

Managing the Risk of Earthquakes Triggered by Waste Water Disposal and Hydraulic Fracturing

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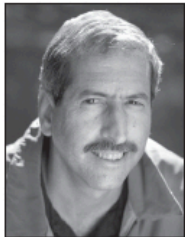
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The development of shale gas resources in an environmentally responsible manner presents a critical opportunity to move toward decarbonizing the global energy system.

Shale Gas Development Opportunities and Challenges



Mark D. Zoback

Mark D. Zoback and
Douglas J. Arent

The use of horizontal drilling and multistage hydraulic fracturing technologies has enabled the production of immense quantities of natural gas, to date principally in North America but increasingly in other countries around the world. The global availability of this resource creates both opportunities and challenges that need to be addressed in a timely and effective manner.

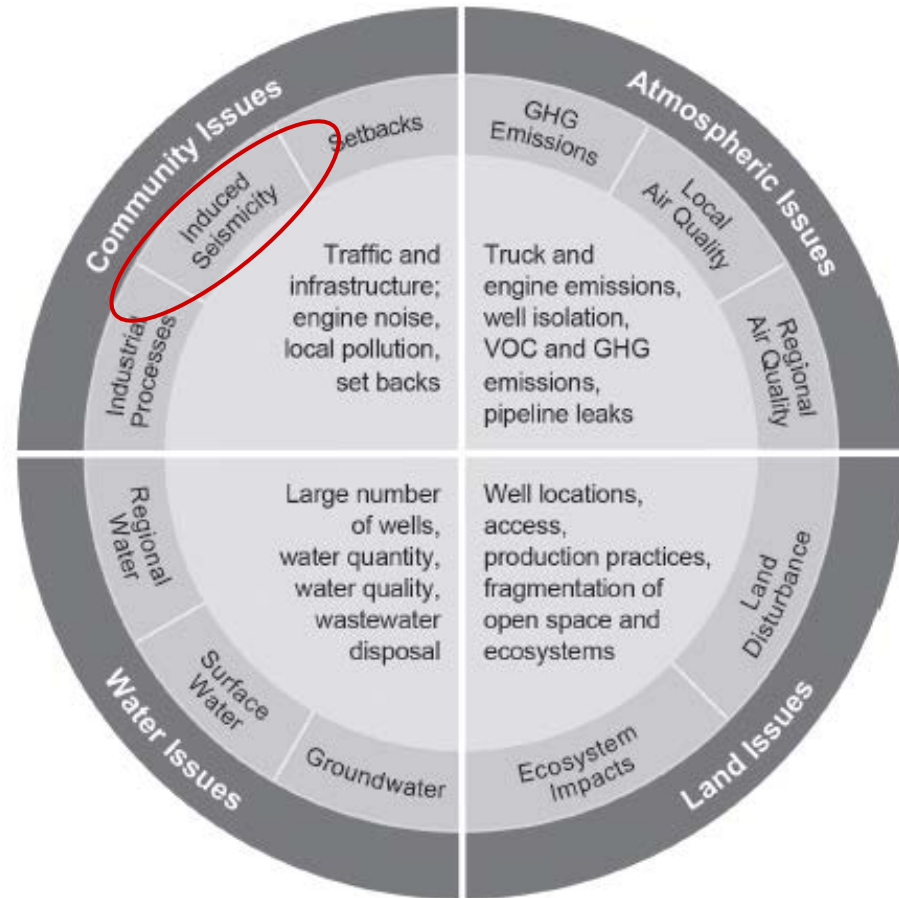
There is little question that rapid shale gas development, coupled with fuel switching from coal to natural gas for power generation, can have beneficial effects on air pollution, greenhouse gas emissions, and energy security in many countries. In this context, shale gas resources represent a critically important transition fuel on the path to a decarbonized energy future. For these benefits to be realized, however, it is imperative that shale gas resources be developed with effective environmental safeguards to reduce their impact on land use, water resources, air quality, and nearby communities.

Background

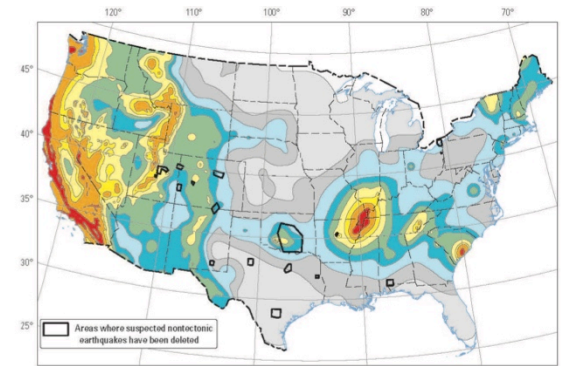
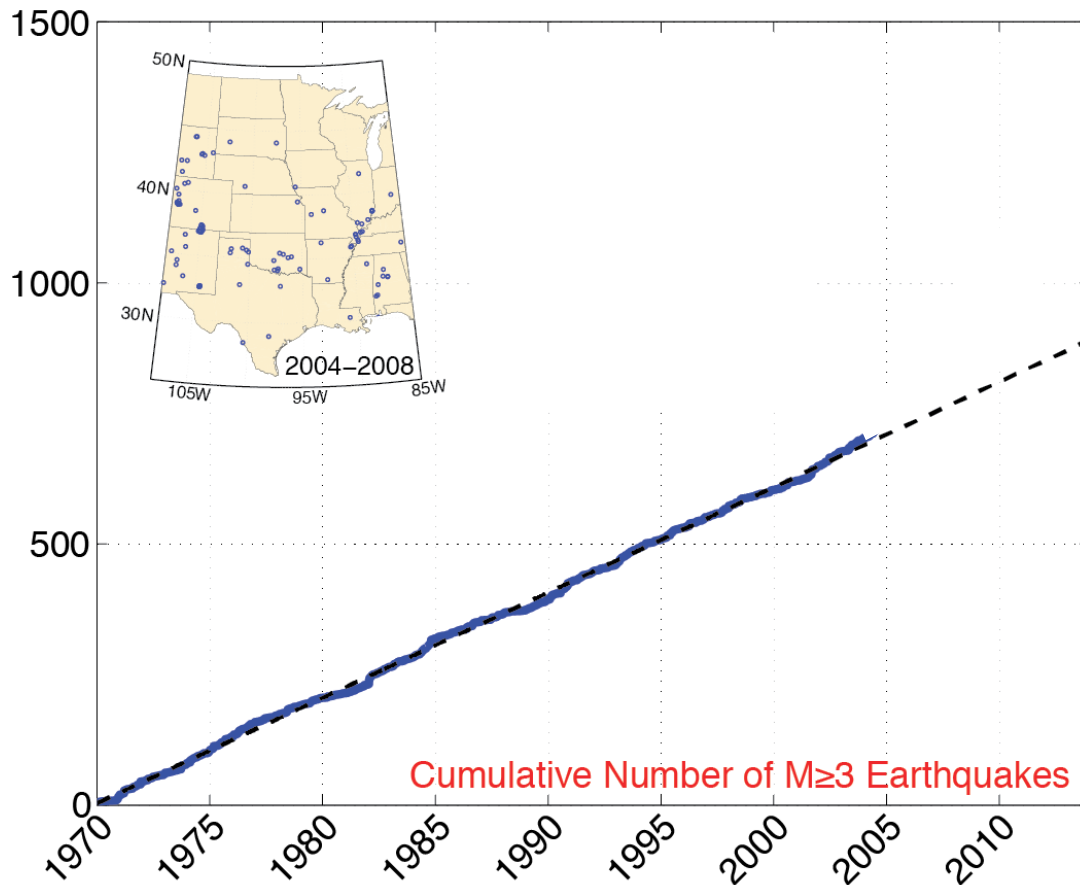
Geologists have long known that large amounts of organic matter and natural gas are trapped (usually by clay and other fine-grained minerals) in many



Douglas J. Arent

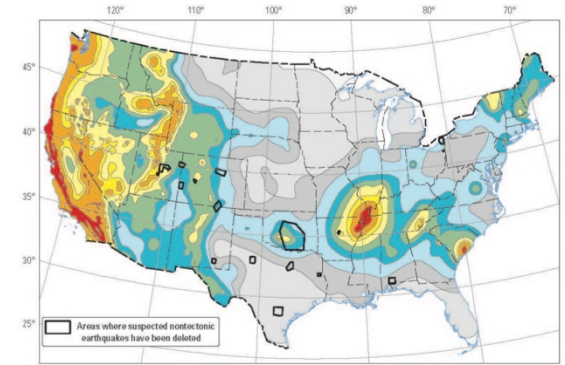
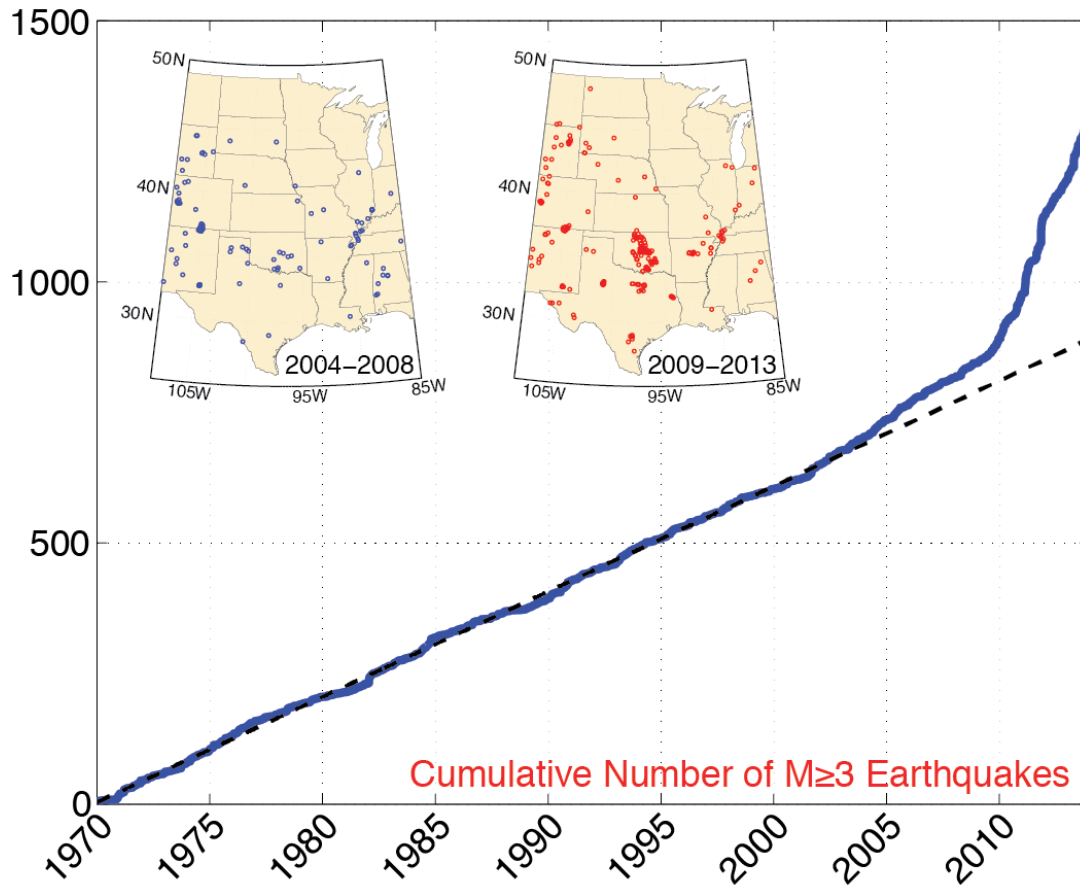


Earthquakes in the Mid-Continent

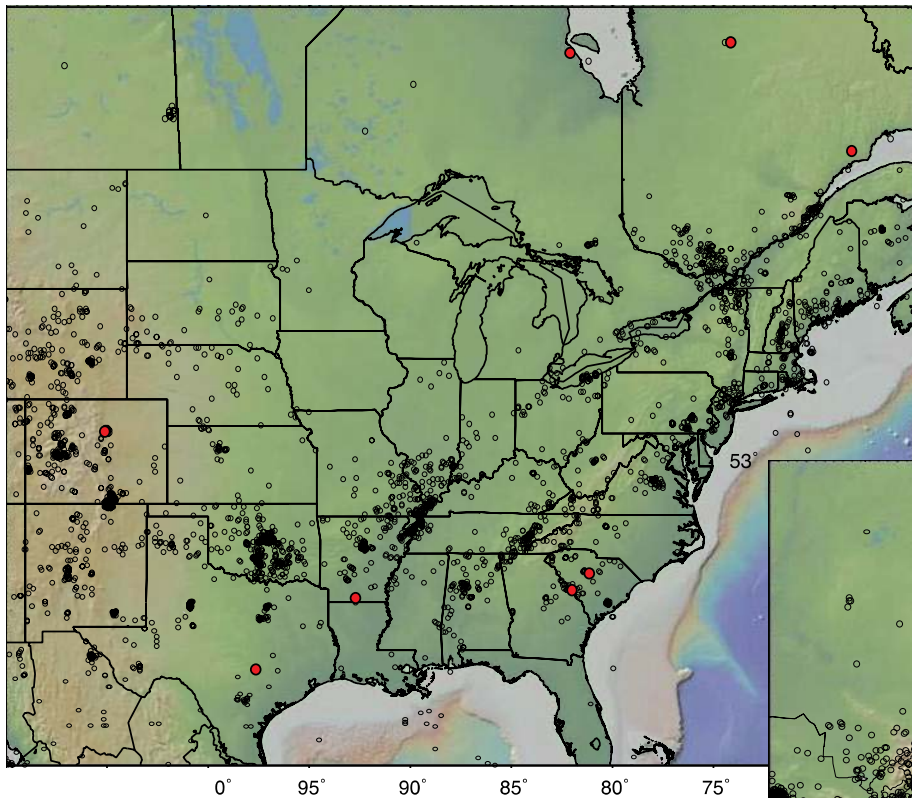


Ellsworth (2013)

Earthquakes in the Mid-Continent

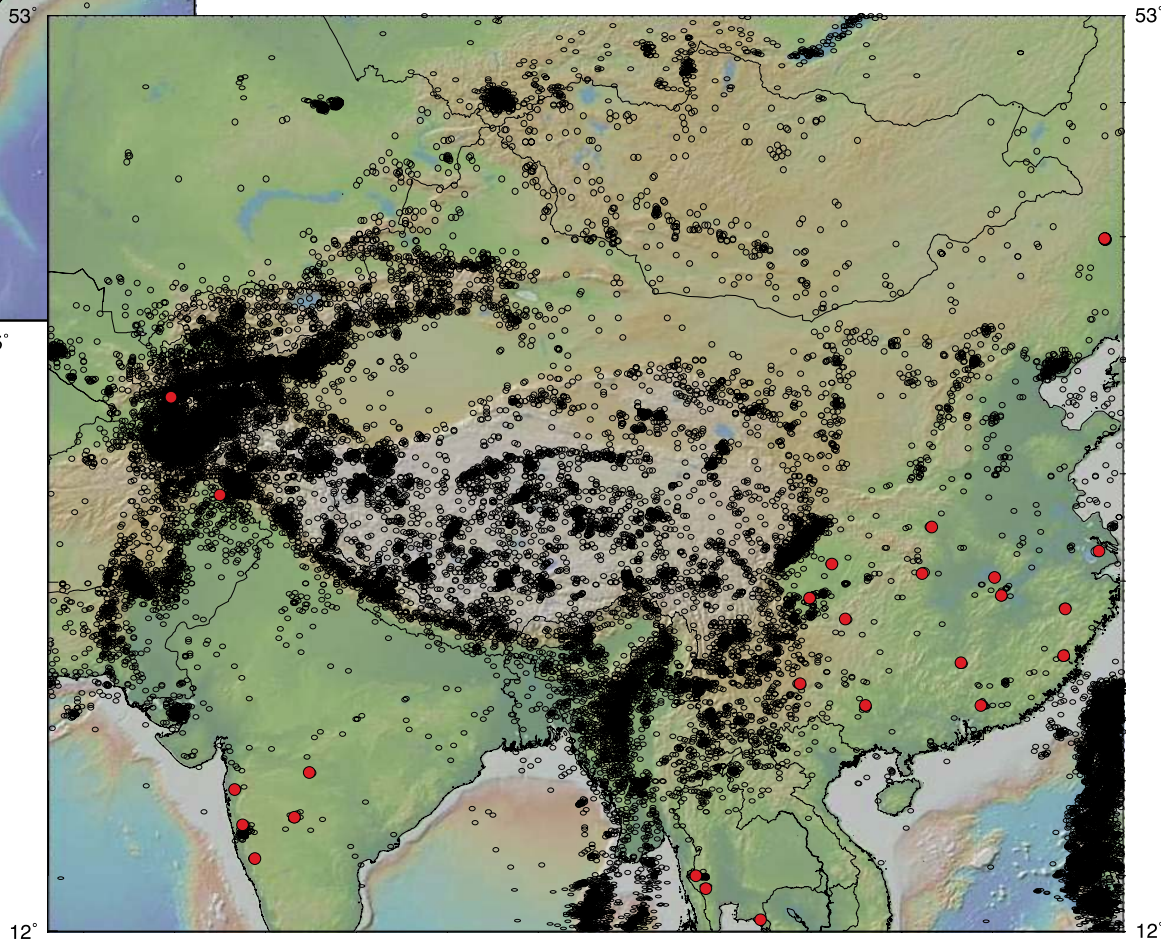


Ellsworth (2013)

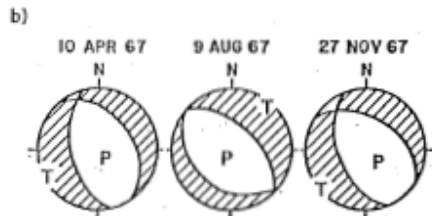
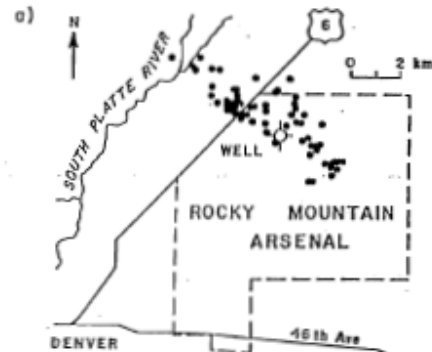
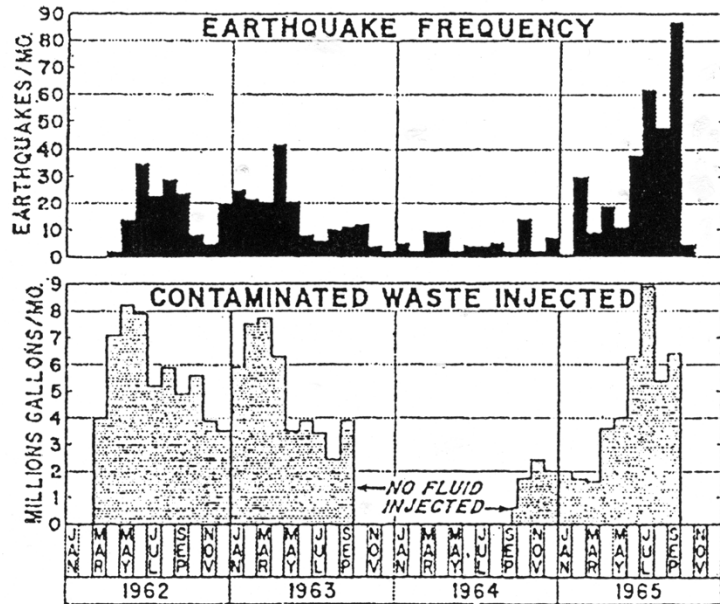


The Critically-Stressed Crust

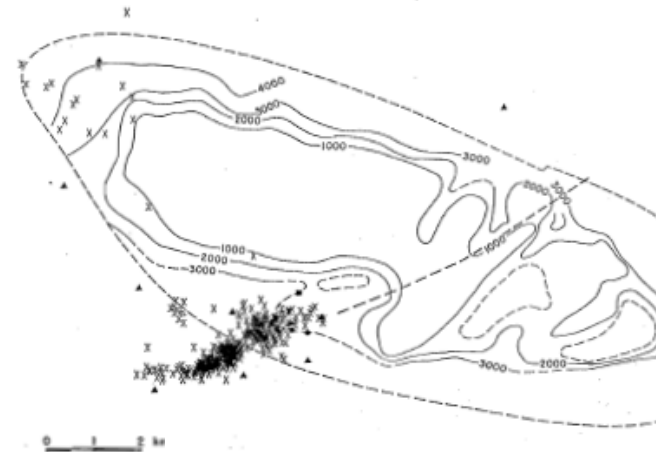
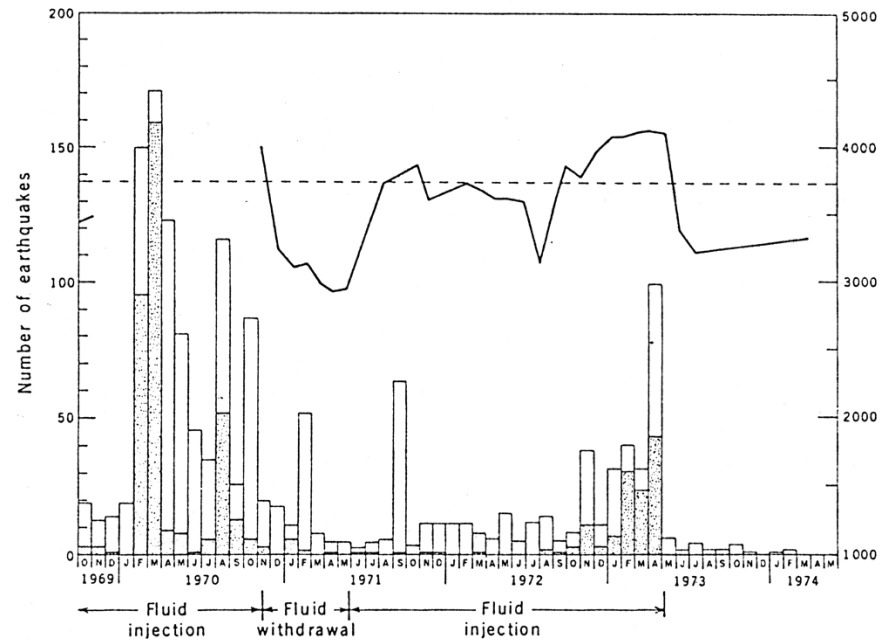
- Earthquakes Occur Nearly Everywhere in Intraplate Areas
- Small Perturbations <RIS> Capable of Triggering Seismicity, Even in “Stable Areas”



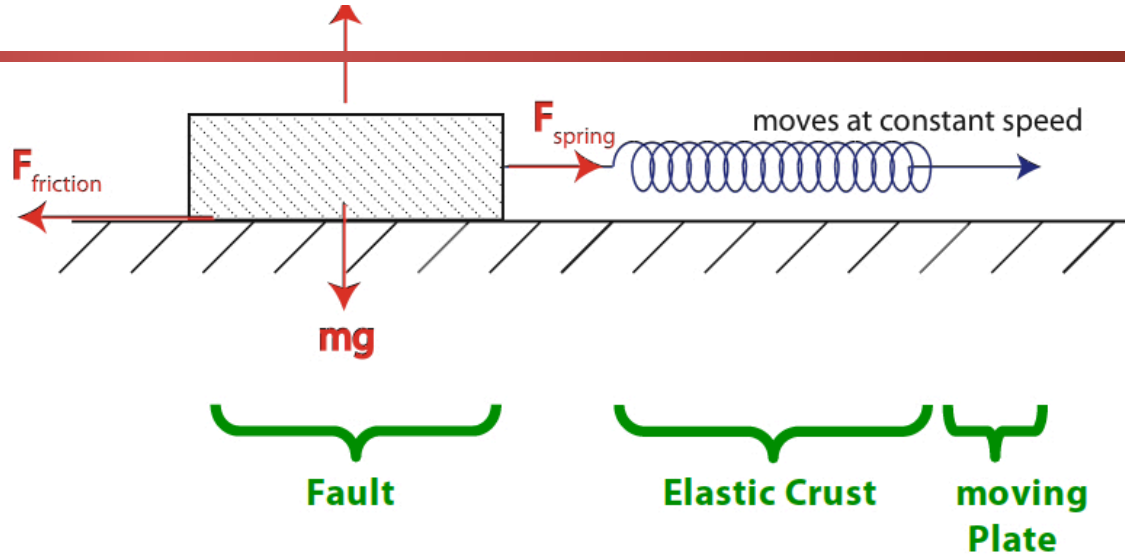
Waste Injection Denver Arsenal



Fluid Injection Rangely Oil Field

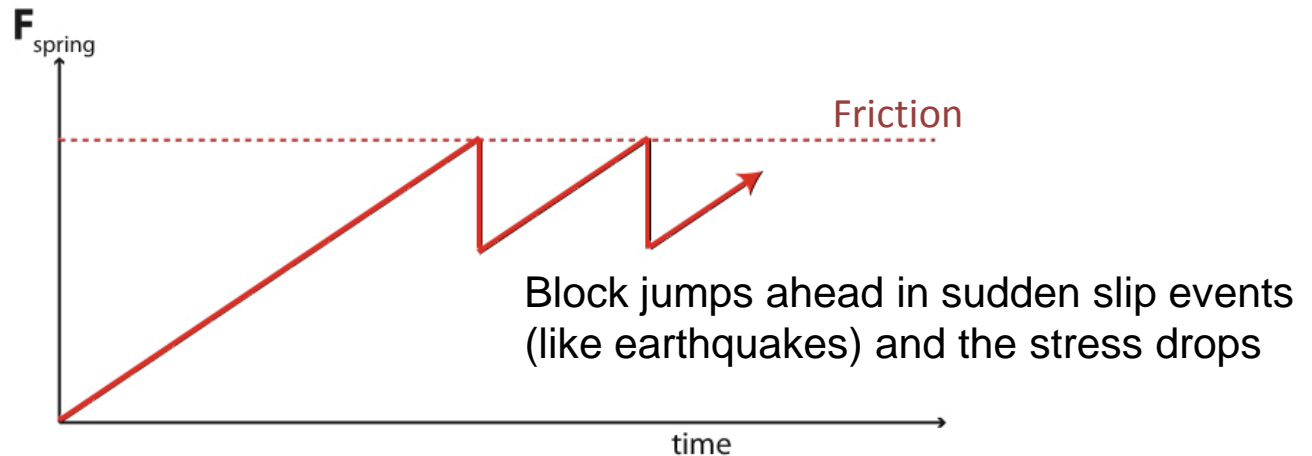


A Simple Earthquake Machine

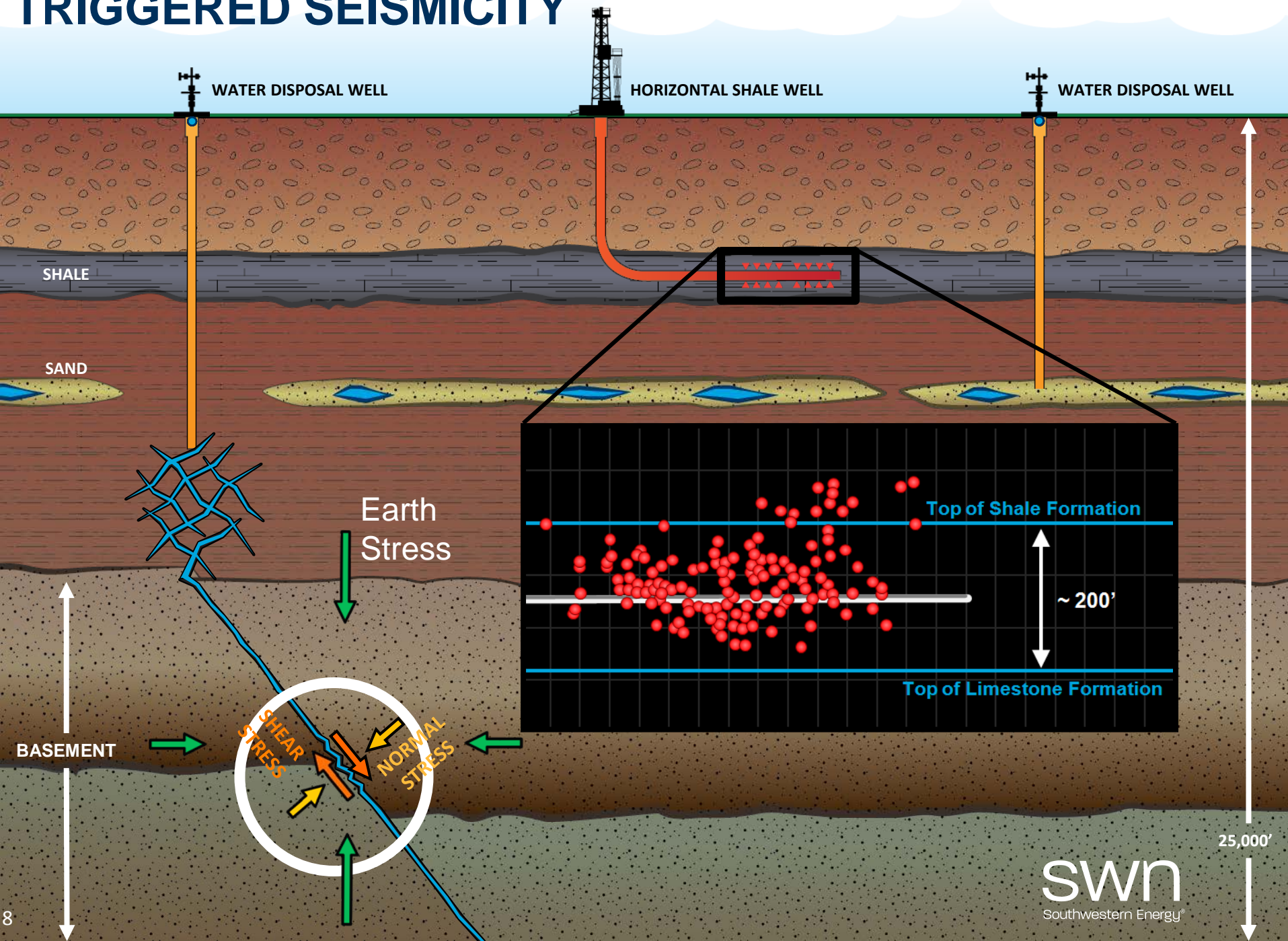


$$\tau = \mu \sigma_n$$

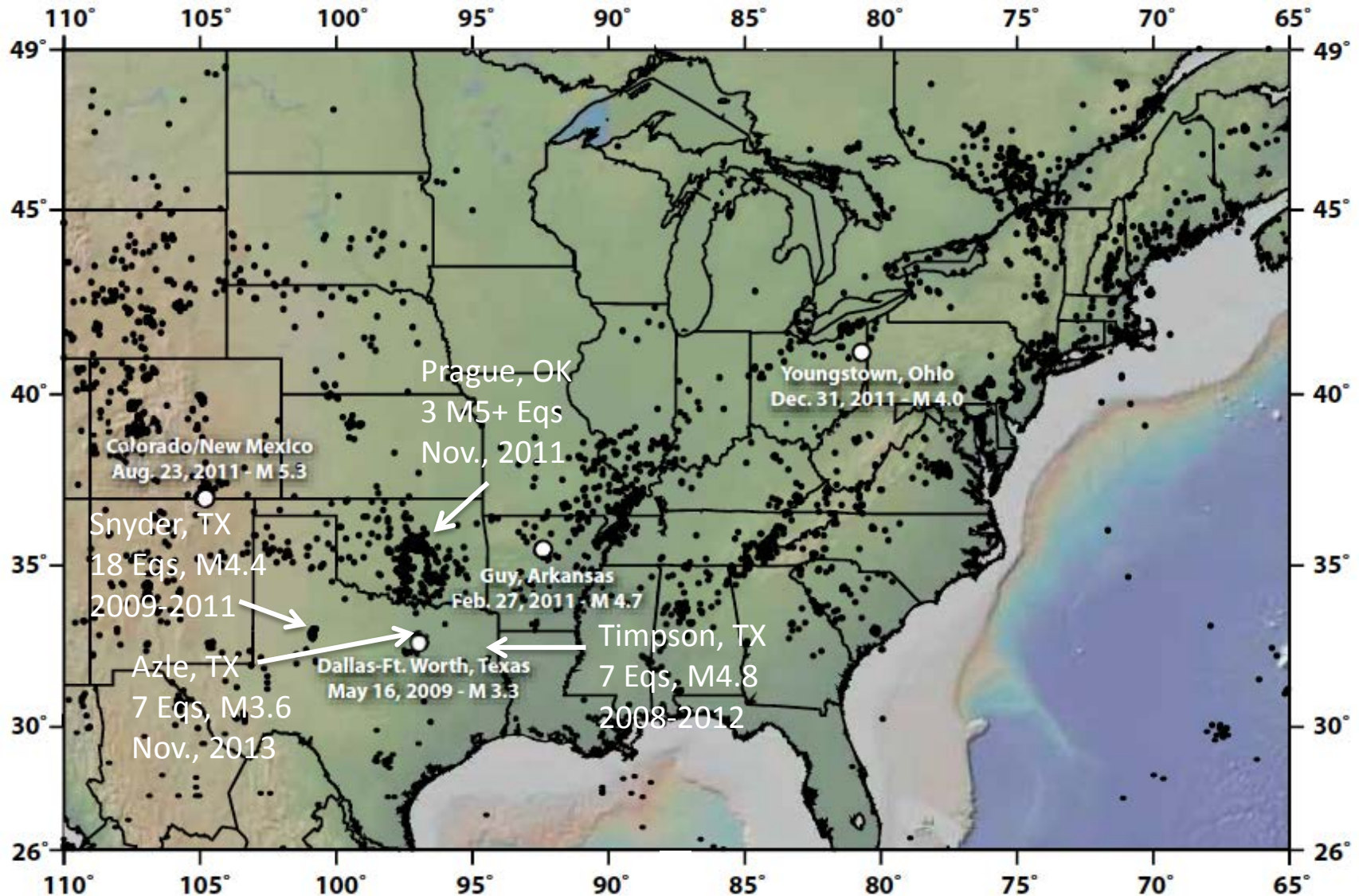
$$\sigma_n = S_n - P_p$$



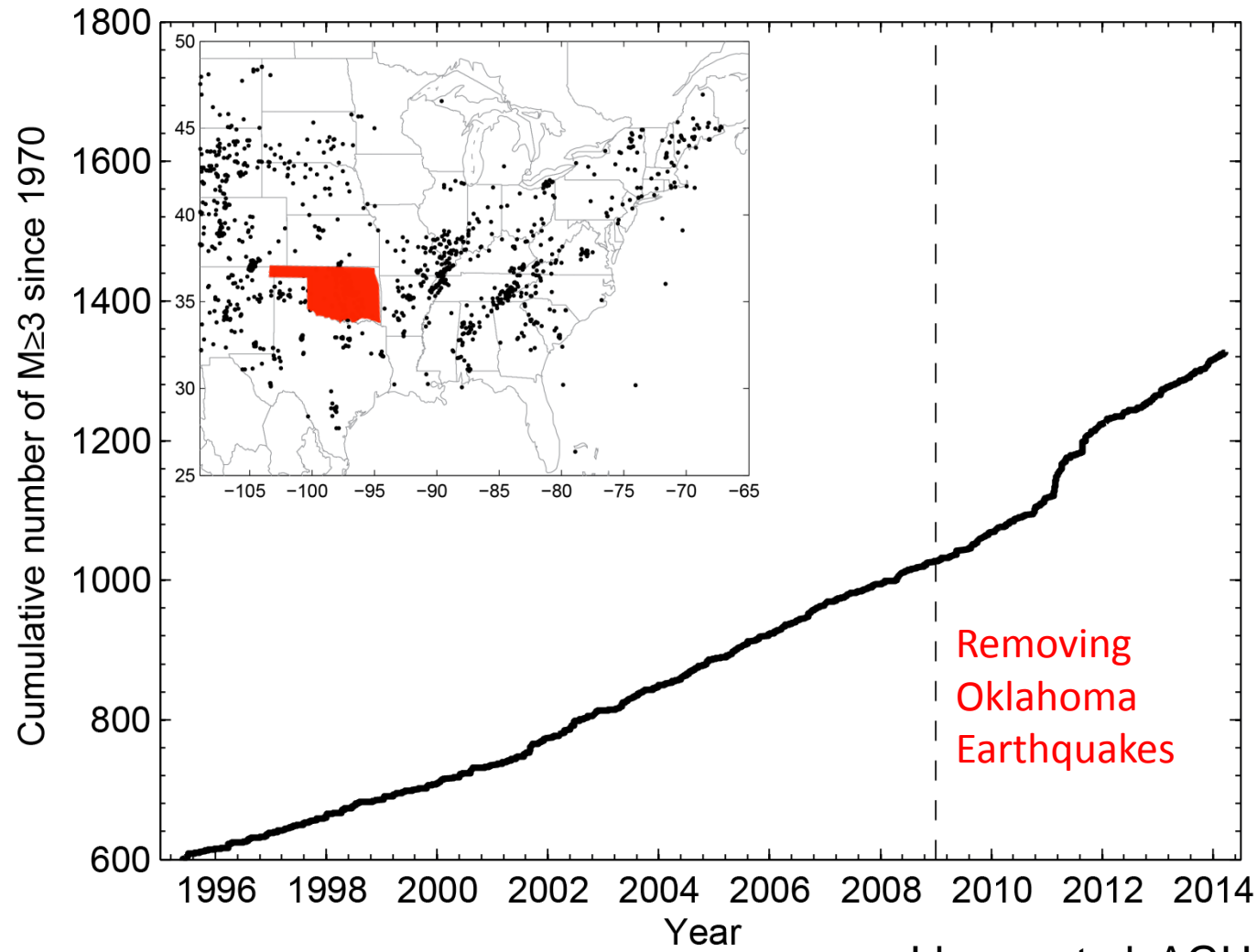
TRIGGERED SEISMICITY



Mostly Waste Water Injection

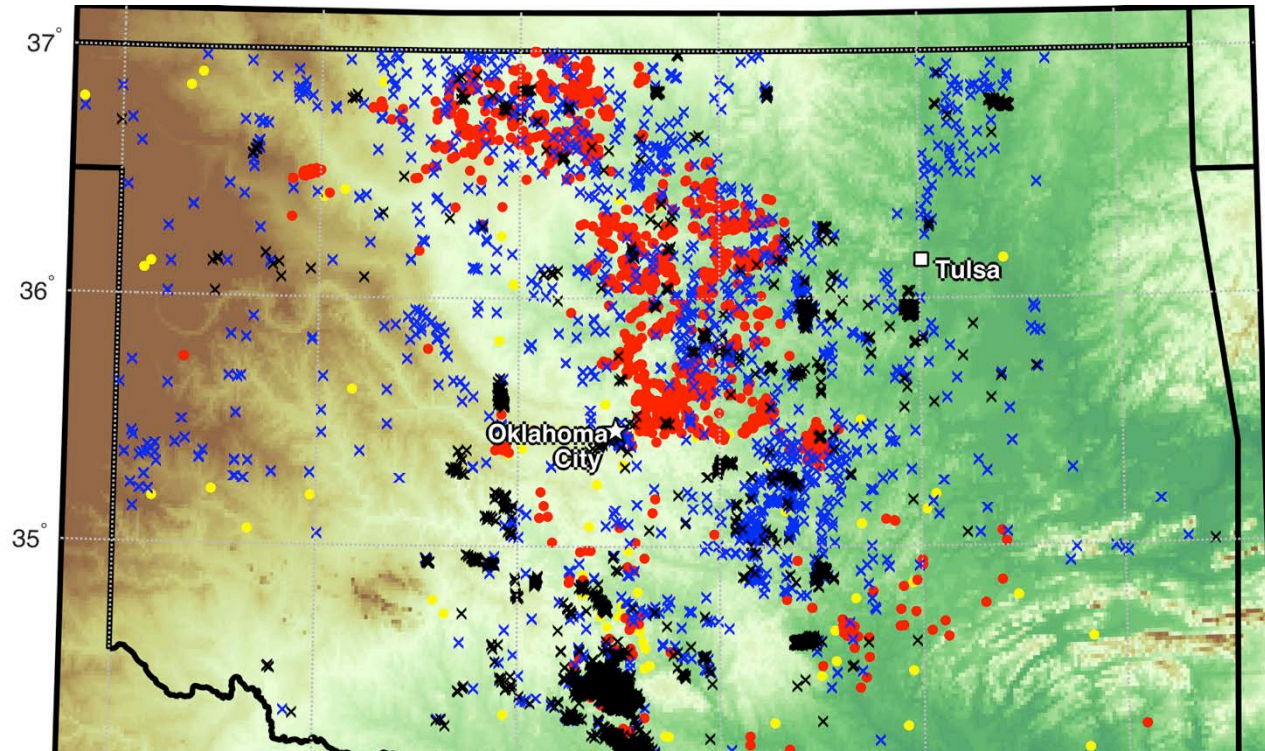


Oklahoma Has Had 69% of the Recent Earthquakes

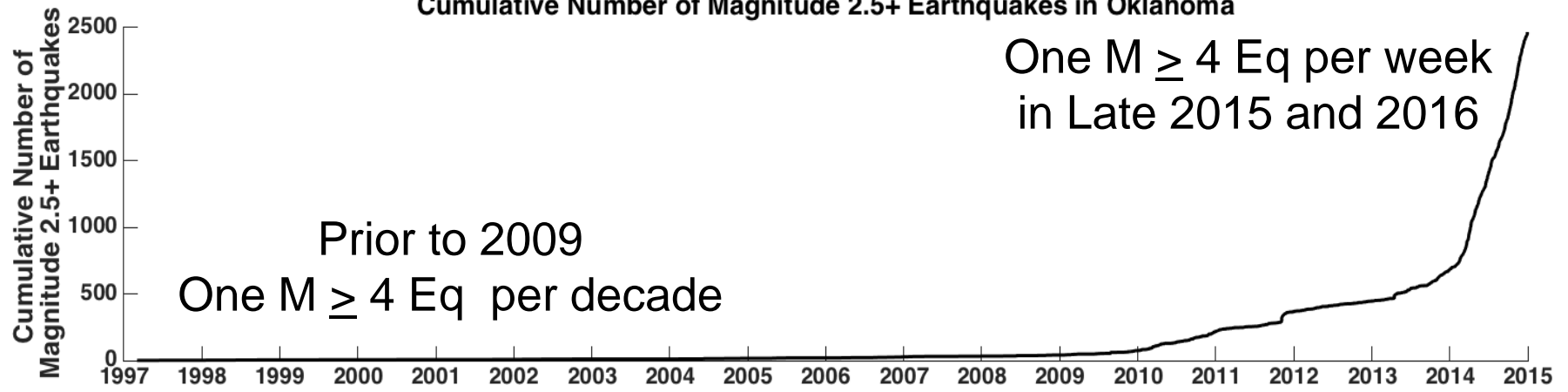


Llenos et al. AGU (2014)

Recent Earthquakes and Disposal Wells

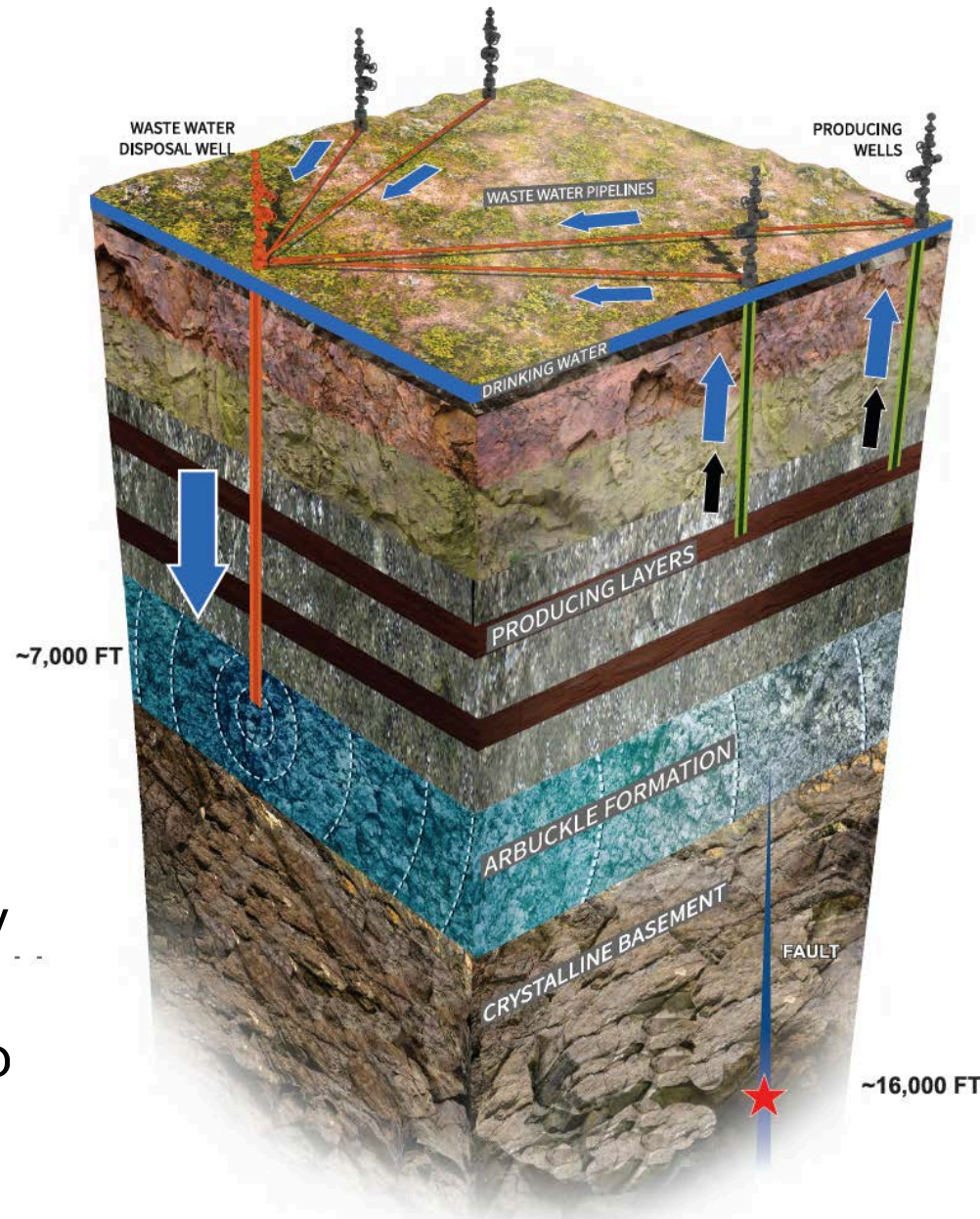


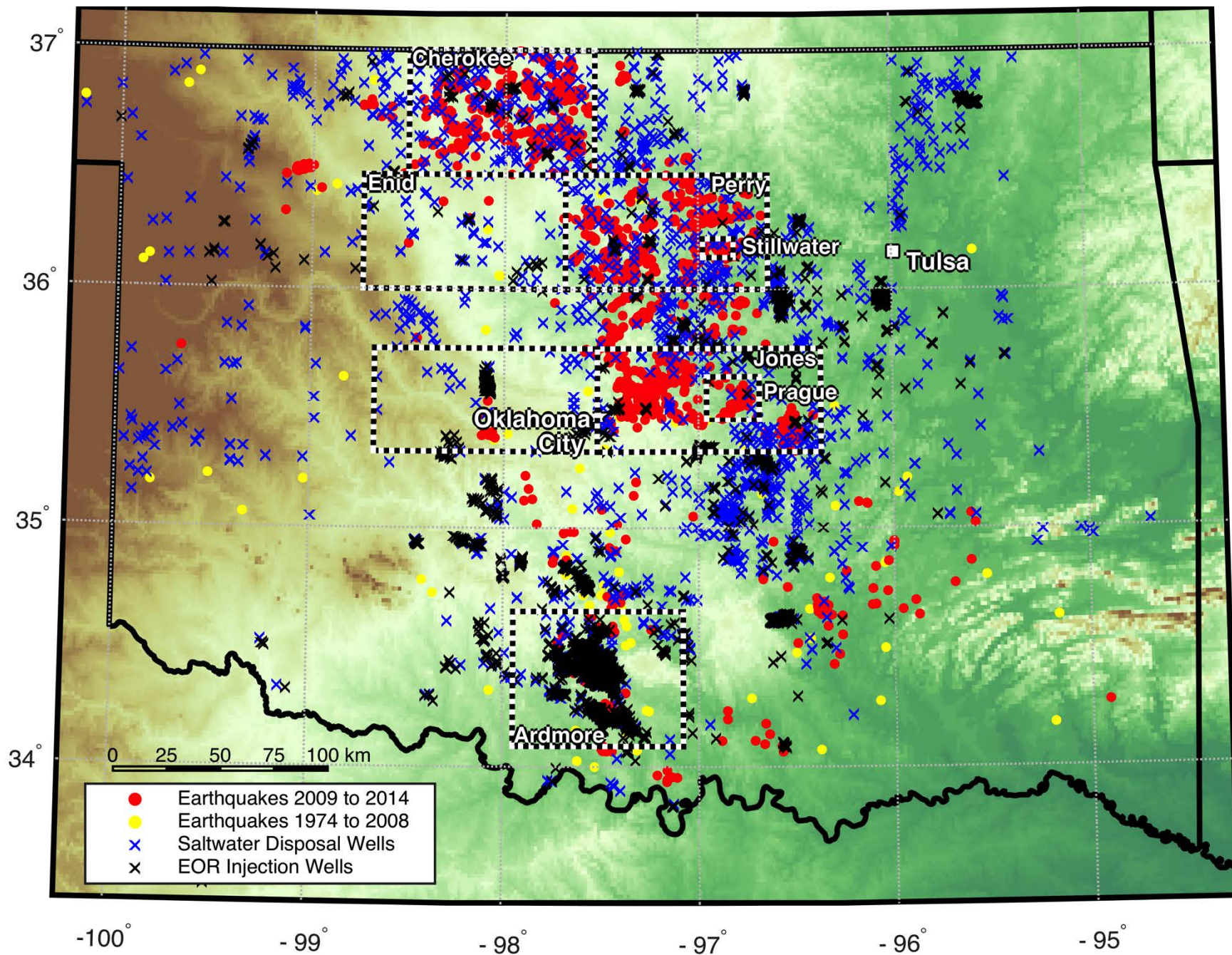
Cumulative Number of Magnitude 2.5+ Earthquakes in Oklahoma



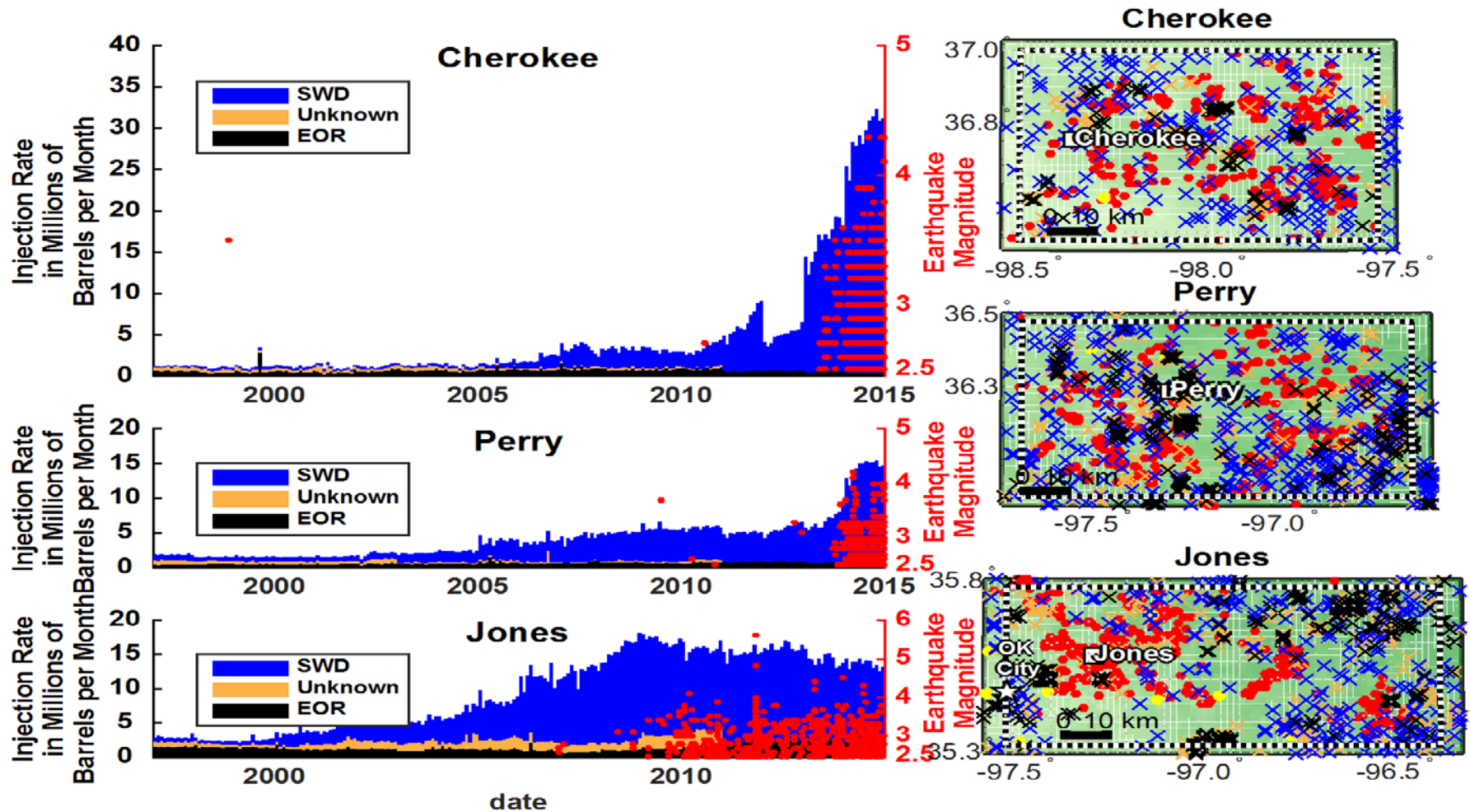
Saltwater Disposal is Triggering Earthquakes

- Shallow, very high water cut producing formations – Miss. Lime is most well known
- Massive quantities of produced saltwater is being disposed into the basal Arbuckle group.
- About 700 million barrels injected in 2014 alone.
- Earthquakes occur on pre-existing faults in basement due to increases in pore pressure.
- Potentially active faults are likely to be permeable, and extend from the crystalline basement up to the Arbuckle.

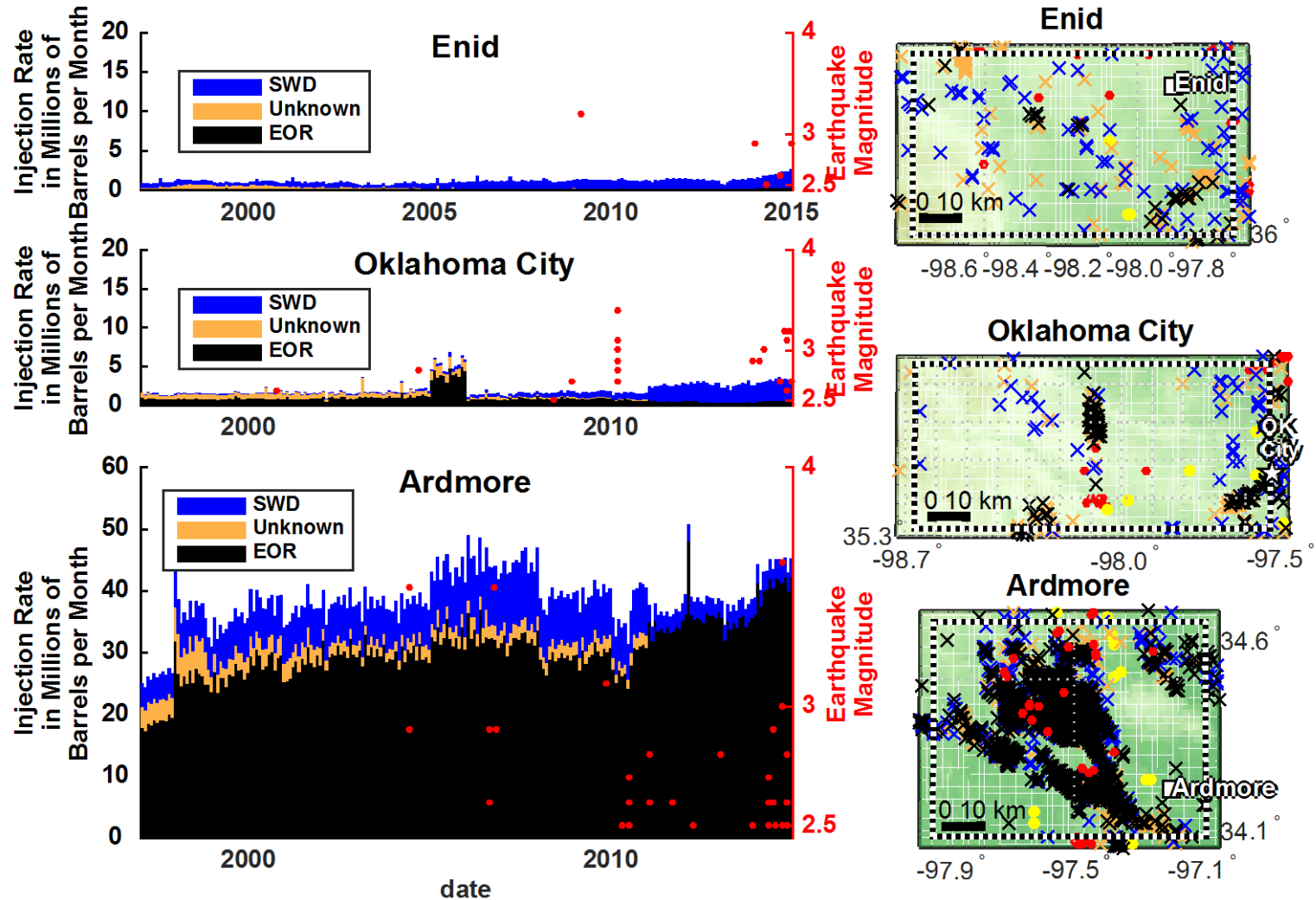




Seismically Active Areas in Oklahoma



Seismically Quiet Areas in Oklahoma





Liquid carbon dioxide has been injected into the Sleipner gas- and oilfield in the North Sea for 15 years without triggering any seismicity. It serves as a good example of how fluid injection can be done safely.

Managing the Seismic Risk Posed by Wastewater Disposal

Mark D. Zoback

From an earthquake perspective, 2011 was a remarkable year. While the devastation accompanying the magnitude-9.0 Tohoku earthquake that occurred off the coast of Japan on March 11 still captures attention worldwide, the relatively stable interior of the U.S. was struck by a somewhat surprising number of small-to-moderate earthquakes that were widely felt. Most of these were natural events, the types of earthquakes that occur from time to time in all intraplate regions. For example, the magnitude 5.8 that occurred in central Virginia on Aug. 23 was felt throughout the northeast, damaged the Washington Monument, and caused the temporary shutdown of a nuclear power plant. This earthquake occurred in the Central

Virginia Seismic Zone, an area known to produce relatively frequent small earthquakes.

However, a number of the small-to-moderate earthquakes that occurred in the U.S. interior in 2011 appear to be associated with the disposal of wastewater, at least in part related to natural gas production. Several small earthquakes were apparently caused by injection of wastewater associated with shale gas production near Guy, Ark.; the largest earthquake was a magnitude-4.7 event on Feb. 27. In the Trinidad/Raton area near the border of Colorado and New Mexico, injection of wastewater associated with coalbed methane production seems to be associated with a magnitude-5.3 event that occurred on Aug. 22, and small earthquakes that appear to have been triggered by

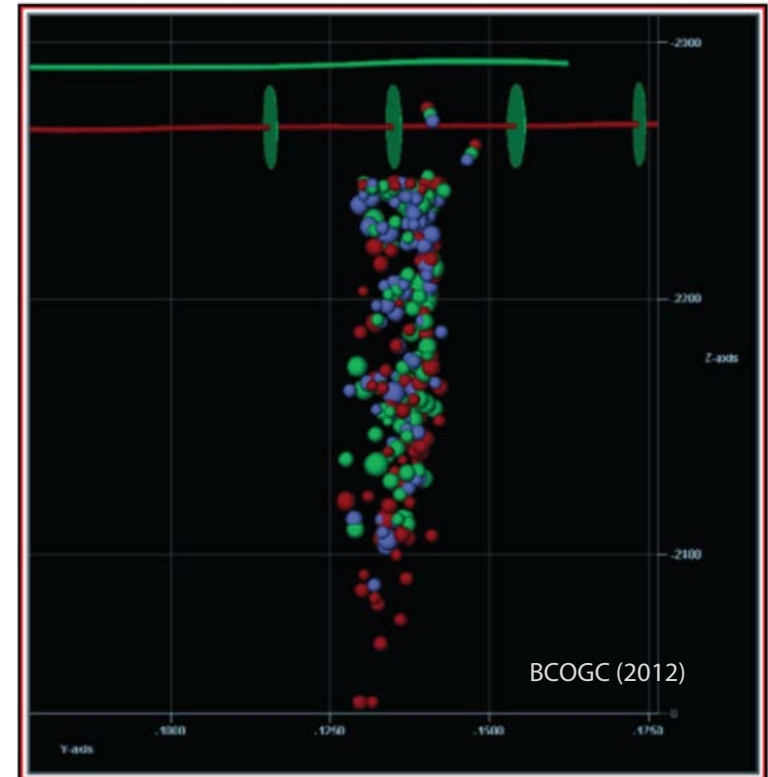
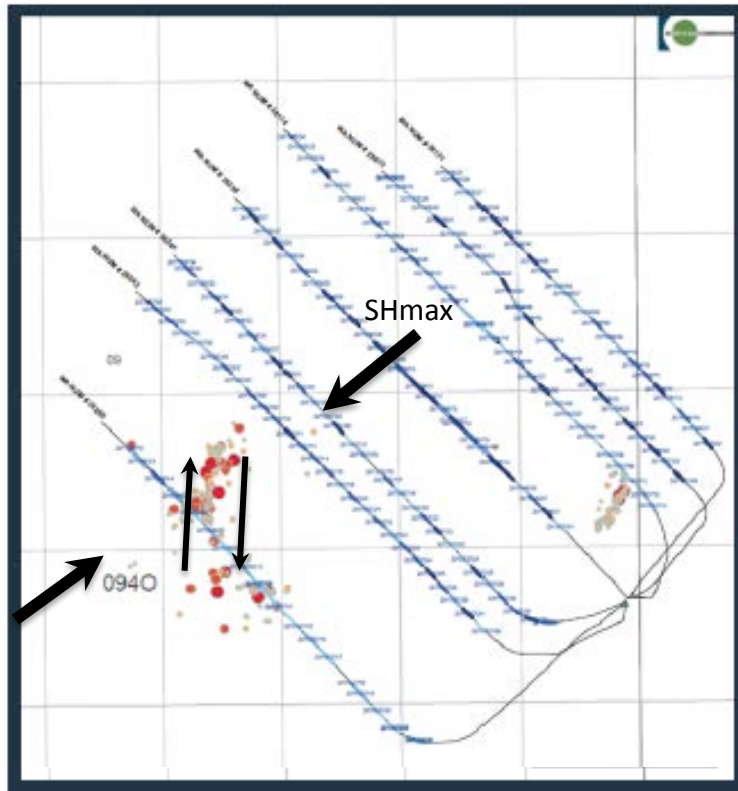
Photo: Shutterstock

Water Recycling – Western Pennsylvania



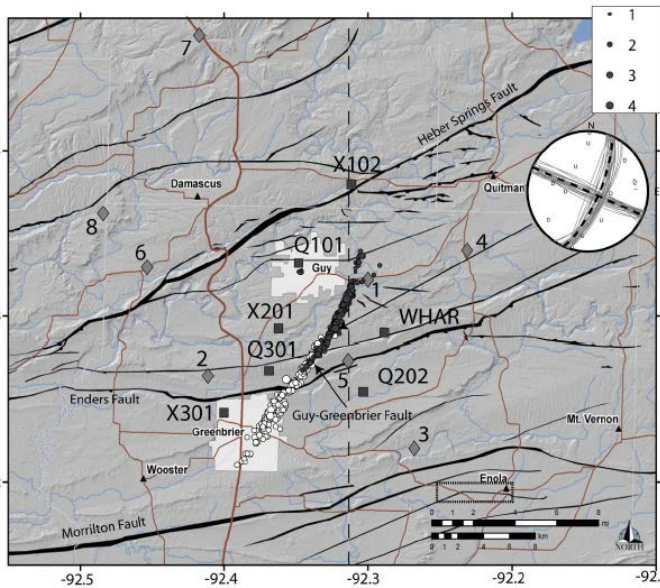
Flow Back Water Does Not Need to be Injected

Avoid Faults During Hydraulic Fracturing



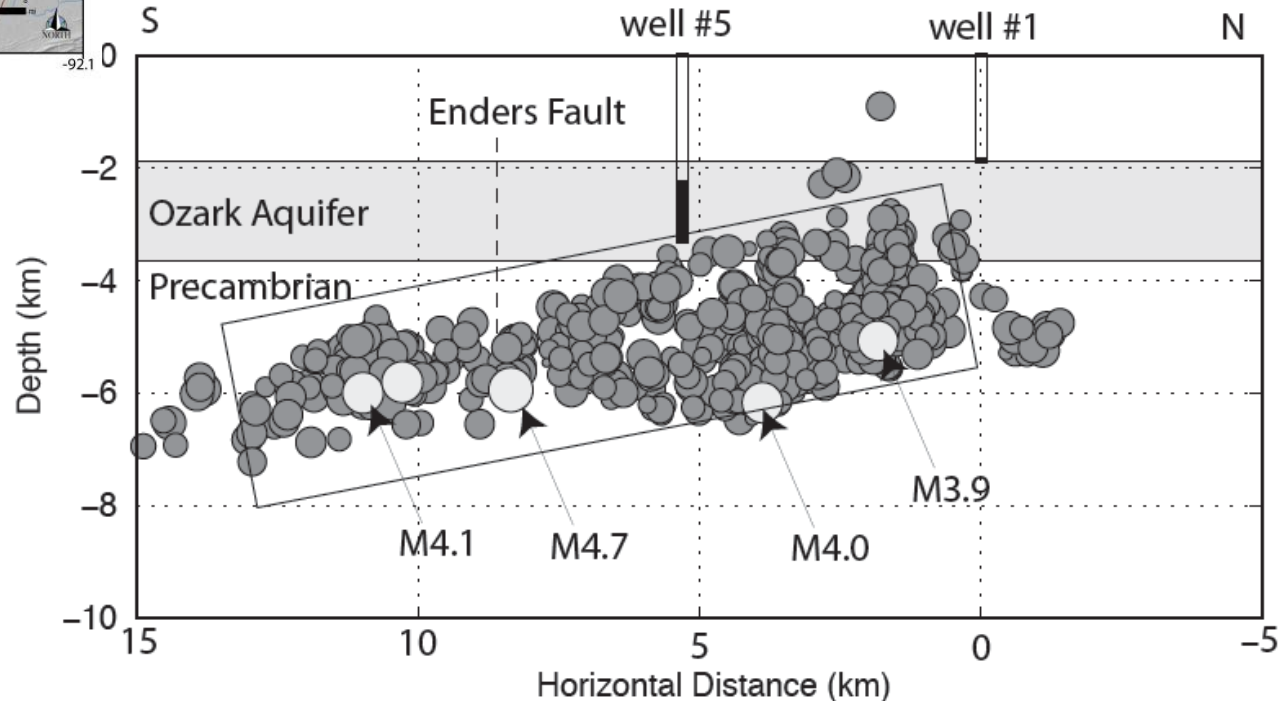
Distribution of earthquakes indicates slip along a pre-existing fault at the Horn River Basin hydraulic fracturing project in British Columbia

Faulting on Basement Faults in Response to Injection in Overlaying Sedimentary Formations

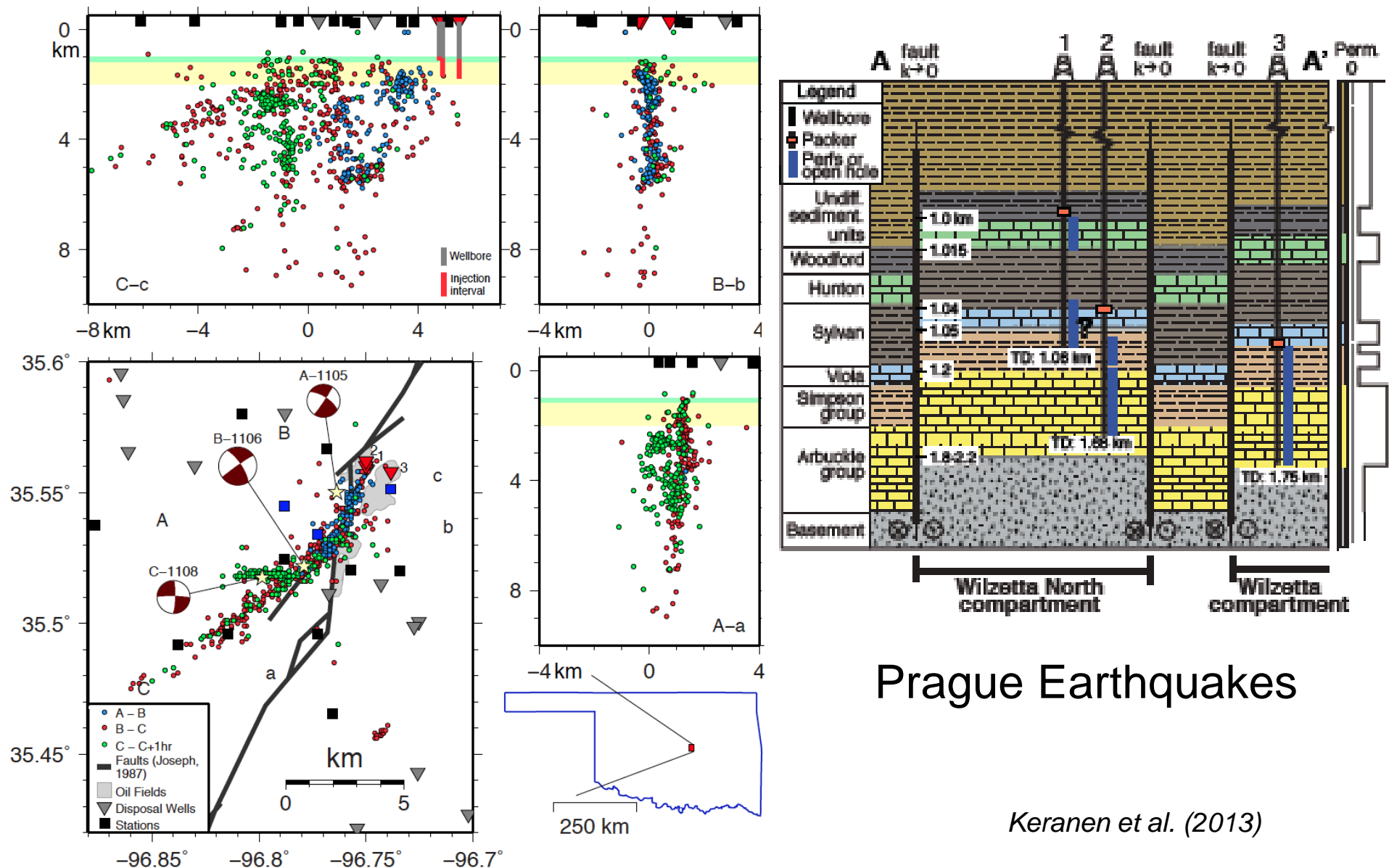


Horton (2012)

Earthquake Hazard Depends on Whether Injection into Sedimentary Rocks Increases Pore Pressure in Potentially Active Basement Faults



Faulting on Basement Faults in Response to Injection in Overlaying Sedimentary Formations

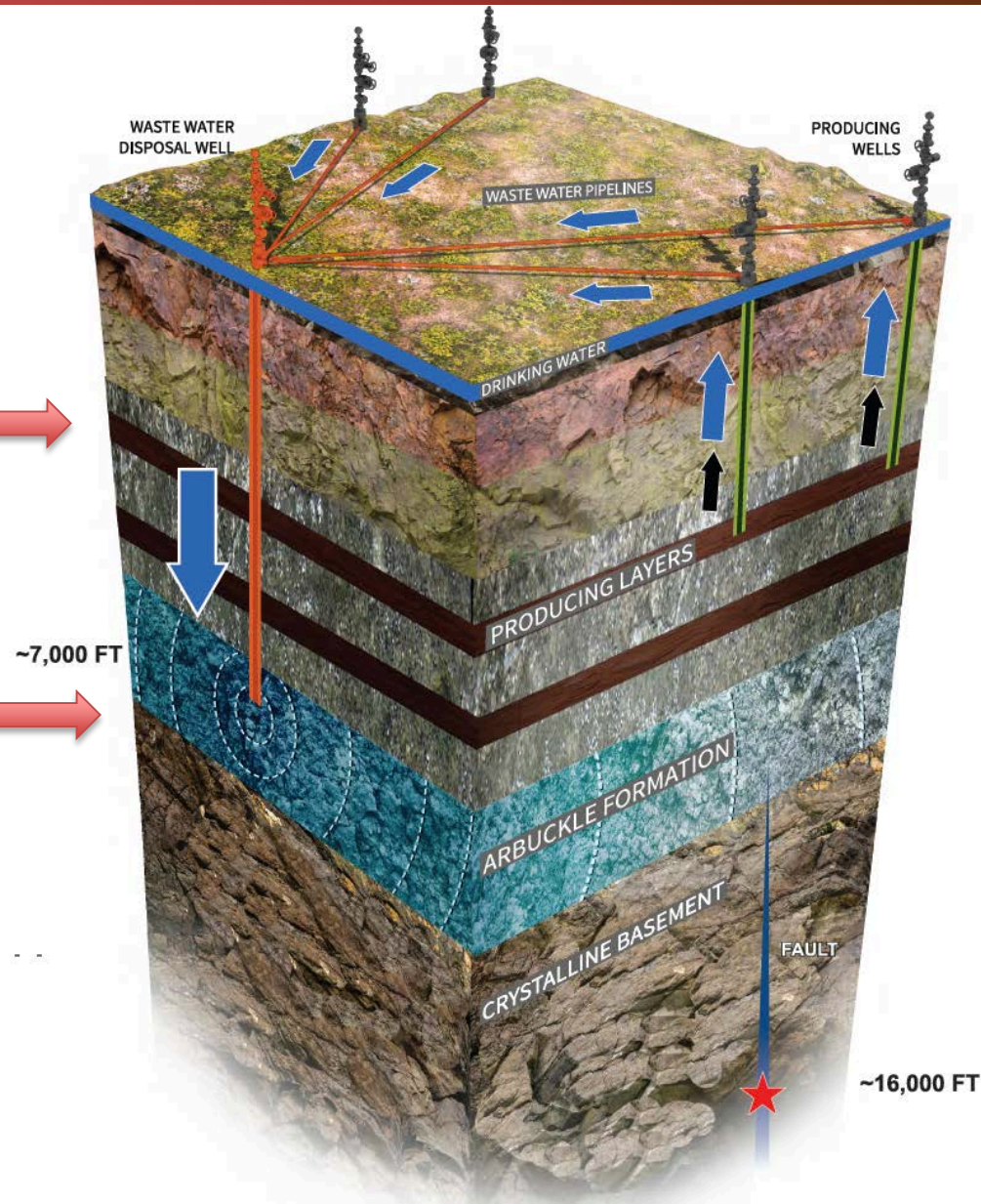


Massive SWD in Oklahoma

Is There a Possible Solution?

Re-inject produced water into shallower formations, ideally the producing formation

Avoid injecting into formations without a bottom seal.





Thank you