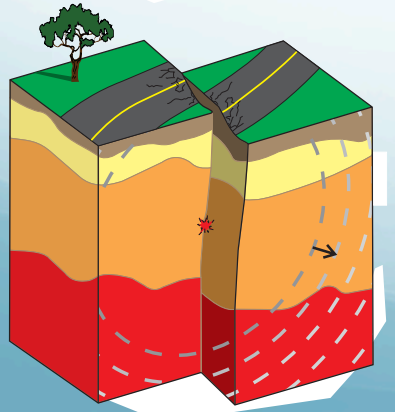
Outline

- Earthquakes, global/regional and local seismicity
- Increased hazards and Earthquake Preparedness
- Triggered/Induced seismicity by fracking and injection wells
- EQ triggering: What we know and what we can say
- Ongoing research and projects at the OGS

What is an Earthquake?





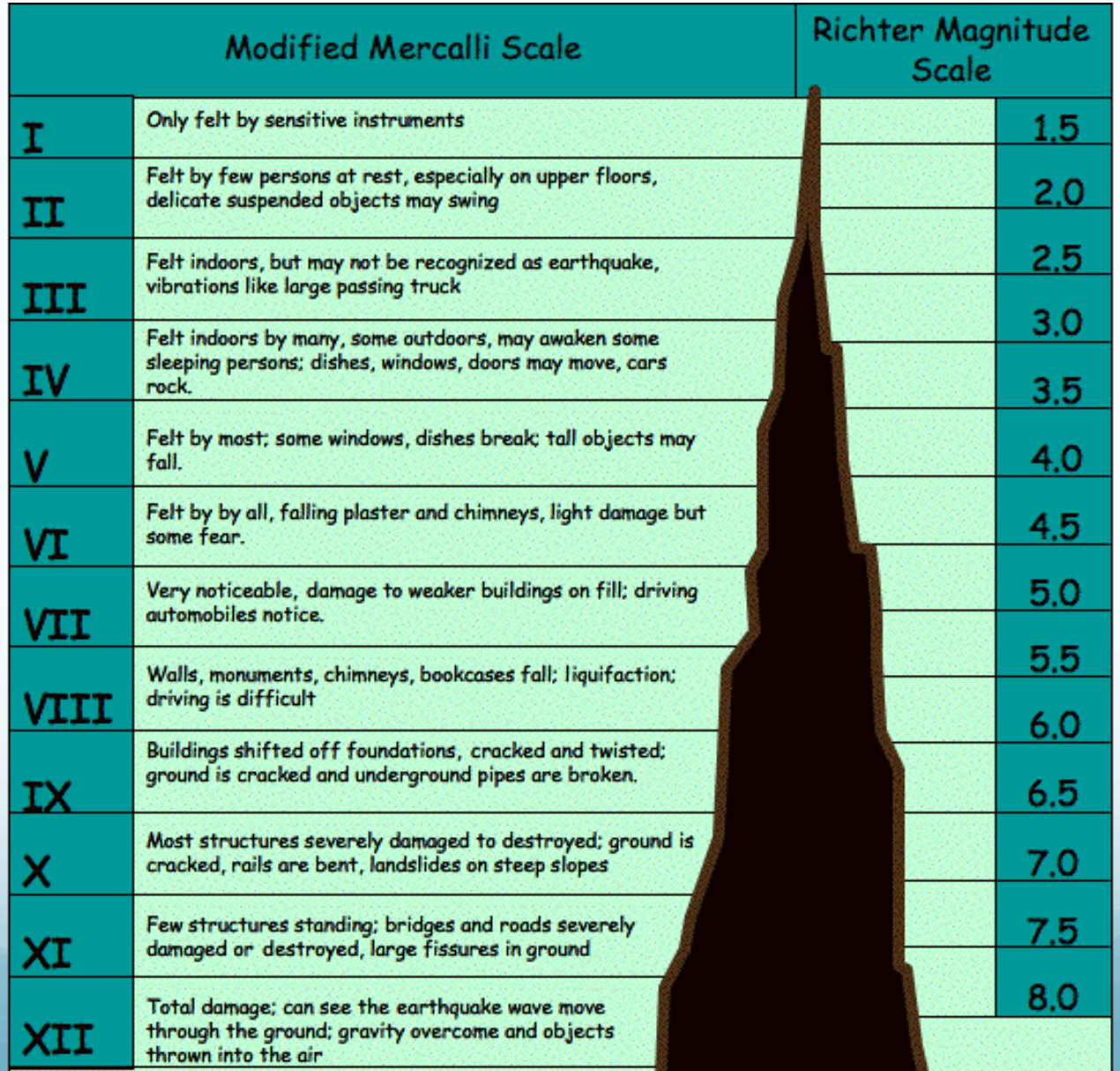


- When one body of rock slides past another
- When this occurs seismic waves "sound" is generated
- This sound radiates out in all directions and is what is measured at a seismic station
  - The recording is a seismogram
  - Waves are used locate and determine the size of the earthquake (magnitude)
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

Measuring an Earthquake

- Magnitude several different measures
  - logarithmic scales (1 mag = ~10 times shaking & 30 times the energy)
  - Magnitude is a scaled estimate of energy released as seismic waves
  - Magnitude estimates are rarely the same between different methods and have uncertainty in the estimate
- Modified Mercalli Intensity – human scale

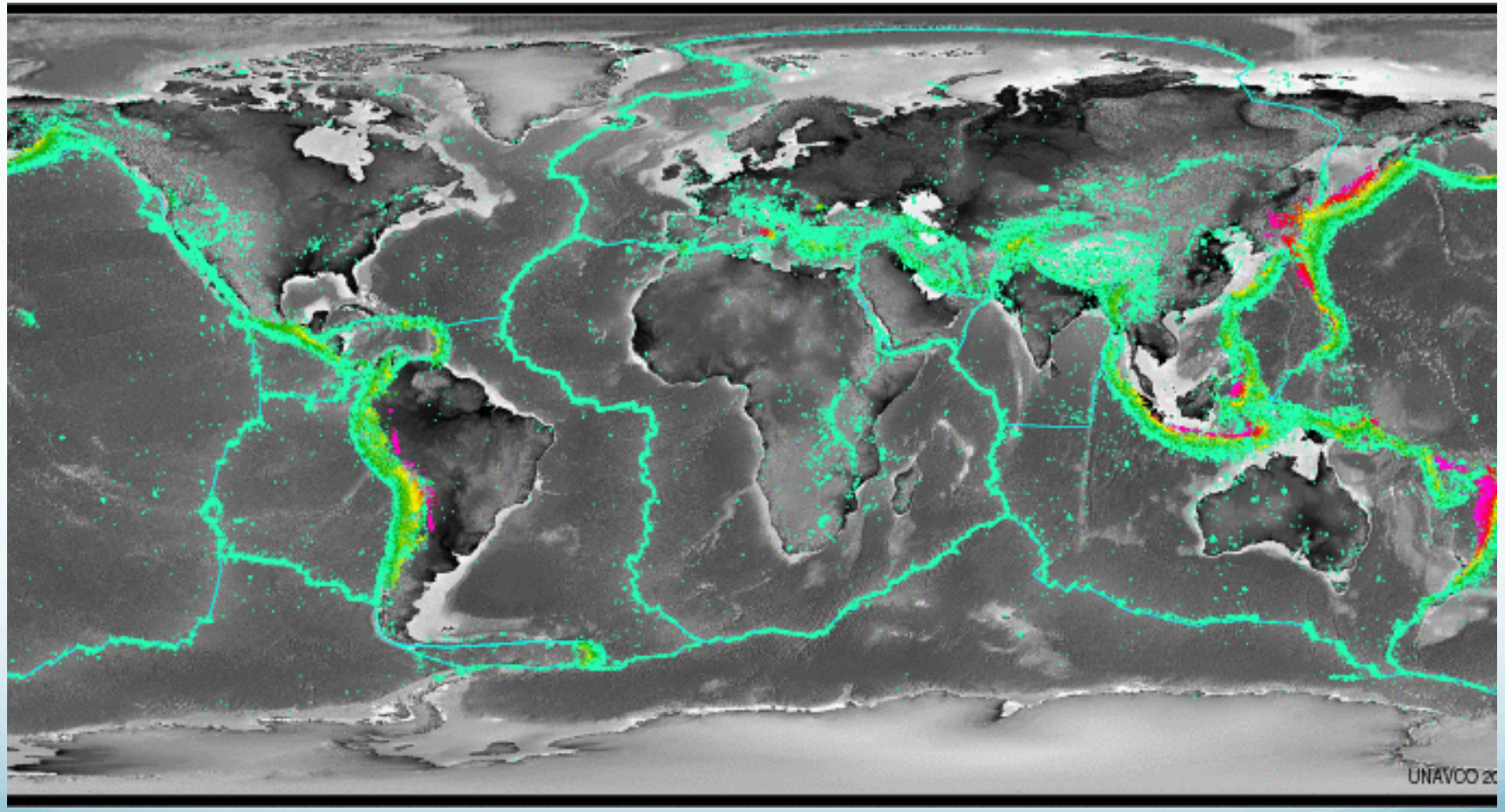
Modified Mercalli Intensity



Modified Mercalli Scale		Richter Magnitude Scale
I	Only felt by sensitive instruments	1.5
II	Felt by few persons at rest, especially on upper floors, delicate suspended objects may swing	2.0
III	Felt indoors, but may not be recognized as earthquake, vibrations like large passing truck	2.5
IV	Felt indoors by many, some outdoors, may awaken some sleeping persons; dishes, windows, doors may move, cars rock.	3.0
V	Felt by most; some windows, dishes break; tall objects may fall.	3.5
VI	Felt by by all, falling plaster and chimneys, light damage but some fear.	4.0
VII	Very noticeable, damage to weaker buildings on fill; driving automobiles notice.	4.5
VIII	Walls, monuments, chimneys, bookcases fall; liquifaction; driving is difficult	5.0
IX	Buildings shifted off foundations, cracked and twisted; ground is cracked and underground pipes are broken.	5.5
X	Most structures severely damaged to destroyed; ground is cracked, rails are bent, landslides on steep slopes	6.0
XI	Few structures standing; bridges and roads severely damaged or destroyed, large fissures in ground	6.5
XII	Total damage; can see the earthquake wave move through the ground; gravity overcome and objects thrown into the air	7.0
		7.5
		8.0

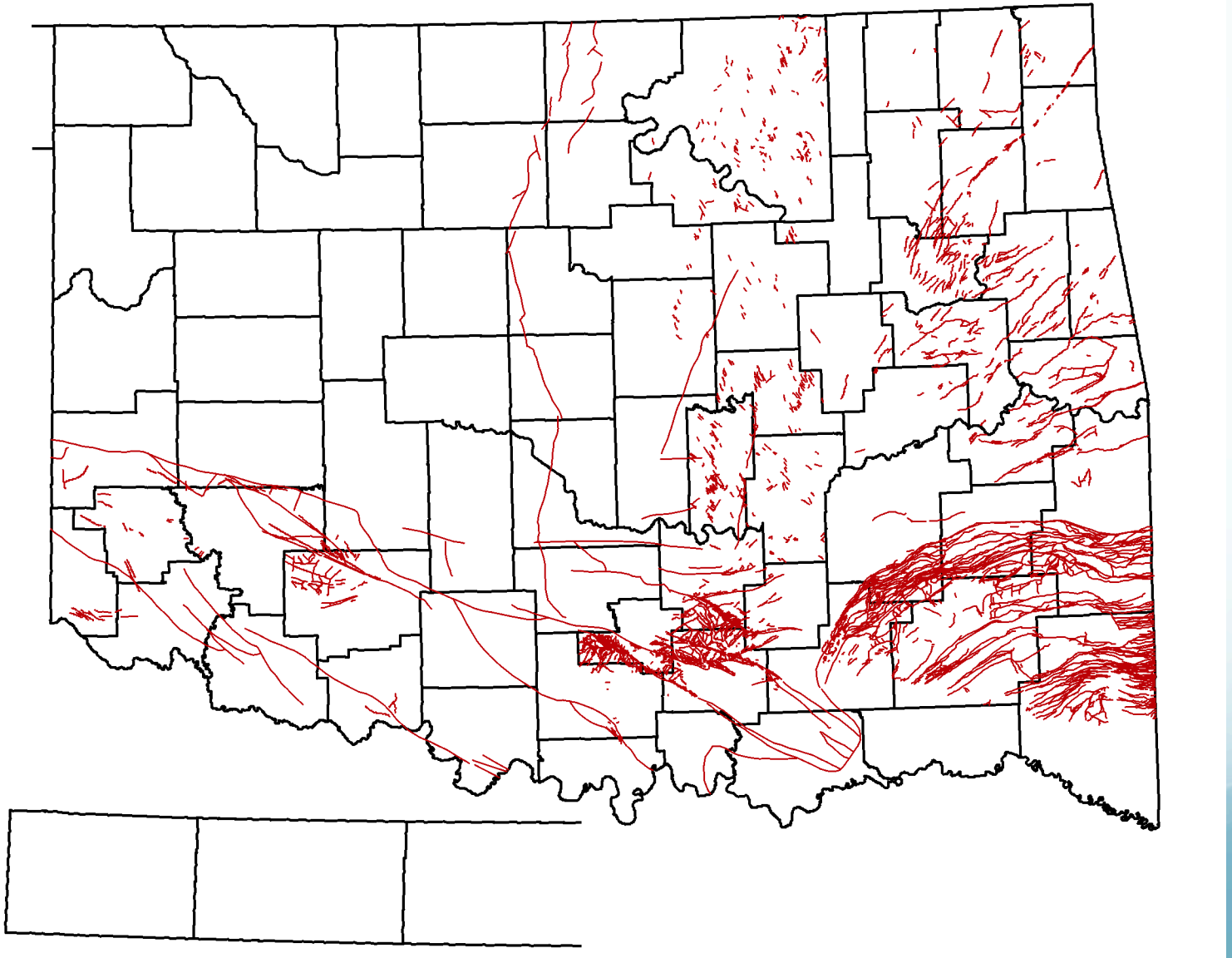
http://scearthquakes.cofc.edu/images/MercalRichtscale.gif

Earthquakes Worldwide



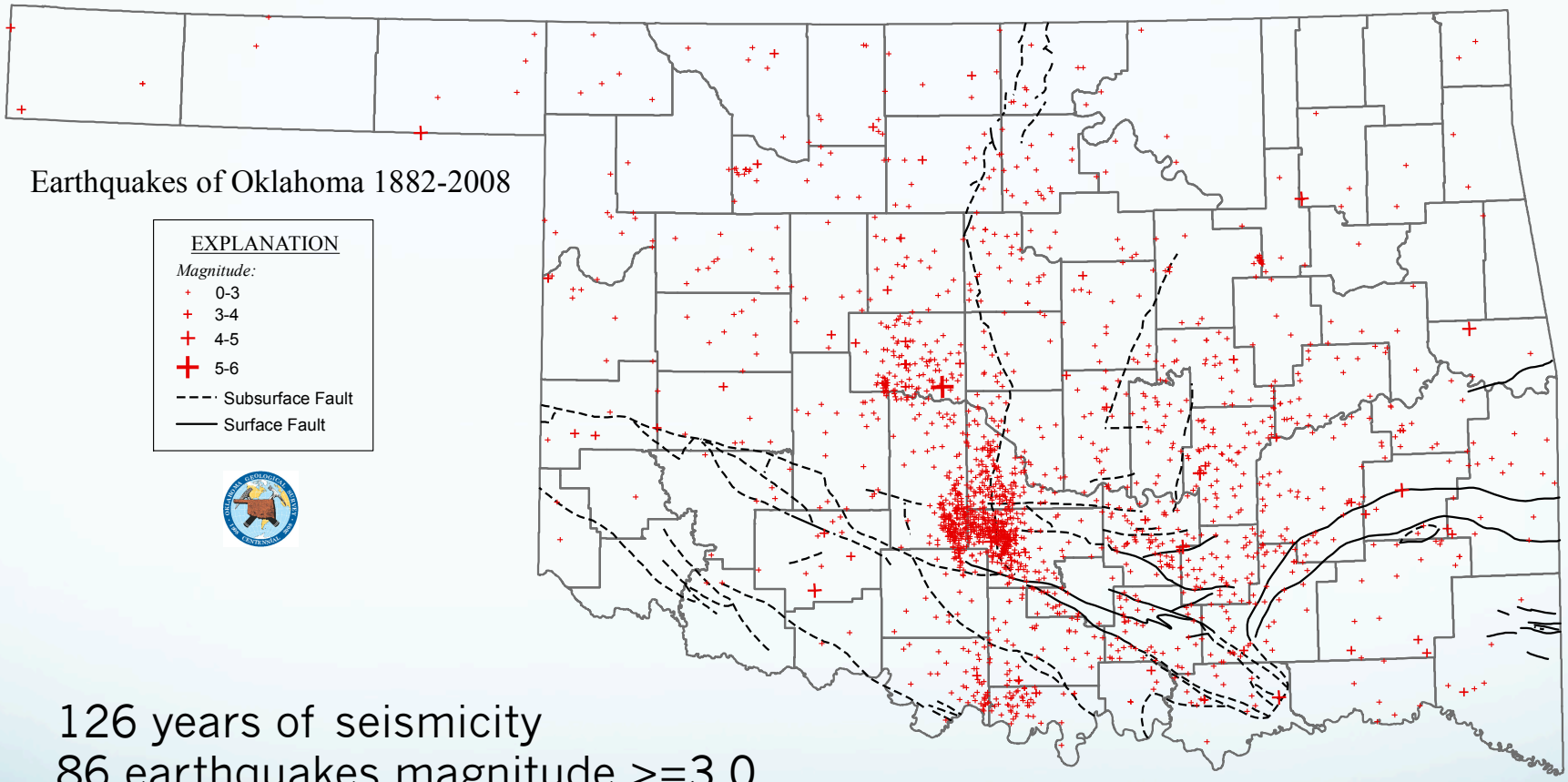
Earthquakes Happen on Faults!

Mapped Faults in Oklahoma



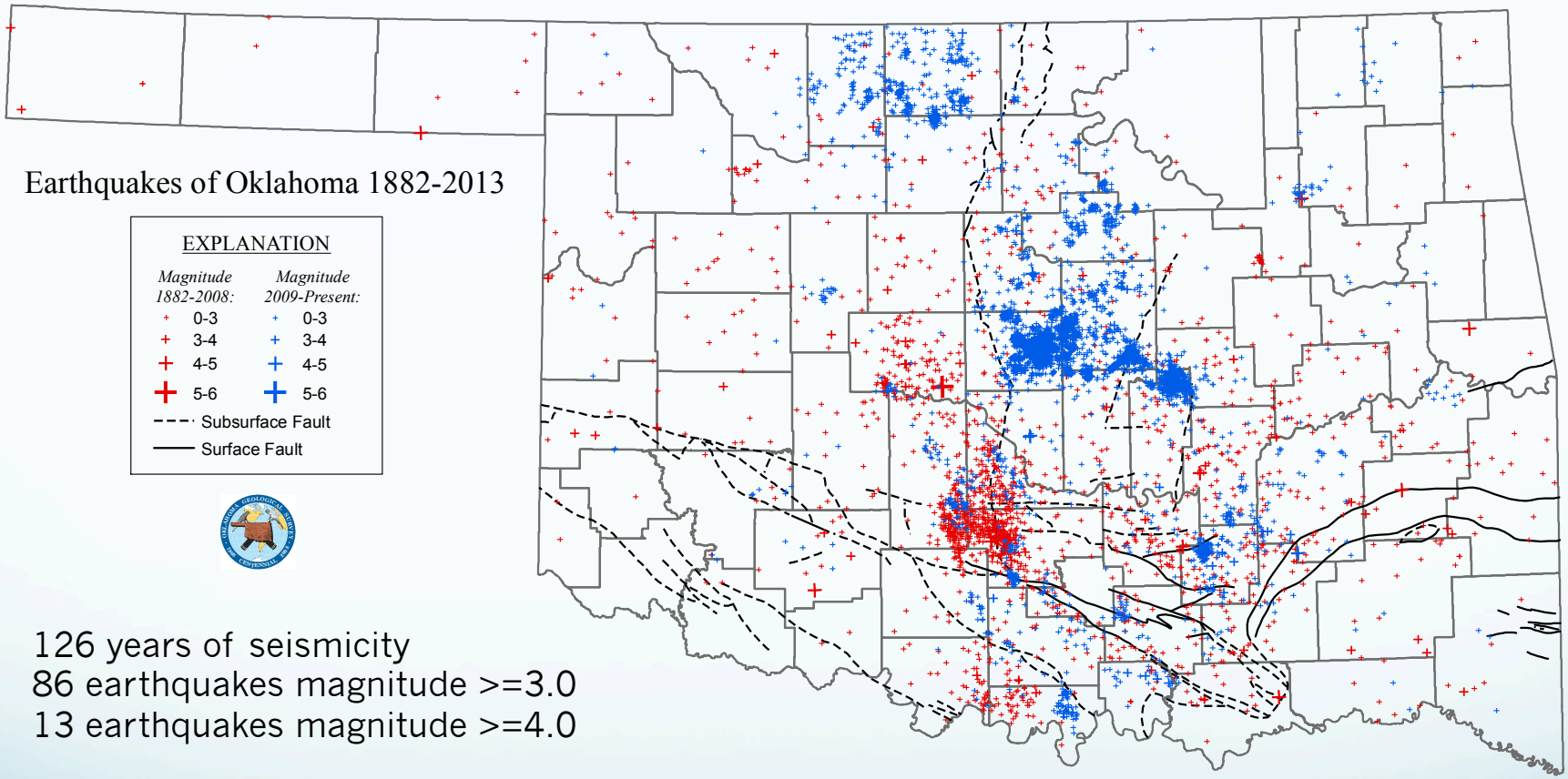
Meers Fault

Earthquakes 1882-2008



126 years of seismicity
86 earthquakes magnitude >=3.0
13 earthquakes magnitude >=4.0

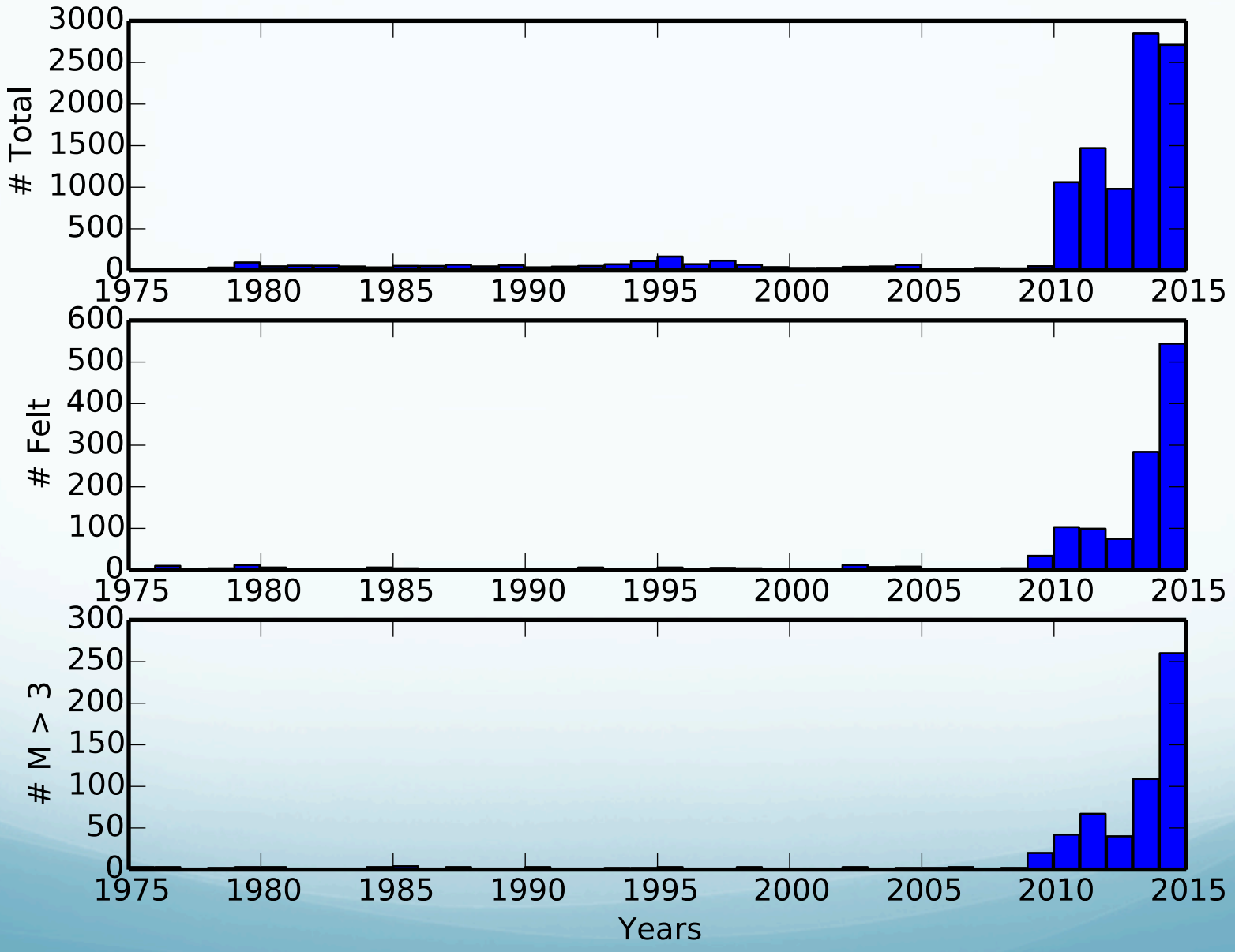
Earthquakes 1882-2013



126 years of seismicity
86 earthquakes magnitude >=3.0
13 earthquakes magnitude >=4.0

4 years of seismicity
278 earthquakes magnitude >=3.0
12 earthquakes magnitude >=4.0

Dramatic Increase in Oklahoma Earthquakes

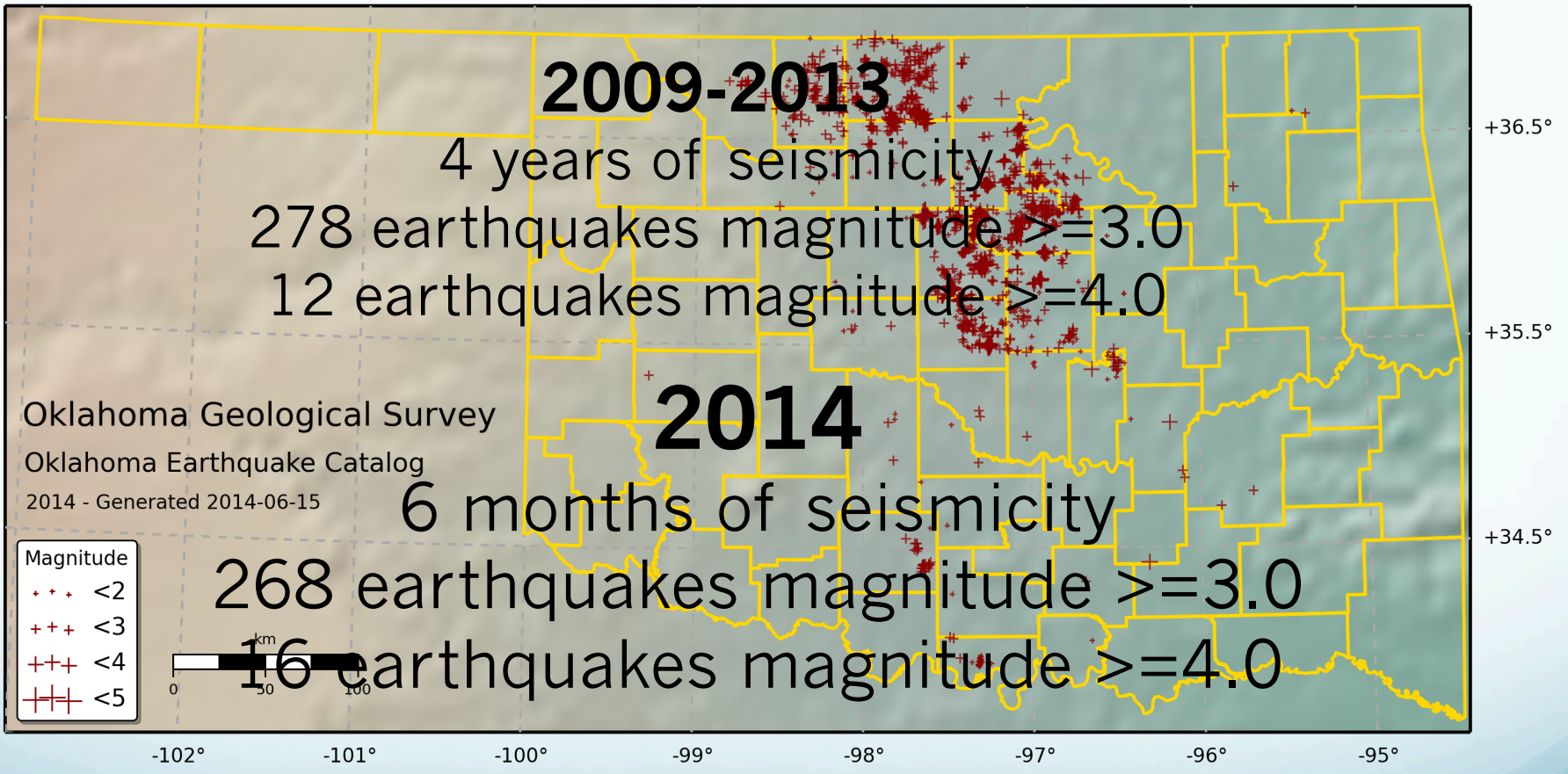


1882-2008

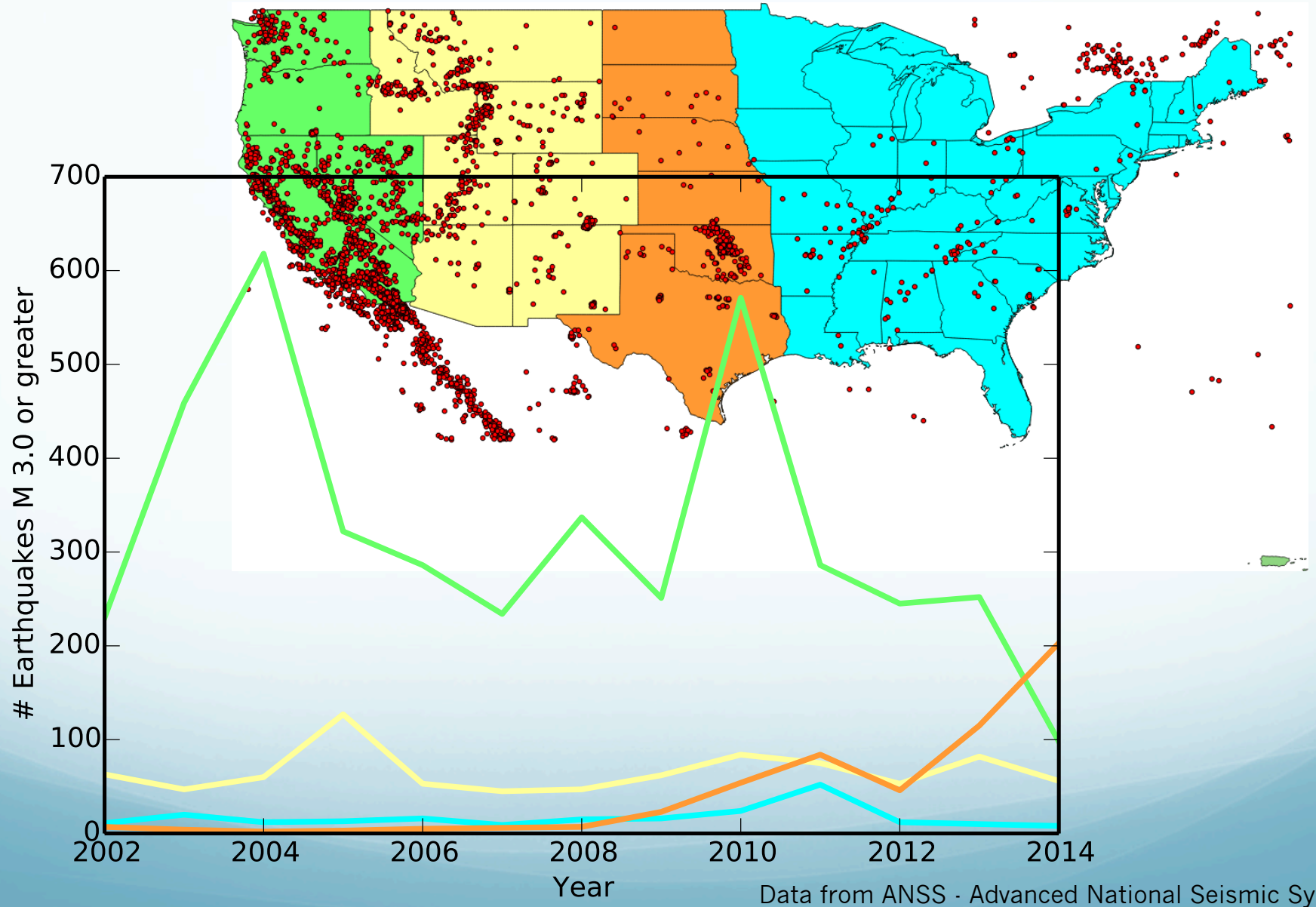
126 years of seismicity

86 earthquakes magnitude >=3.0

13 earthquakes magnitude >=4.0



Earthquakes by Region



Data from ANSS - Advanced National Seismic System

Why the increase in earthquakes?

- Great Question!
- Most likely a combination of factors natural and human induced
- Seismic history is not long enough to rule out natural rate but most Seismologist believe the drastic rate change is NOT due to natural seismicity
- Looking into the relationship between fluid injection and seismicity
- The increase in earthquakes does a lot to advance earthquake science in Oklahoma and help to determine appropriate actions and regulation proposals

USGS
science for a changing world

OKLAHOMA GEOLOGICAL SURVEY 1908

Record Number of Oklahoma Tremors Raises Possibility of Damaging Earthquakes

Updated USGS-Oklahoma Geological Survey Joint Statement on Oklahoma Earthquakes

Originally Released: 10/22/2013 1:07:59 PM; **Updated May 2, 2014**

The rate of earthquakes in Oklahoma has increased remarkably since October 2013–by about 50 percent – significantly increasing the chance for a damaging magnitude 5.5 or greater quake in central Oklahoma.

The Gutenberg-Richter Law: $\log_{10} N(x) = a - bx$

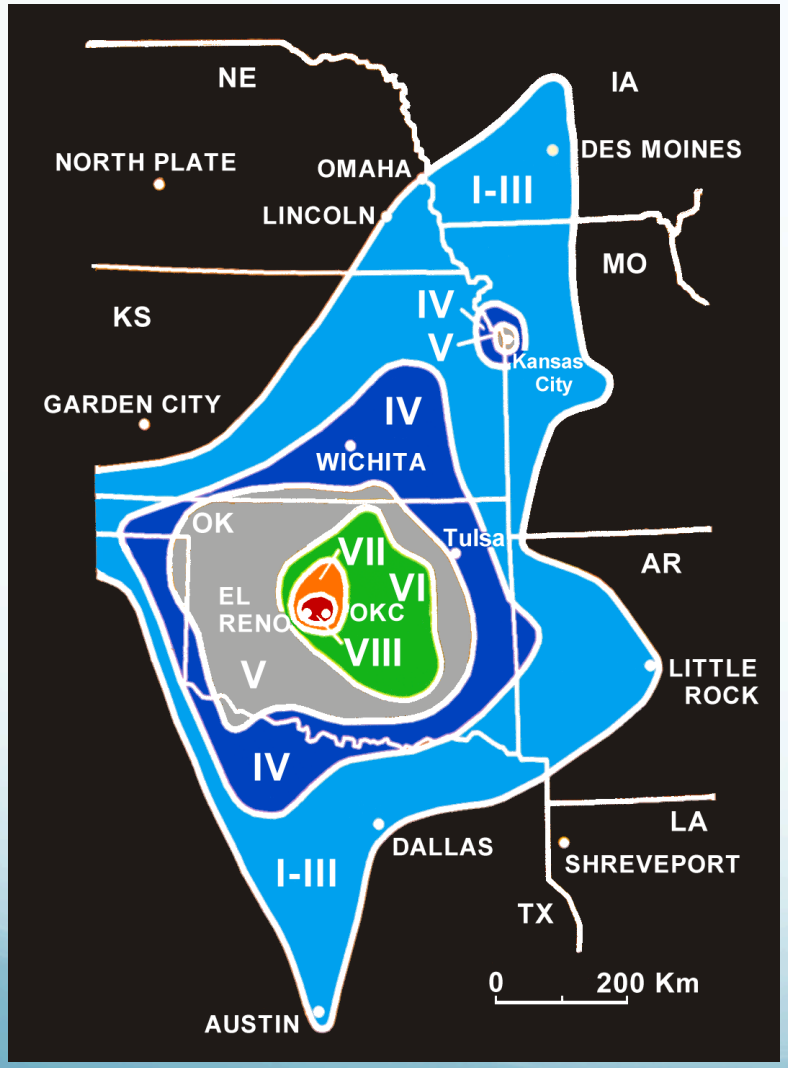
* Simply stated, for every magnitude 4 in a region there are ~10 magnitude 3 earthquakes.

- 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

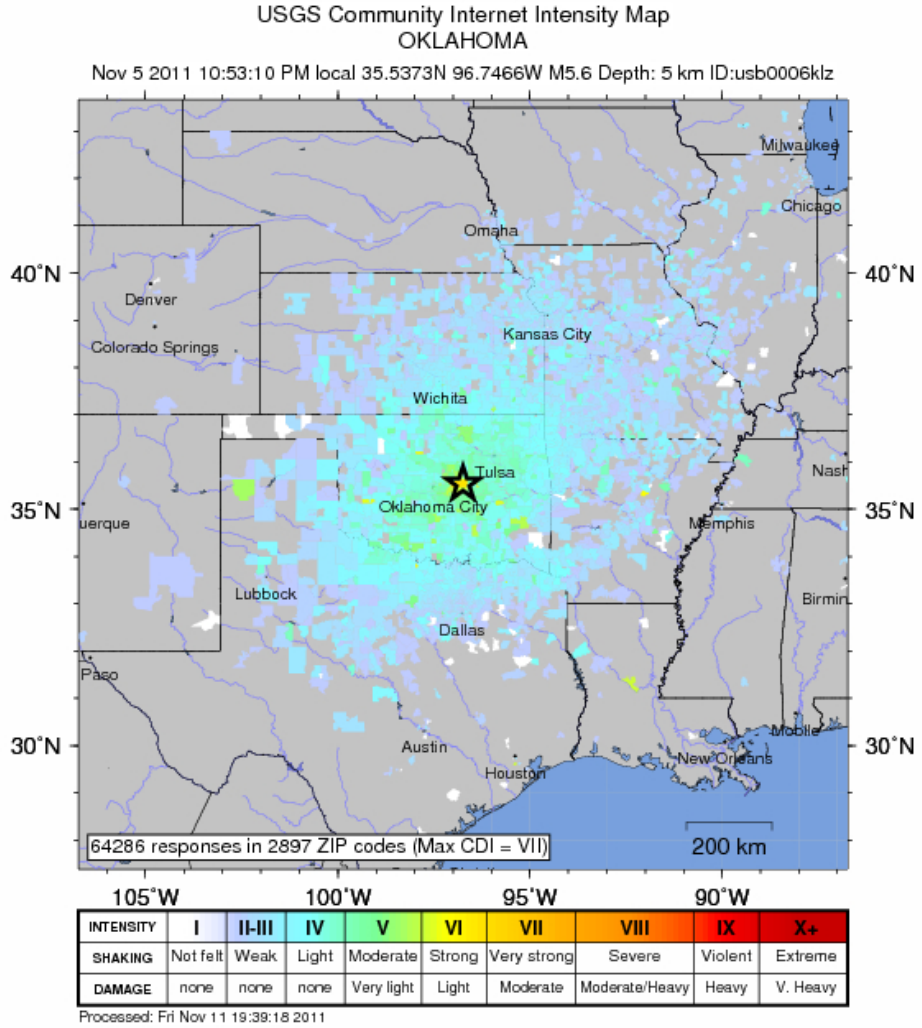
Damaging Earthquakes in Oklahoma

- The chances of a large damaging earthquake in Oklahoma are quite small however, are not zero
- 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

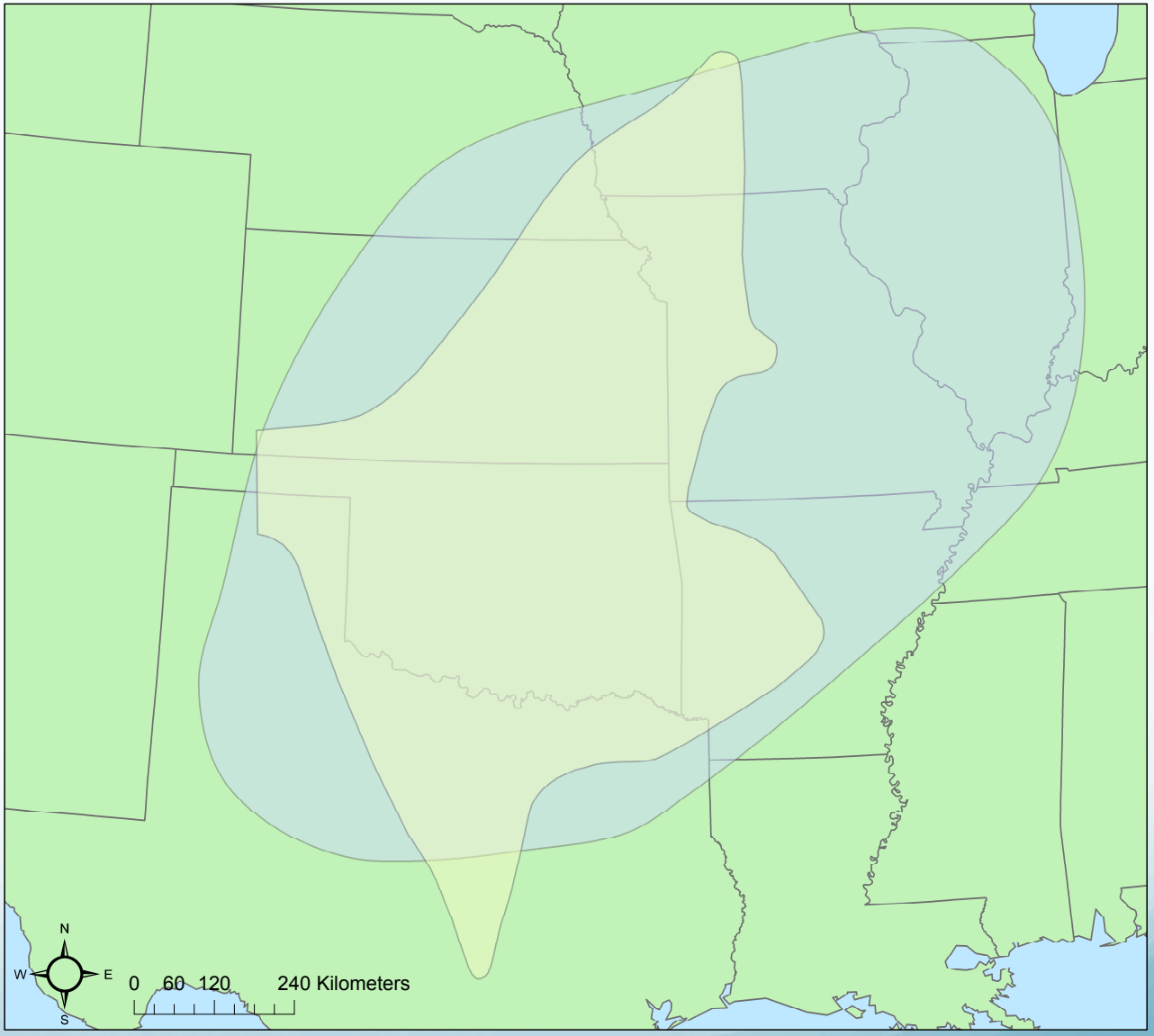
El Reno, April 9 1952



November 2011, Prague Earthquakes



Map of the Central U.S. where people reported feeling both the 1952 and 2011 earthquakes



Data from the USGS

Projected Coordinate System:
USA_Contiguous_Albers_Equal_Area_Conic
Geographic Coordinate System:
GCS_North_American_1983

What to do and not do in an Earthquake

- **DO**

- **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

How do we prepare?

- Identify hazards in your home and workplace and take actions to fix them
- Create a disaster preparedness plan
  - Plan NOW to be safe during an earthquake
  - Plan now on how to respond after an earthquake
  - Plan now on how to communicate and recover after an earthquake
- Prepare a disaster supply kit
  - This kit is useful for many natural disasters including much more likely disasters such as ice storms or tornadoes

http://www.earthquakecountry.info/roots/index.php

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

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.

Induced Seismicity

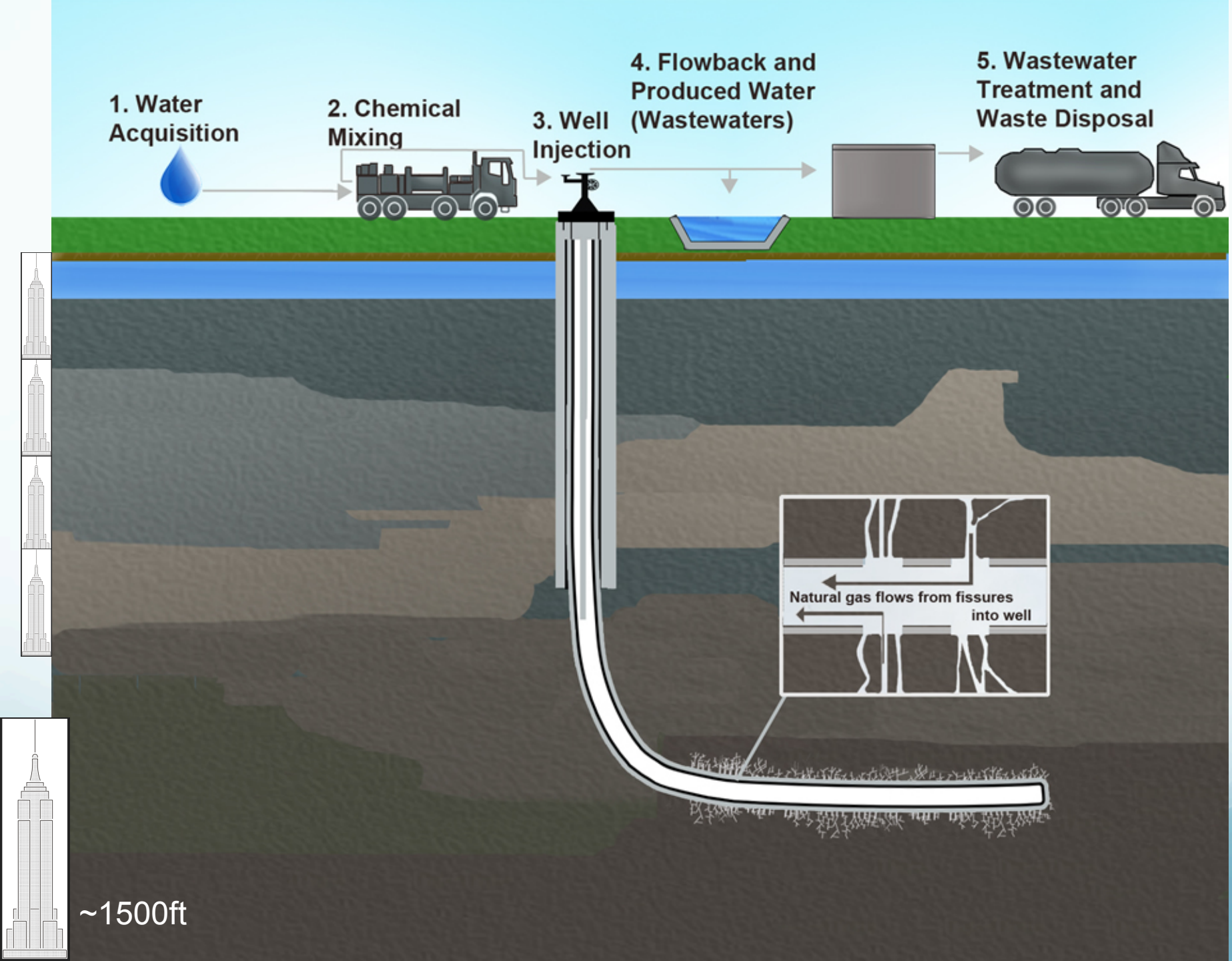
- We do see earthquakes likely triggered by hydraulic fracturing
  - Up to 10% of the earthquakes could be due to triggered seismicity from hydraulic fracturing
- Likely cases of earthquakes triggered by salt-water disposal (SWD)
  - No clear causal links established yet, some likely cases
  - Mississippi Lime Play, North-central Oklahoma increase in injection preceded increase in earthquakes
  - Nationally observed rate 1:4,000 wells NRC (2013)
  - Just over 4,000 SWD wells operating in Oklahoma
- Unlikely that all the earthquakes are due to O&G

What about hydraulic fracturing?

- Has occurred in Oklahoma since 1948, on well over 100,000 wells in Oklahoma
- 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
- Preliminary results suggest this is fairly rare occurrence between 2:100 or 1:1,000 wells
- Could contribute as much as 10% of observed earthquakes but likely much less

Hydraulic Fracturing

- Hydraulic fracturing produces fractures in the rock formation that stimulate the flow of natural gas or oil.
- Wells may be drilled vertically hundreds to thousands of feet below the land surface and may include horizontal or directional sections extending thousands of feet.
- Fractures are created by pumping large quantities of fluids (water, proppant and chemical additives) at high pressure down a wellbore.
- These fractures can extend several hundred feet away from the wellbore.
- The injected and produced water is typically stored on site in tanks or pits before treatment, disposal or recycling. In many cases, it is injected underground for disposal in UIC class II wells.


1. Water Acquisition
2. Chemical Mixing
3. Well Injection
4. Flowback and Produced Water (Wastewaters)
5. Wastewater Treatment and Waste Disposal
Natural gas flows from fissures into well
~1500ft
http://www2.epa.gov

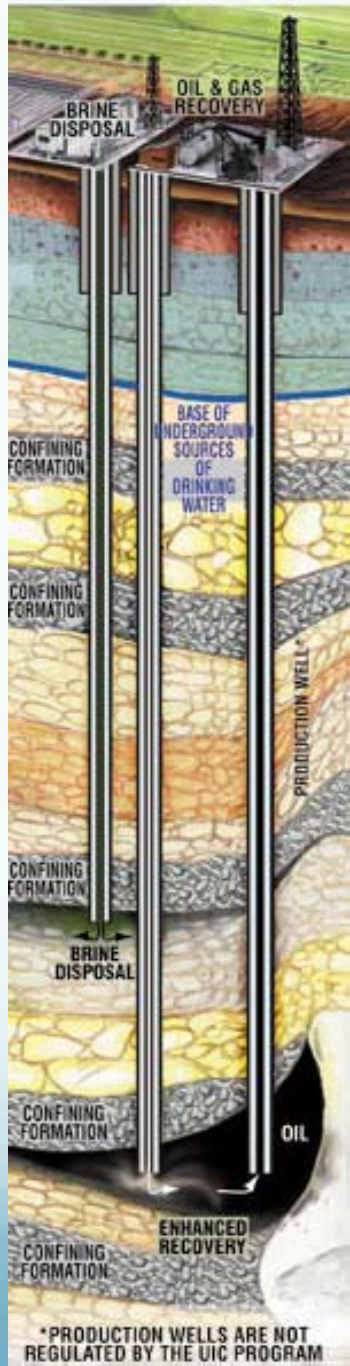
What about salt water disposal wells?

- Has occurred in Oklahoma for decades
- We do see some potential cases of induced seismicity from disposal wells (UIC Class II Wells)
- NRC “Induced Seismicity Potential in Energy Technologies” has a nation-wide rate of documented cases at ~1:4,000 wells
- Scientists generally agree that this triggered seismicity poses the greater risk (larger magnitudes)

UIC Class II Wells

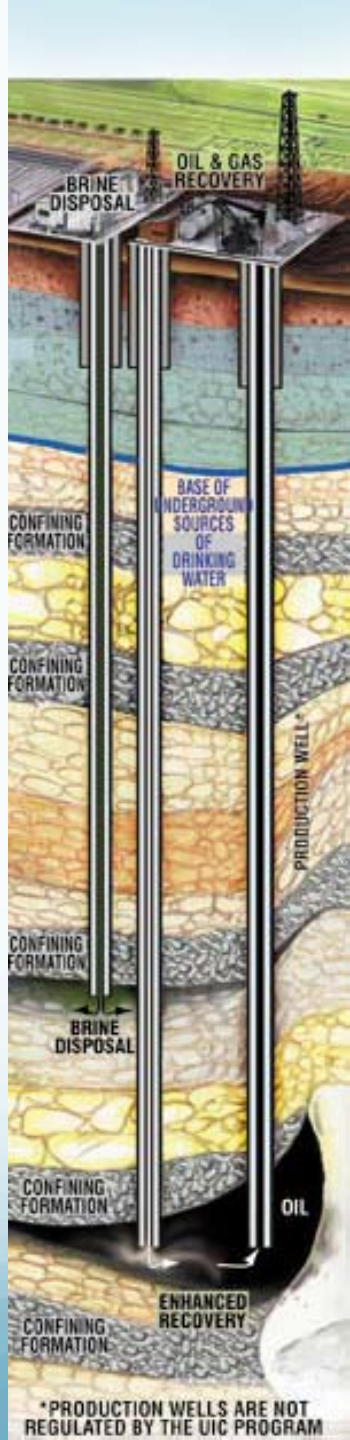
- Regulated by the EPA to protect drinking water sources
  - States can apply for primacy to manage UIC programs, OCC has primacy.
  - Many different types of waste disposal wells
- Class II wells – Are all deep injection wells related to oil and gas activity
  - Enhanced Recovery Wells
  - Waste water disposal Wells
  - Hydrocarbon Storage Wells
  - http://water.epa.gov/type/groundwater/uic/class2

Source: EPA



Class II: Disposal Wells

- Disposal wells take waste-water and inject it into the subsurface, above the basement rock.
  - This water is not generally what we think of as water
    - High salinity >> sea water
    - Other hydro-carbon and chemical contaminants
  - This waste-water comes from two primary sources
    - Hydraulic fracturing (minor amount of total volume)
    - Naturally occurring water that is removed with oil and gas (Produced Water)



Source: EPA

Earthquake Triggering

How?

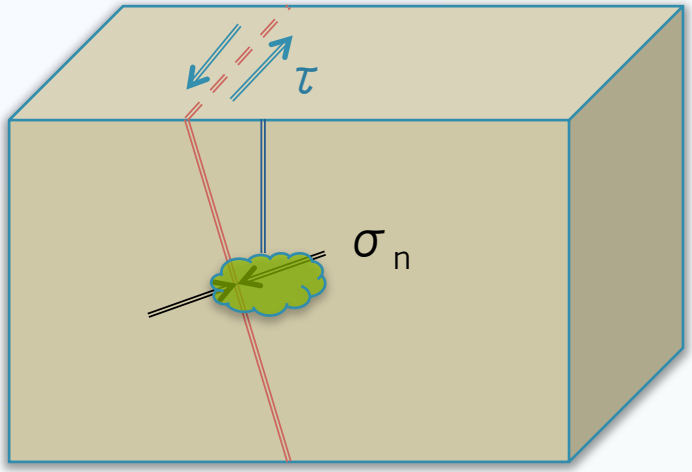
- Increase in shear stress
  - Mass changes
  - Permeability barriers
  - Thermal changes
- Increase in pore pressure
  - Fluid injected under pressure
  - Fluid injected under little or no pressure can generate a hydraulic head (100 m head ~ 1 MPa)

General Observations

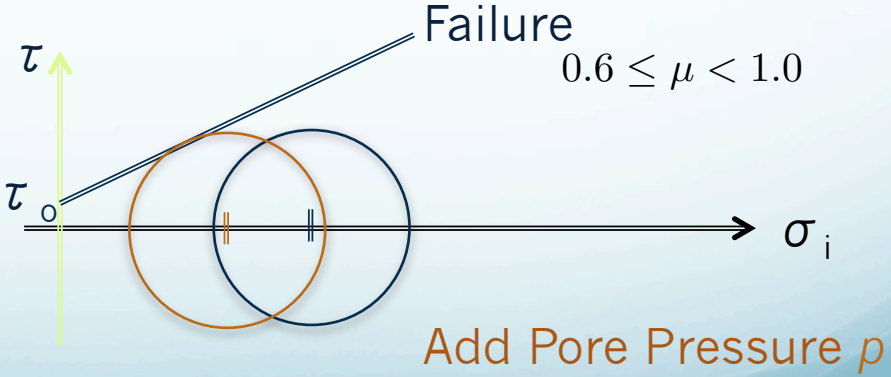
- Most of the Earth's crust is near failure
- Magnitudes tend to increase with time or injected volume
- Earthquakes may start close to a well and migrate outward
- Earthquakes may show temporal correlation to injection

Triggered or 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
- Releasing naturally occurring stress (energy)



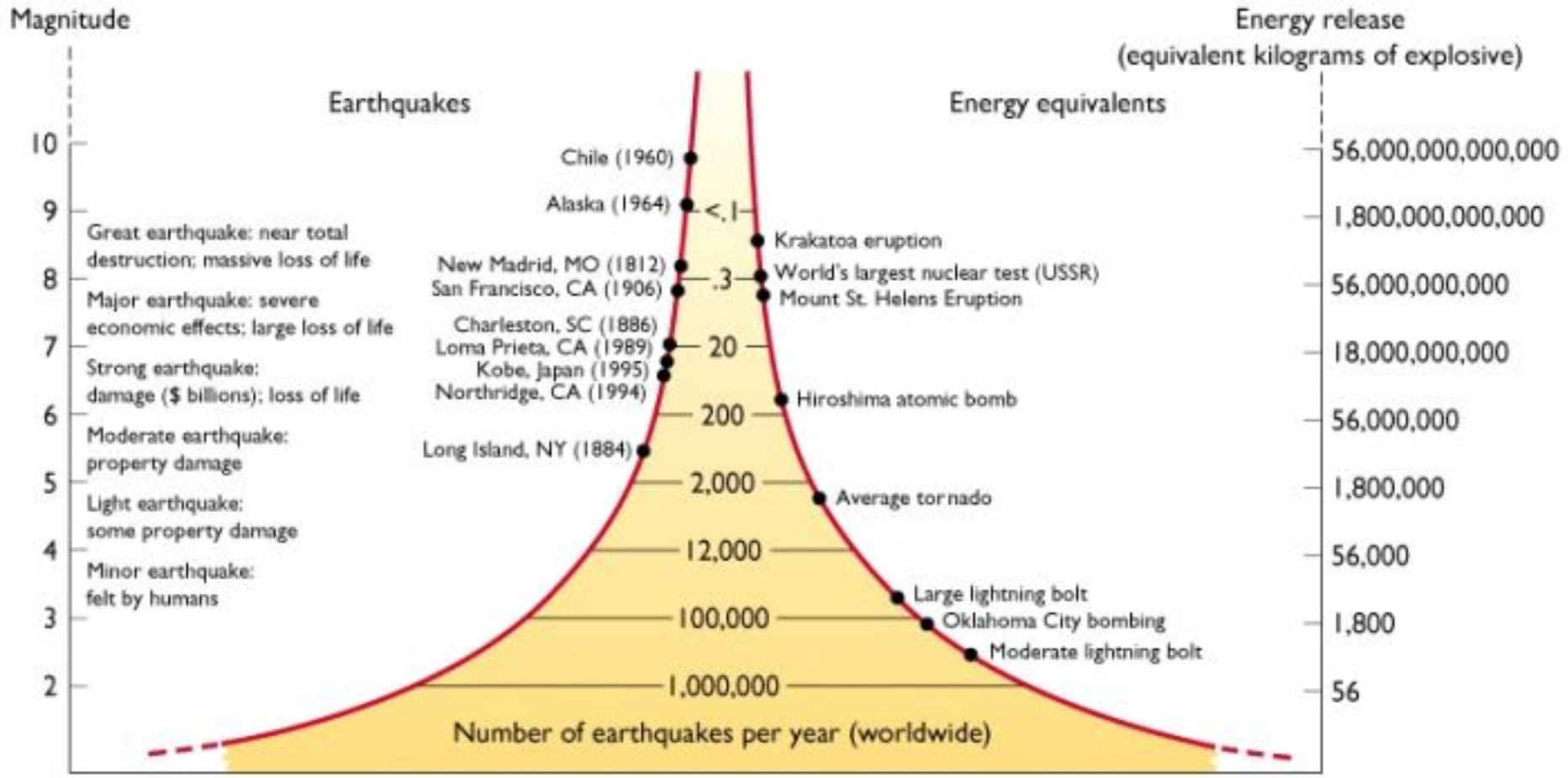
$$\tau_{crit} = \tau_o + \mu(\sigma_n - p)$$



Some common myths…

- All these small earthquakes release stress accumulation on faults making it less likely to have a larger magnitude event.

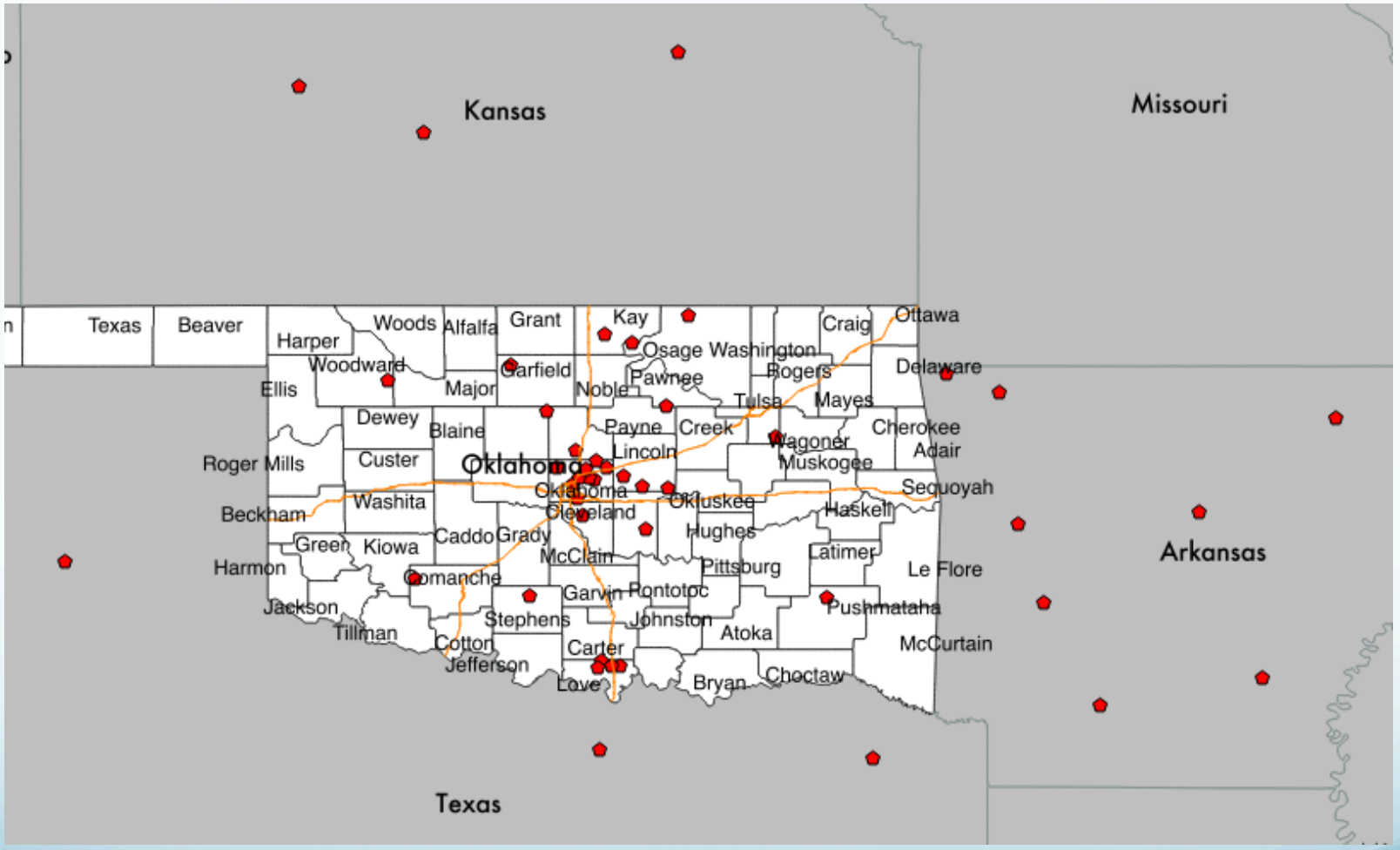
Richter Magnitude Versus Energy



Some common myths…

- All these small earthquakes release stress accumulation on faults making it less likely to have a larger magnitude event.
- We see more earthquakes because we have more seismometers.

Real-Time Stations Used for Locating Oklahoma Earthquakes

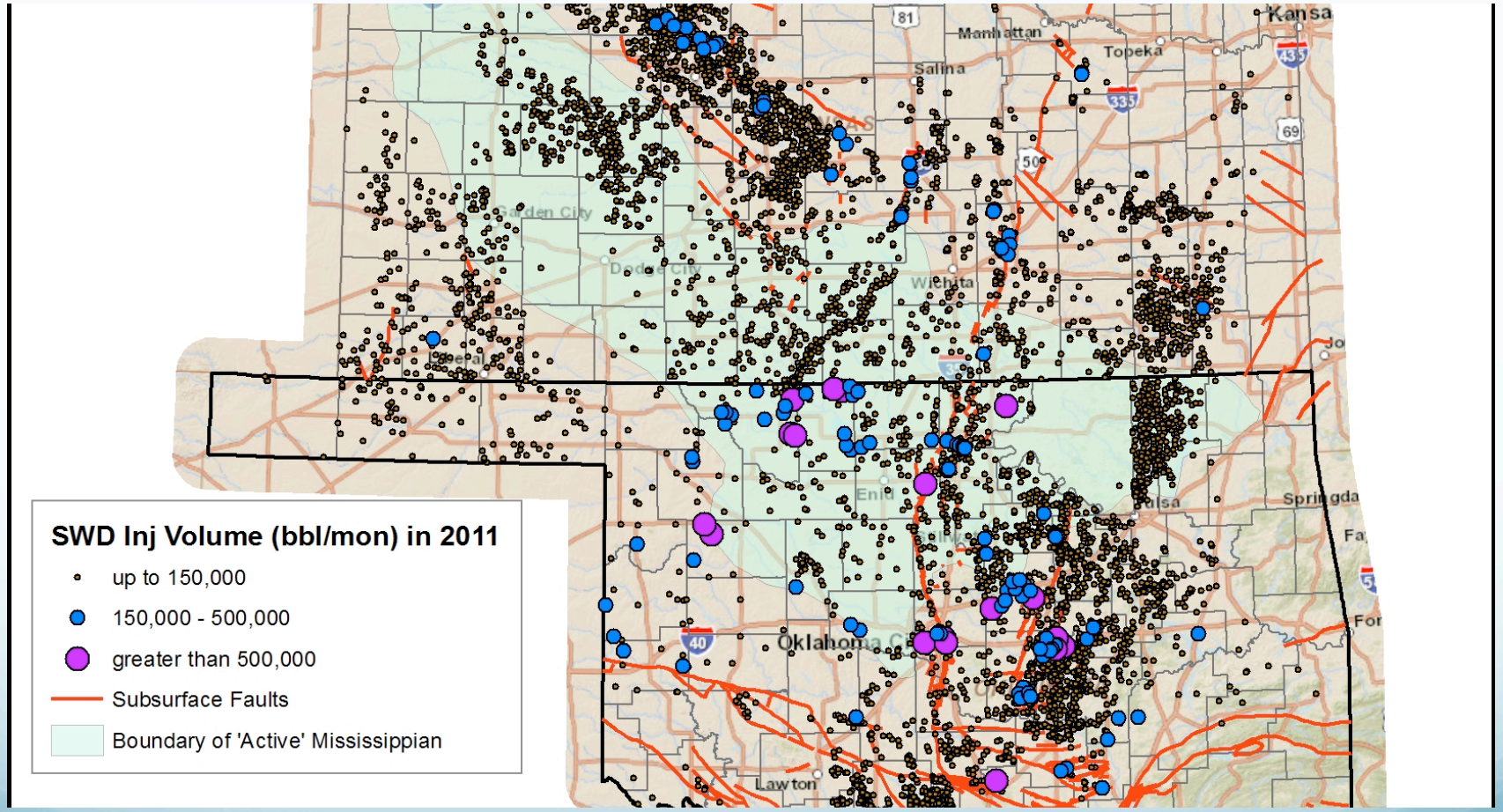


Some common myths…

- All these small earthquakes release stress accumulation on faults making it less likely to have a larger magnitude event.
- We see more earthquakes because we have more seismometers.
- Earthquakes must be induced because they occur near disposal wells.

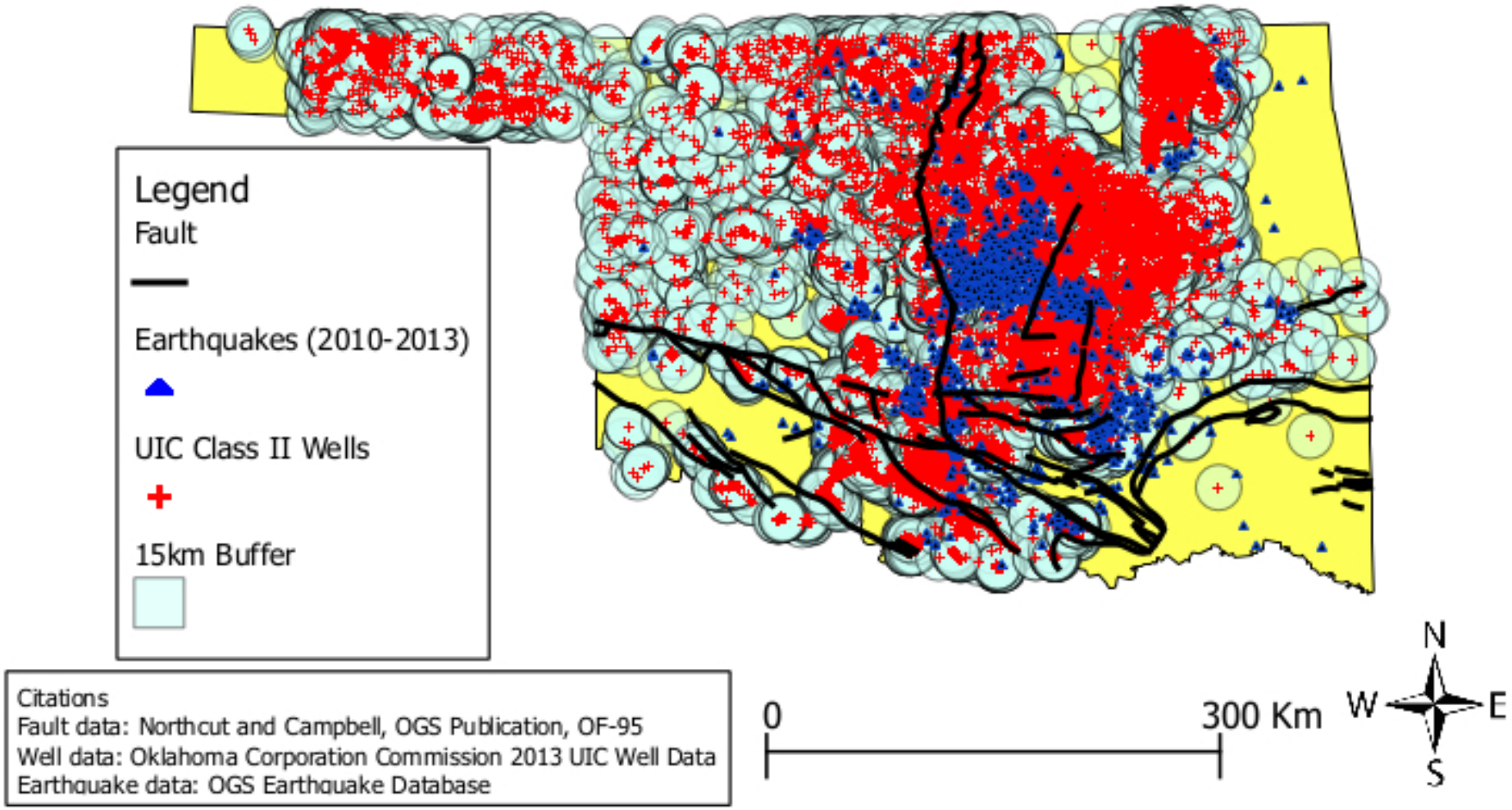
Earthquakes Happen Near Disposal Wells!

Disposal wells in Oklahoma



Murray, K.E. & Holland, A.A., Shale Shaker (2014)

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

Conclusions

- Most likely we are seeing a combination of natural earthquake rate changes and induced seismicity
- We do see induced, or triggered, earthquakes in Oklahoma but a lot more research needs to be done to know what extent!
- The OCC and the OGS continue to work together to get a better understanding of these issues and appropriate responses.
- The incredible volumes of data pose unique challenges for both agencies
- To date operators have all voluntarily responded to requests for additional data and information not required by current OCC rules or regulations

Uniquely Oklahoma Challenges

- OCC
  - 2011 UIC Class II Wells; 5506 EOR wells and 4124 SWD wells
  - About 2,000 producing wells being completed each year
  - About 400 permits for new Class II wells each year
  - Vast majority of disposal is produced water
  - Updated UIC database still working out logistics
- OGS
  - Prior to 2009, about 50 earthquakes/year with a few of those being felt
  - Aging seismic monitoring network
  - Unprecedented amounts of data and public interest have added logistical challenges

Cooperation between the OGS and the OCC

- OCC is a regulatory body regulating much more than Oil and Gas
  - Primacy over the UIC Class II program (EOR and SWD wells ~ 10,000 active)
- OGS is a research and public outreach state agency based out of the University of Oklahoma, we provide scientific results to the public and local government
- Began interactions regarding potential induced seismicity in 2010
- Built a working relationship over the years since
  - Difference in missions and culture sometimes make addressing issues a challenge

Current OGS 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

Questions or Comments?

http://www.ogs.ou.edu

http://www.okgeosurvey1.gov

- Report Feeling an Oklahoma Earthquake
- Ask a Seismologist
- Earthquake FAQ
- Recent Earthquakes