Oklahoma's Recent Earthquakes and Saltwater Disposal*

F. Rall Walsh[1], Randi J. Walters[2], Mark D. Zoback[2], Jack W. Baker[2], and Gregory C. Beroza[2]

Search and Discovery Article #80516 (2016)**
Posted February 22, 2016

*Adopted from oral presentation given at AAPG Mid-Continent Section meeting in Tulsa, Oklahoma, October 4-6, 2015

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Abstract

The number of small-to-moderate sized earthquakes in much of the central and eastern United States began to increase markedly in 2009. About three quarters of the anomalous seismicity in the central and eastern U.S. has been in Oklahoma, which went from approximately one M≥4 earthquake every decade, to one nearly every 2 weeks. In five study areas that encompass 82% of the recent M≥3 seismicity, we show that the increases in seismicity follow increases in the rates of saltwater disposal with varying temporal relationships. Adjacent areas where there is relatively little saltwater disposal have had comparatively few earthquakes. In the areas of greatest seismic activity, the saltwater disposal comes principally from produced water, saline pore water that is co-produced with oil and then injected into deeper sedimentary formations, not flowback water. The injection formations appear to be in hydraulic communication with potentially active faults in crystalline basement, where nearly all the earthquakes are occurring. Although the majority of the recent earthquakes have posed little danger to the public, the possibility of triggering damaging earthquakes on potentially active basement faults cannot be discounted. Injection of the produced water into depleted portions of the reservoirs from which it was produced should reduce the rate of seismicity.

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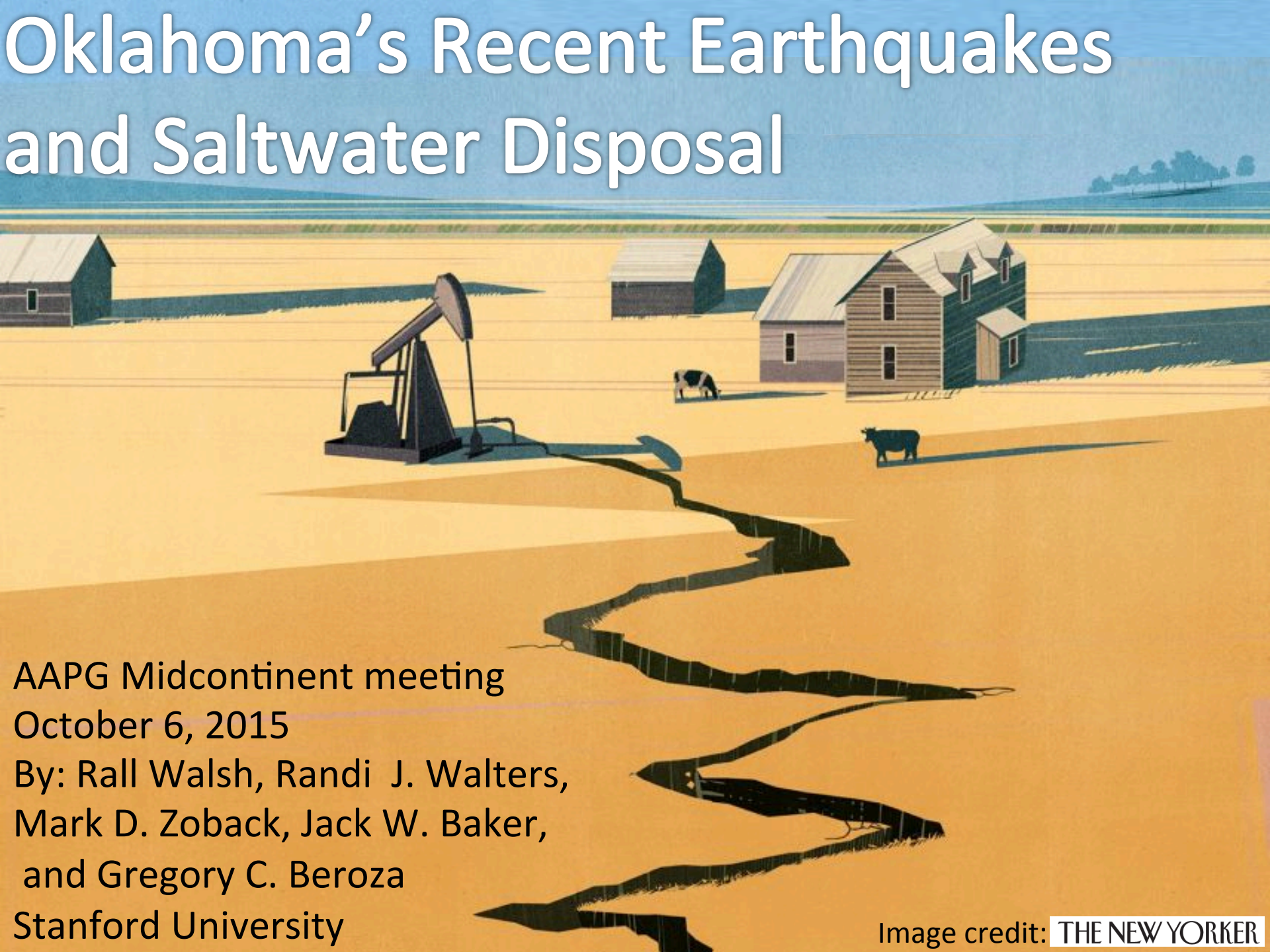
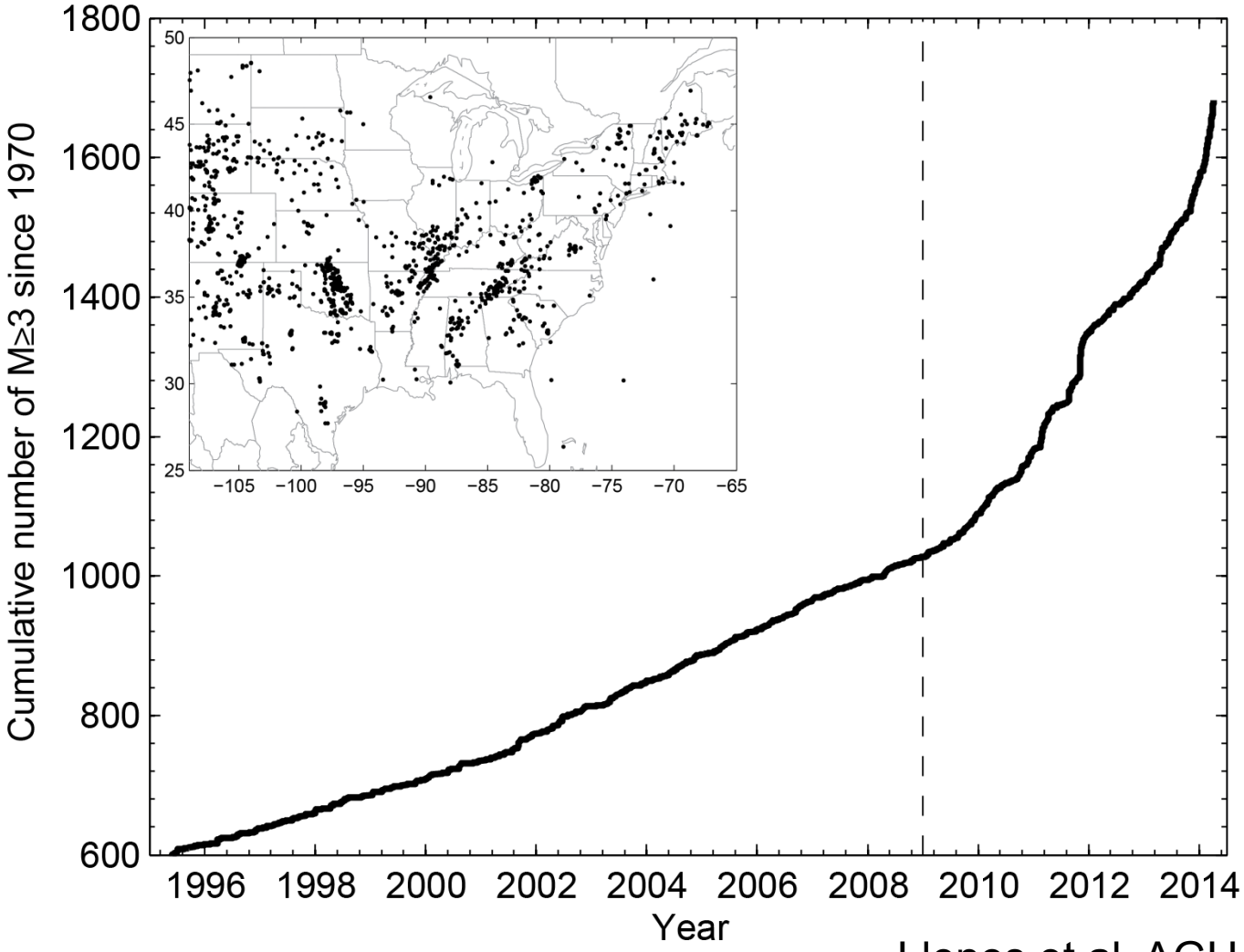


AAPG Midcontinent meeting
October 6, 2015
By: Rall Walsh, Randi J. Walters, Mark D. Zoback, Jack W. Baker, and Gregory C. Beroza
Stanford University

Image credit: THE NEW YORKER

Oklahoma Has Had 69% of the Recent CEUS Earthquakes



Llenos et al. AGU (2014)

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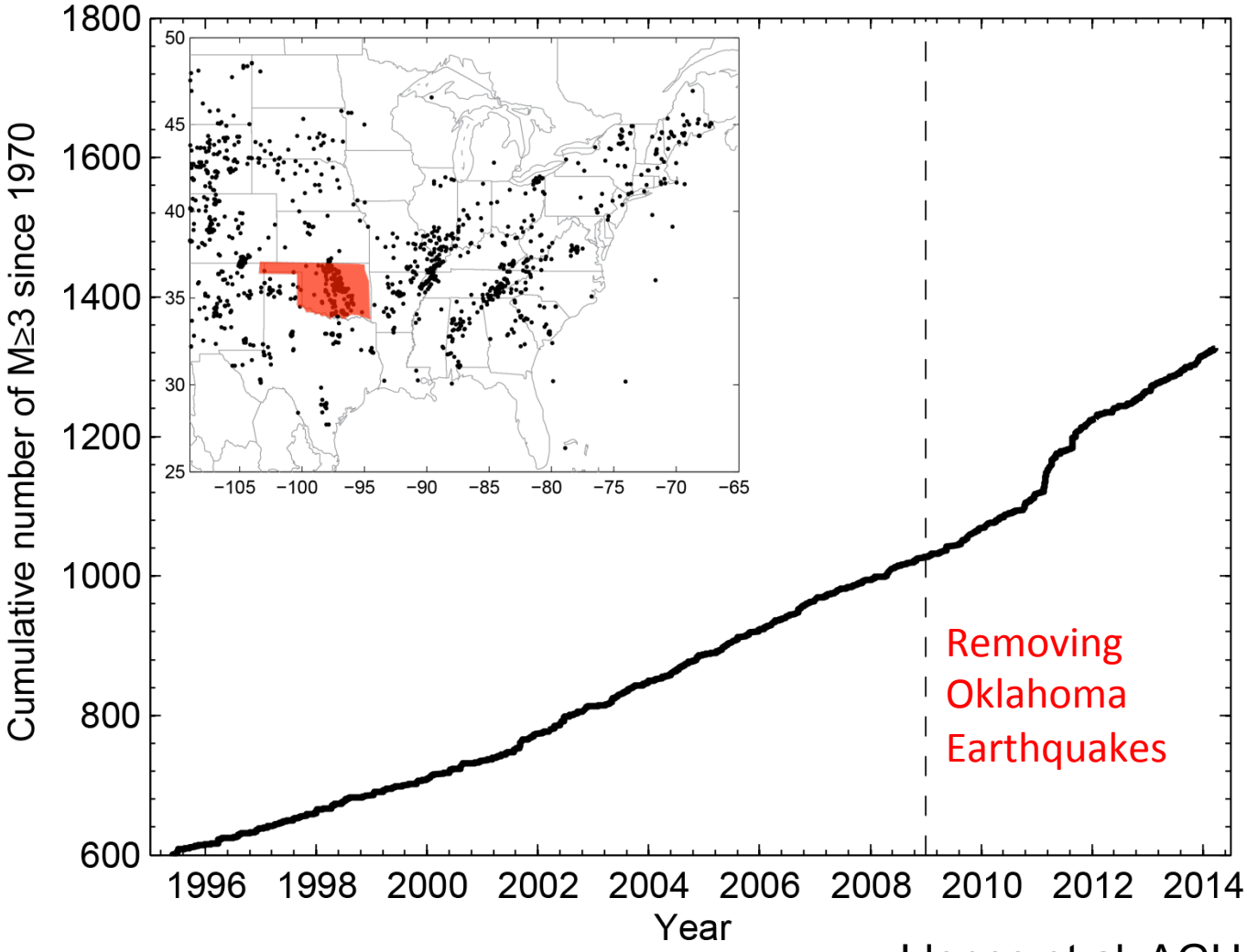

Llenos et al. AGU (2014)

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RESEARCH ARTICLE

SEISMOLOGY

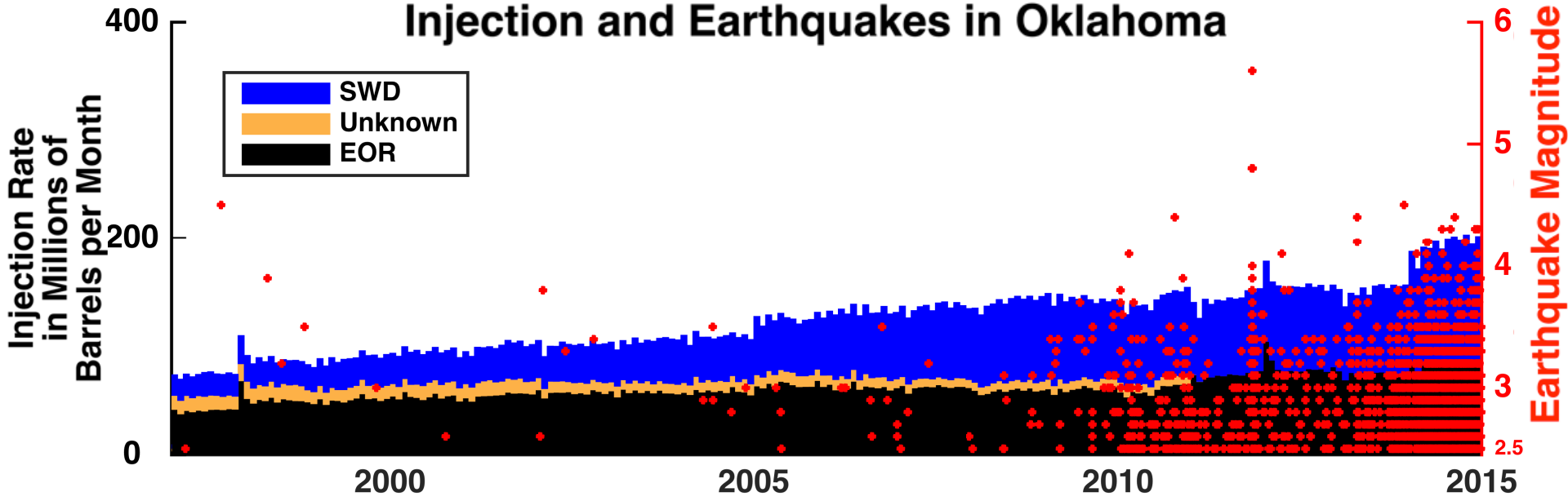
Oklahoma's recent earthquakes and saltwater disposal

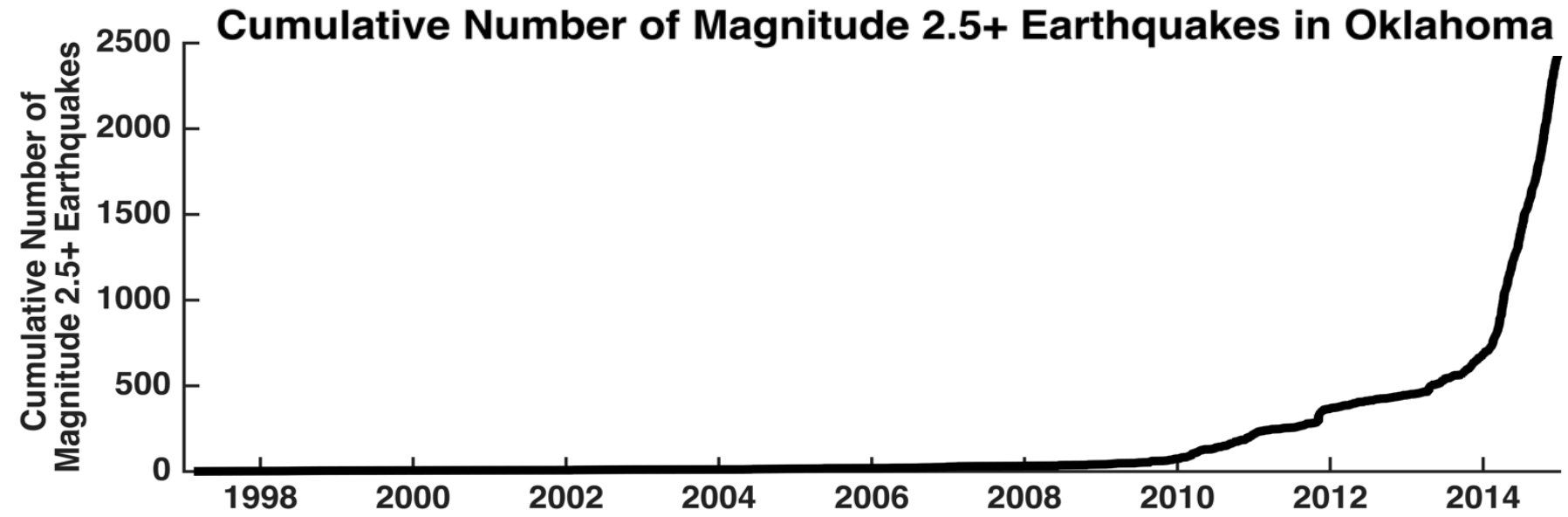
F. Rall Walsh III* and Mark D. Zoback

Over the past 5 years, parts of Oklahoma have experienced marked increases in the number of small- to moderate-sized earthquakes. In three study areas that encompass the vast majority of the recent seismicity, we show that the increases in seismicity follow 5- to 10-fold increases in the rates of saltwater disposal. Adjacent areas where there has been relatively little saltwater disposal have had comparatively few recent earthquakes. In the areas of seismic activity, the saltwater disposal principally comes from "produced" water, saline pore water that is coproduced with oil and then injected into deeper sedimentary formations. These formations appear to be in hydraulic communication with potentially active faults in crystalline basement, where nearly all the earthquakes are occurring. Although most of the recent earthquakes have posed little danger to the public, the possibility of triggering damaging earthquakes on potentially active basement faults cannot be discounted.

Whole State Vol

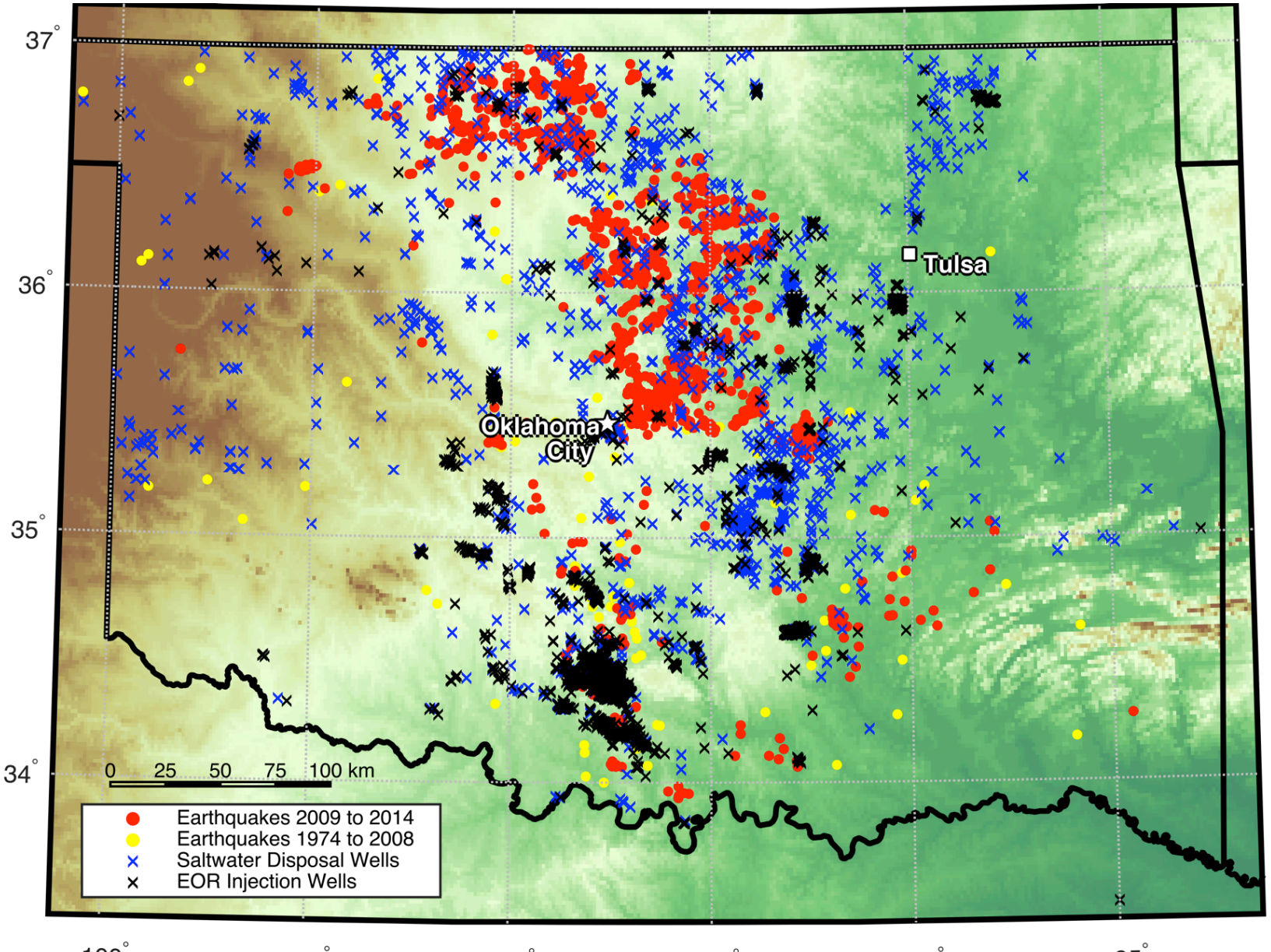
Oklahoma had Increases in Both Saltwater Disposal and Earthquakes



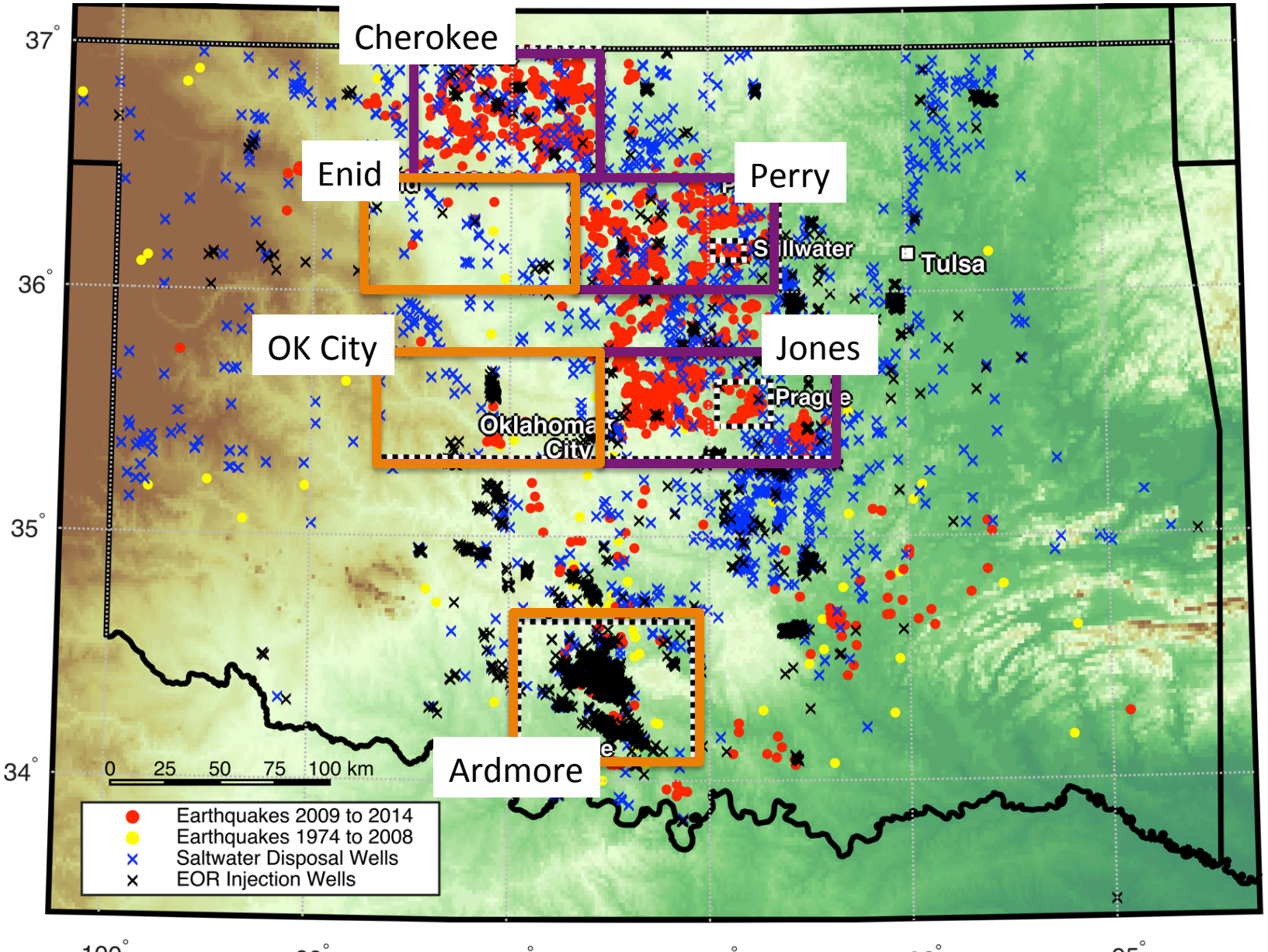


map

the Increases in Disposal Were In the Areas Where Earthquakes Happened.

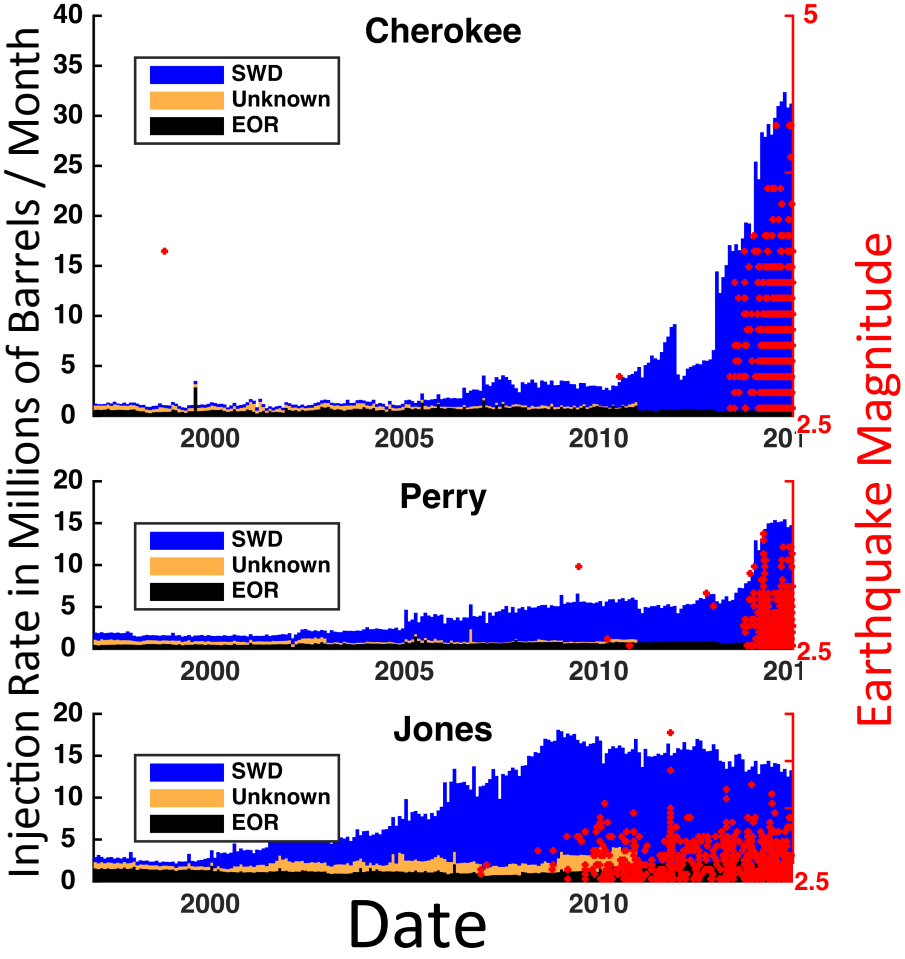


Selected Study Areas

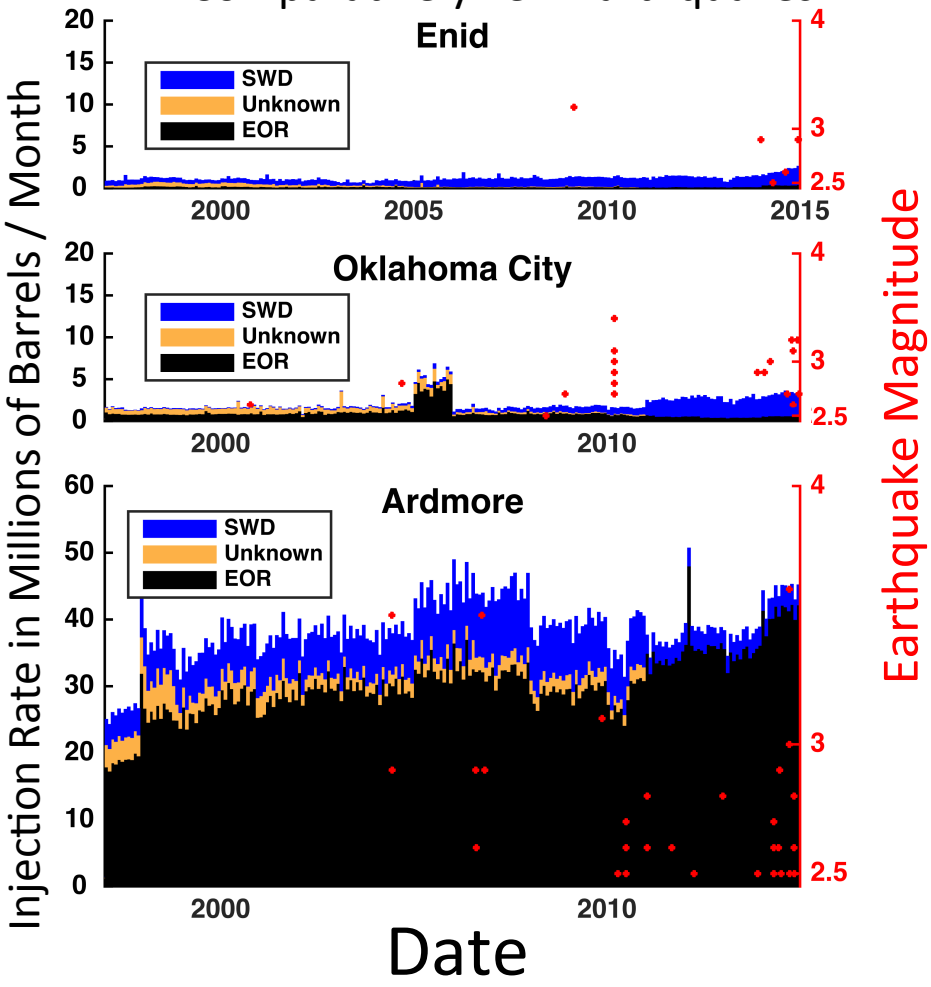


The Areas With Increased Disposal Had The Earthquakes

3 Areas with 71% of Oklahoma's Earthquakes and 8% of it's land area



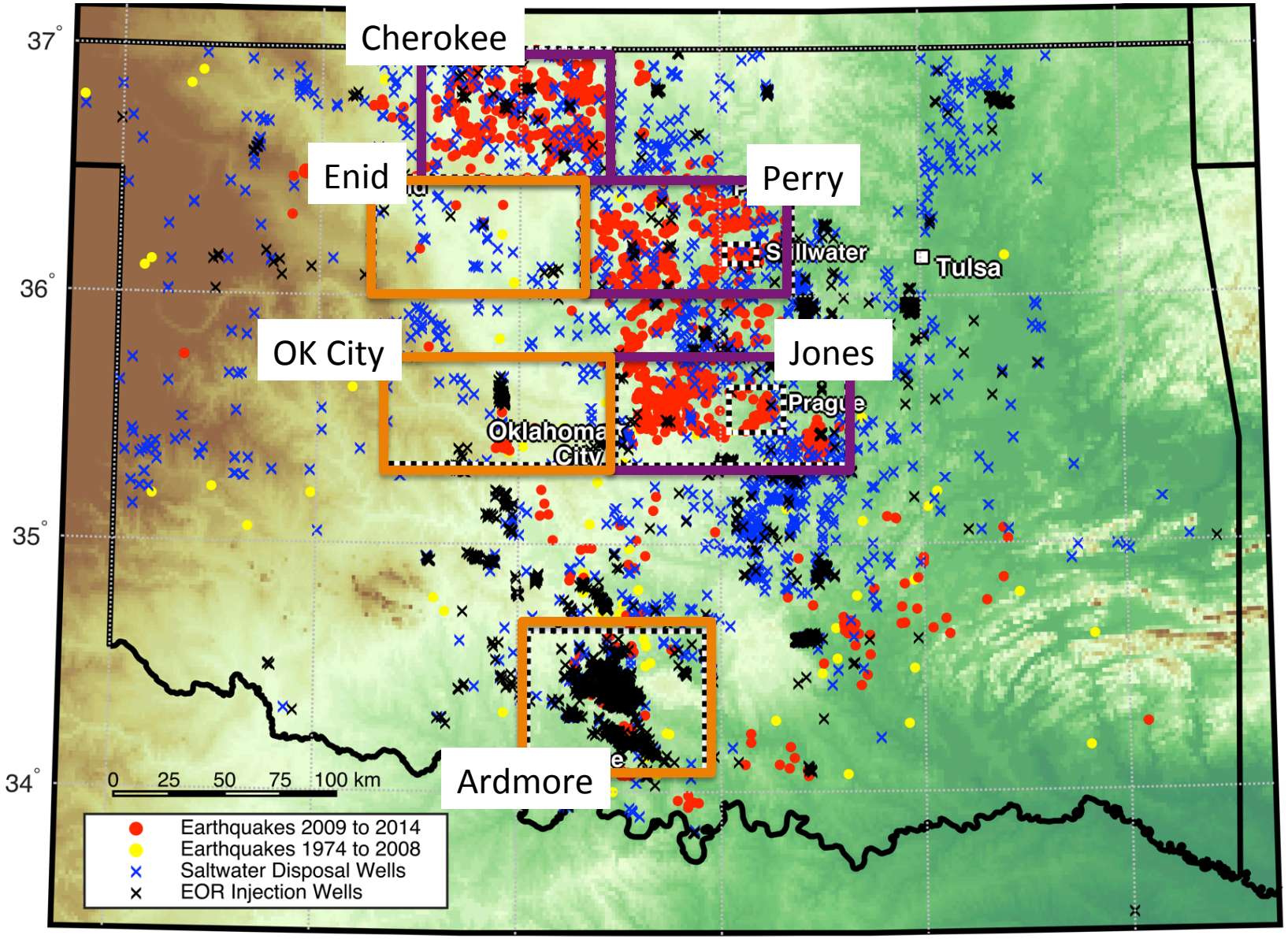
3 equal areas with Comparatively Few Earthquakes:



Ardmore had lots of EOR but little SWD, and few earthquakes.

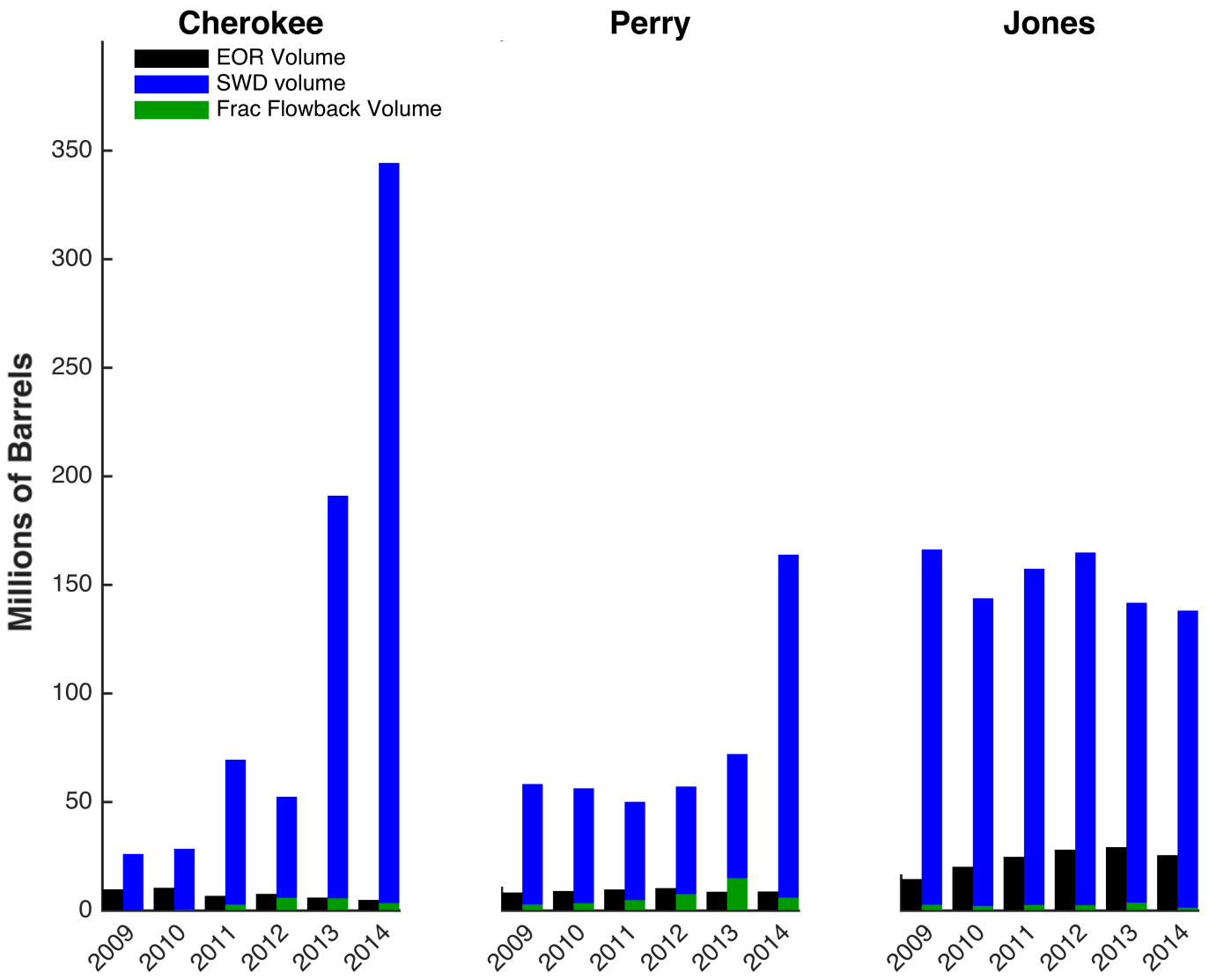
Map

Selected Study Areas



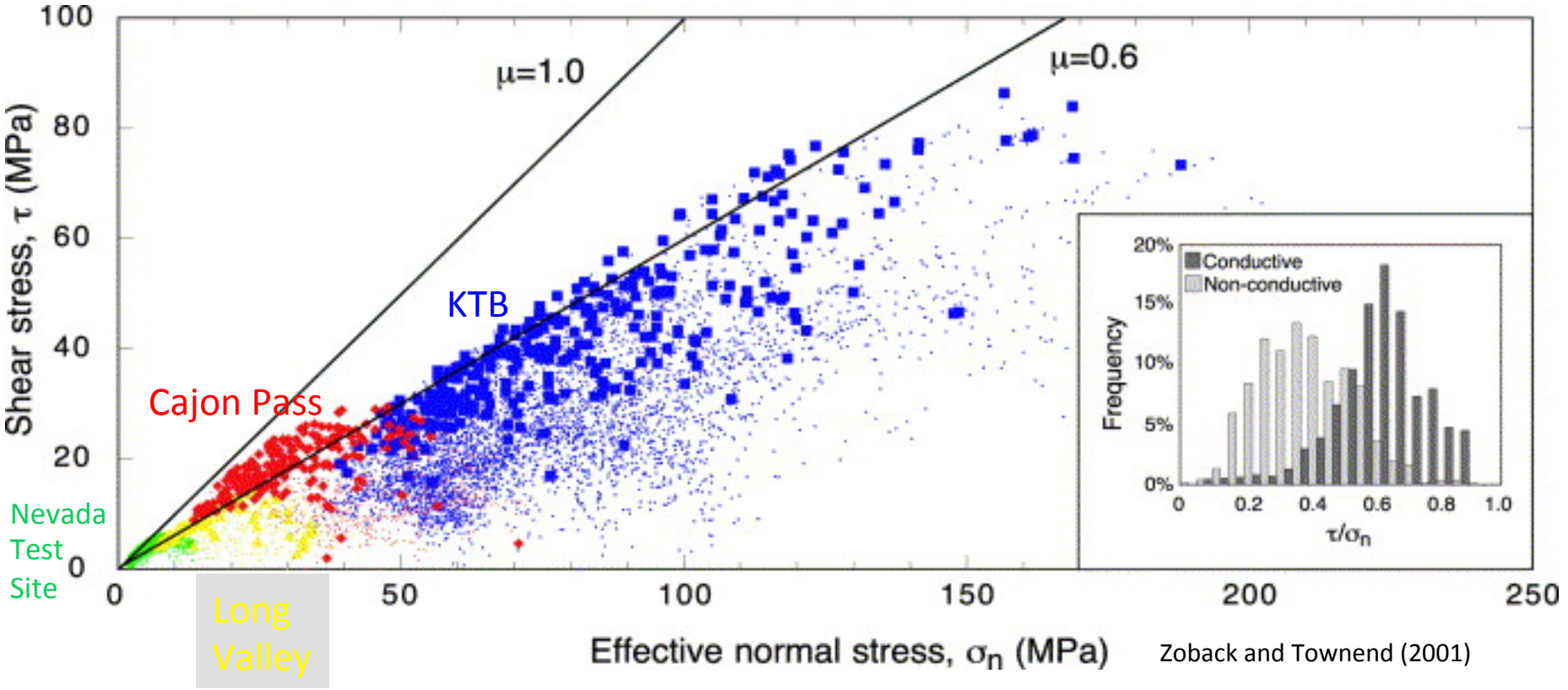
Is this Water Hydraulic Fracturing Flowback Water?

No. The Water is Mostly Produced Water (Blue)



Infographic Solution

Hydrologic Characterization of Basement: Active Faults are Permeable

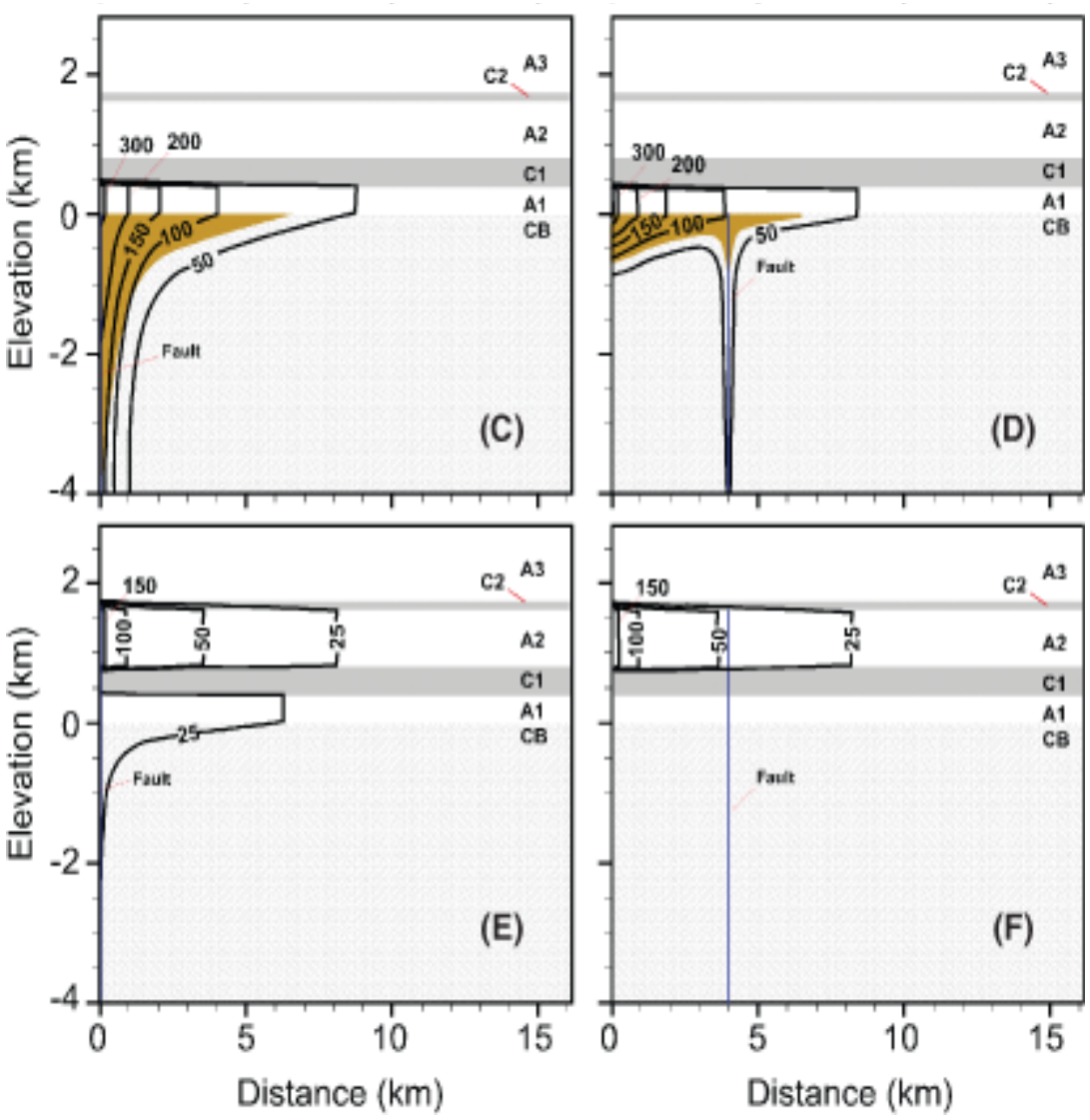


Zoback and Townend (2001)

Permeable faults (big symbols) are more likely to be active in basement.

Just because the basement is essentially impermeable do not mean basement faults are impermeable!

Geomechanical characterization: active basement faults are permeable and vertical



Even when faults are a significant distance from injection, basement faults could be perturbed

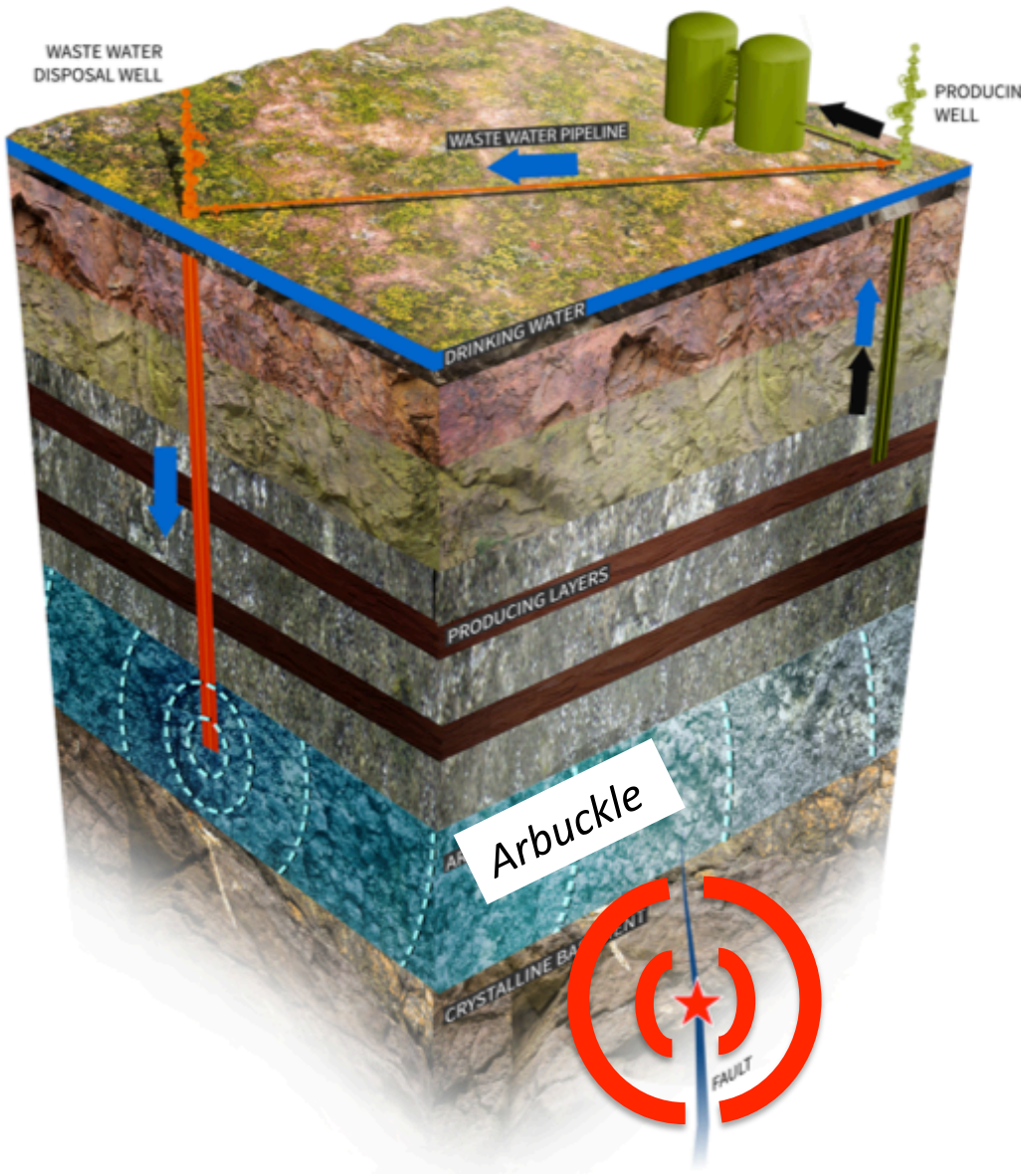
Sealing formations can limit pressure communication to the basement

Zhang et al. (2013)

Solution?

Saltwater Disposal Wells Are Triggering Earthquakes

- Shallow high water cut producing formations



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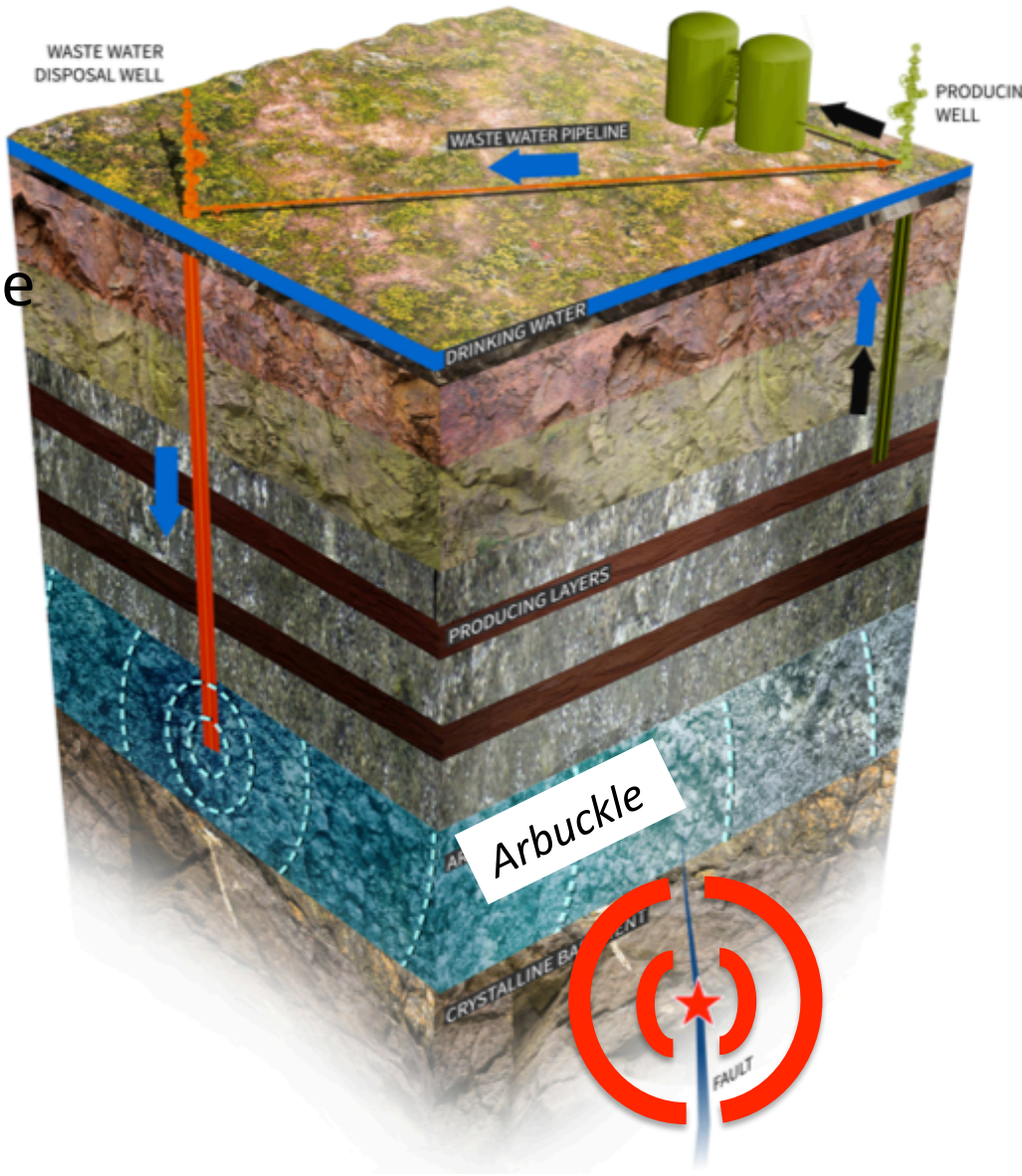
Saltwater Disposal Wells Are Triggering Earthquakes

- Shallow high water cut producing formations
- Saltwater is Disposed into the basal Arbuckle group.



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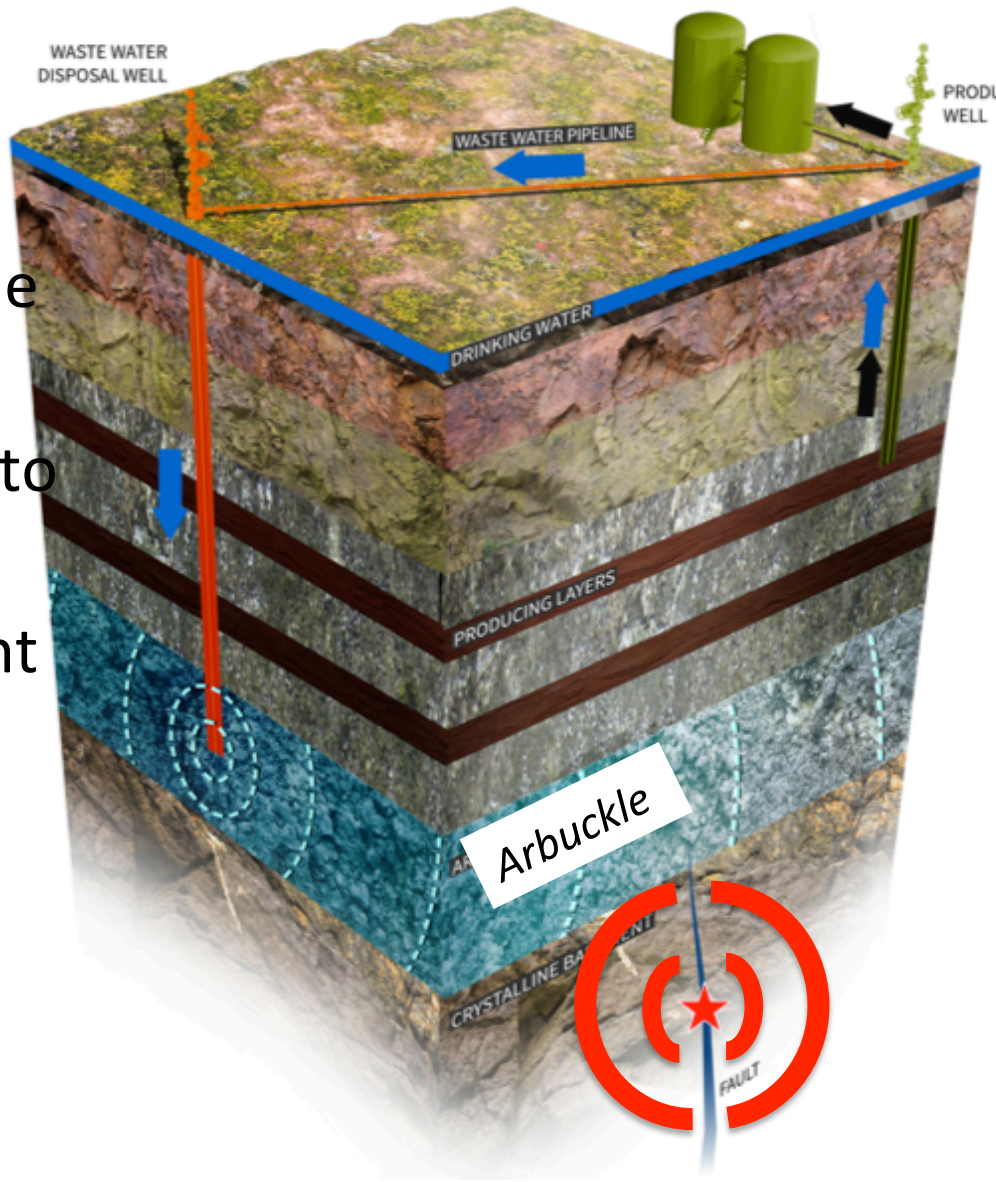

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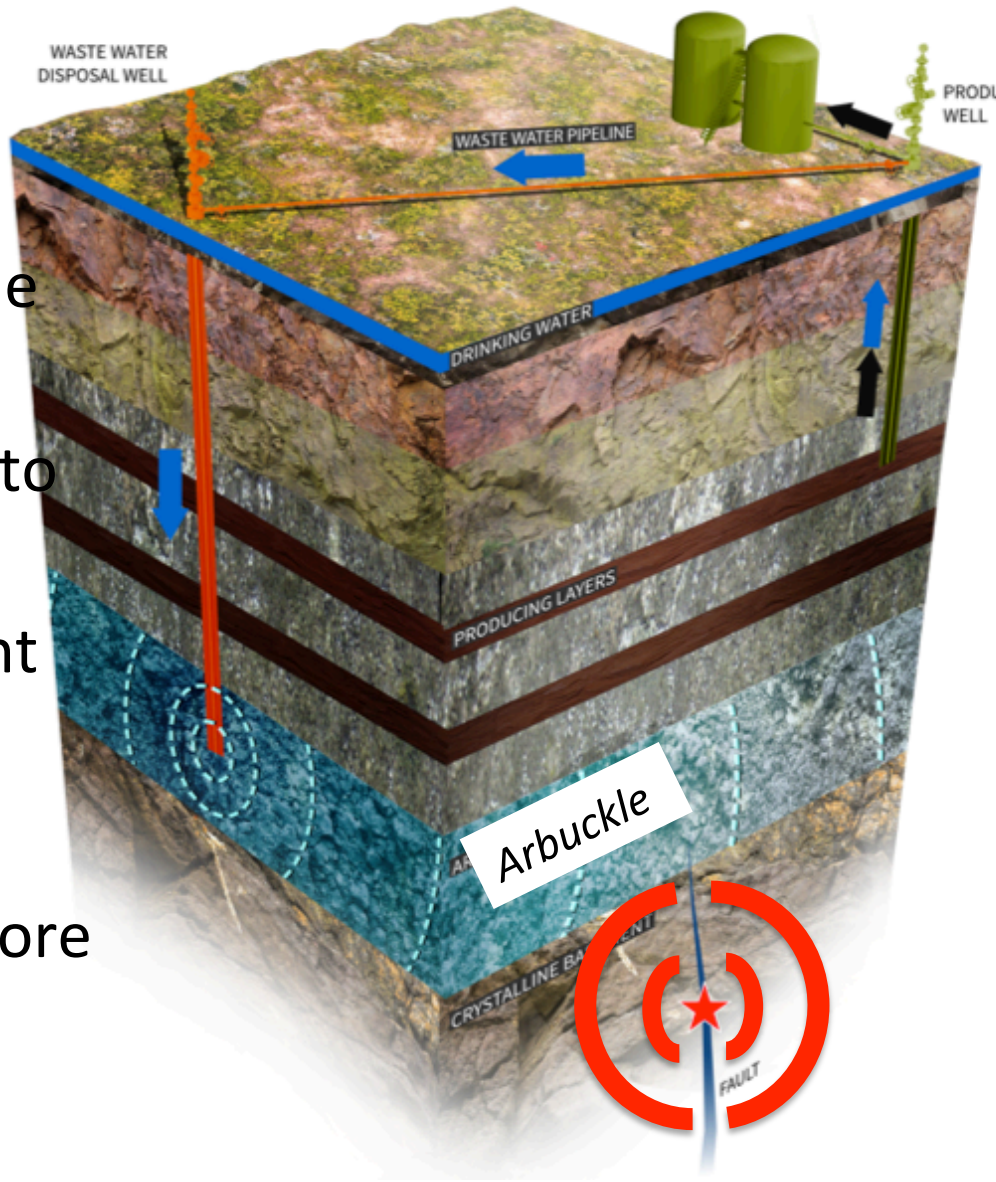

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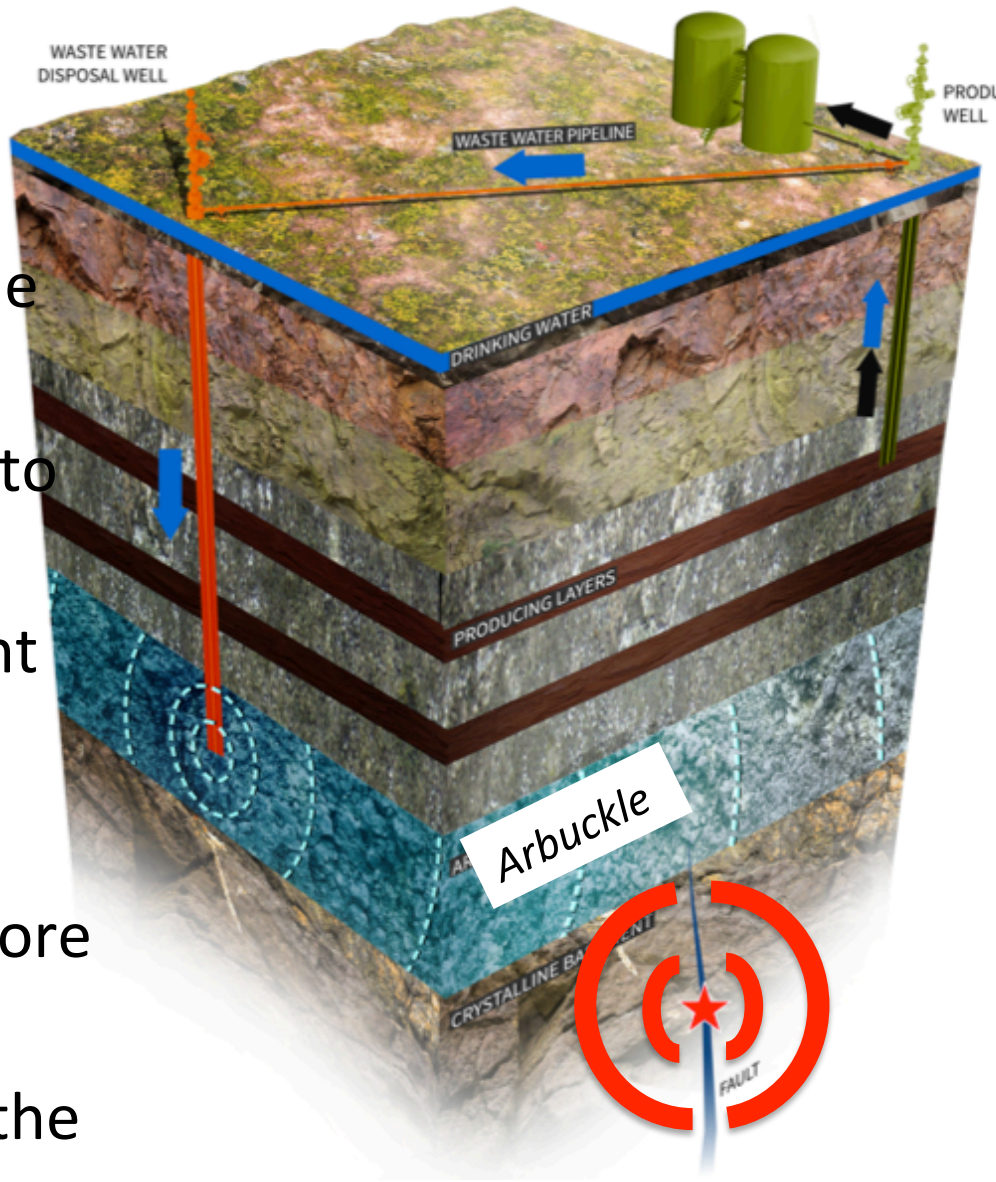
Saltwater Disposal Wells Are Triggering Earthquakes

- Shallow high water cut producing formations
- Saltwater is Disposed into the basal Arbuckle group.
- Active faults are more likely to be permeable, and extend from the crystalline basement up to the Arbuckle.
- Active Faults slip when unclamped by increases in pore pressure.
- Small earthquakes increase the odds of larger ones.



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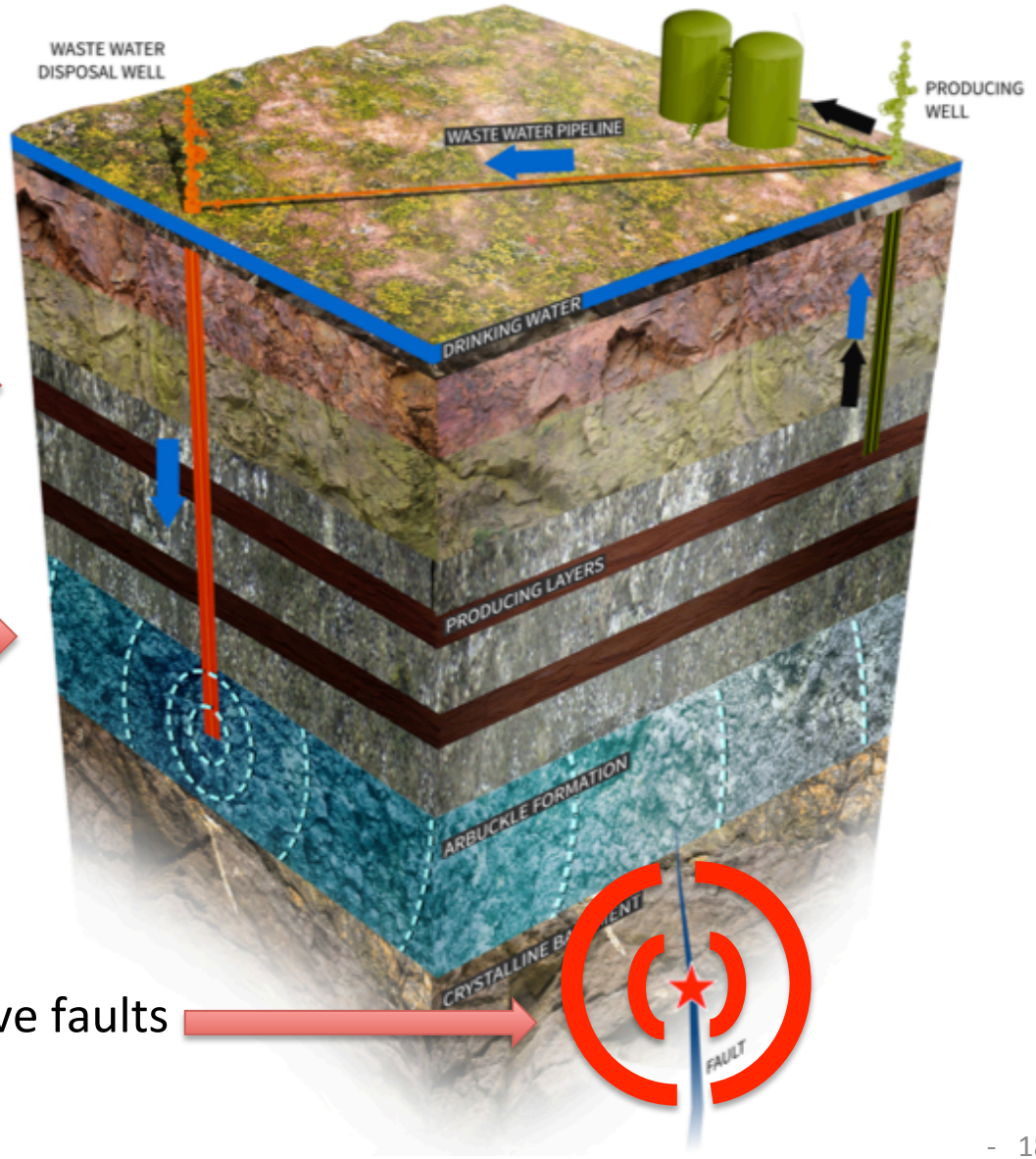
Is There a Possible Solution?

Reinject into shallower formations, ideally the producing formation

Avoid formations without a bottom seal.

Inject far from large active faults



Randi Paper

doi: 10.1785/0220150048 Seismological Research Letters Volume 86, Number 4 July/August 2015

Characterizing and Responding to Seismic Risk Associated with Earthquakes Potentially Triggered by Fluid Disposal and Hydraulic Fracturing

by Randi Jean Walters, Mark D. Zoback, Jack W. Baker, and Gregory C. Beroza

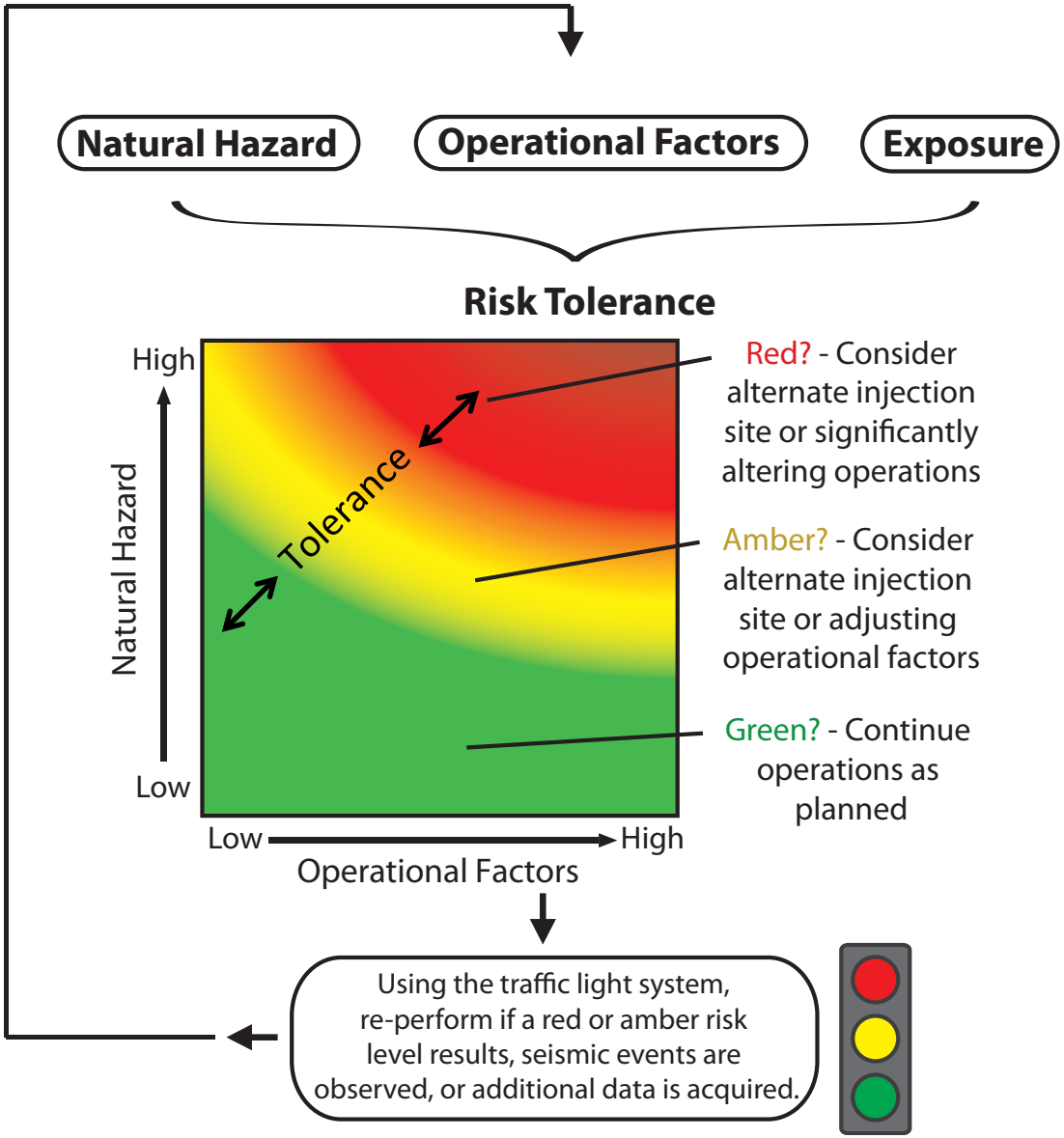
INTRODUCTION AND CONTEXT

For nearly a century, earthquakes apparently triggered by fluid injection have been observed in many parts of the world (National Research Council [NRC], 2012). Although injection-related seismicity is a well-known phenomenon, recent years have seen a dramatic increase in earthquake occurrence apparently associated with oil and gas development. This increase has been most notable in the central and eastern United States (Ellsworth, 2013). Recent occurrences of felt events in areas of significant populations have brought attention to this issue from the public, oil and gas operators, regulators, and academics.

Though fluid disposal and hydraulic fracturing both have the potential to trigger earthquakes, it has become clear that the potential for induced seismicity is higher for fluid (usually saltwater) disposal than for hydraulic fracturing. For instance, saltwater disposal involves very long injection times (years to decades) and very large injection volumes (often thousands to tens of thousands of m^3 per day). This leads to much more extensive pressure perturbations than hydraulic fracturing operations, in which 1000 m^3 might be injected over an ~2 hr period. The inherent differences in injection practices between these two different types of fluid-injection operations, and the apparent differences in the potential for triggering earthquakes, mean that appropriate procedures for risk assessment associated with each of these two types of fluid injection need to be

Risk Tol Matricies

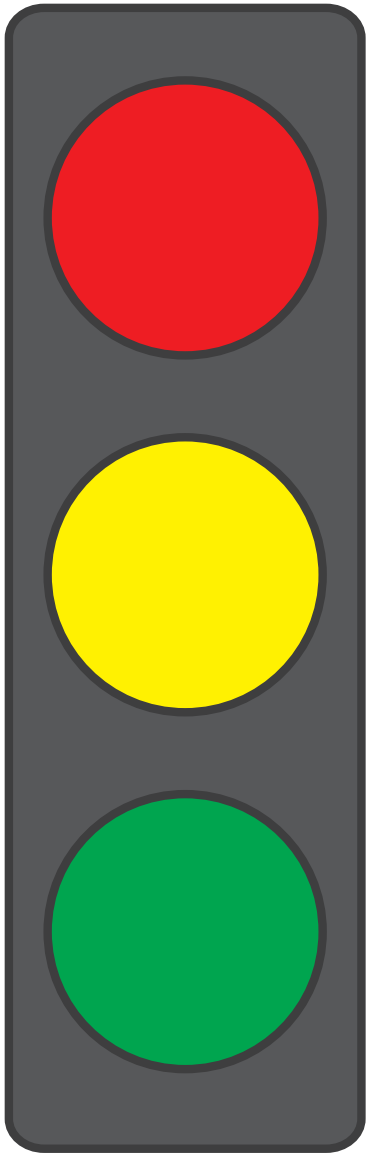
Hazard and Risk Assessment Workflow



Walters et al. 2015

Stoplight

Saltwater Disposal Traffic Light System



Observations:
- Unacceptable ground motions and/or magnitudes
- Events define a fault capable of producing a potentially damaging earthquake, especially when located in the basement rock

Actions:
- Limit injection and consider well abandonment
- Continue earthquake monitoring and analysis
- Report observations and actions to area regulators and neighboring operators

Observations:
- Unexpected event(s) occurring

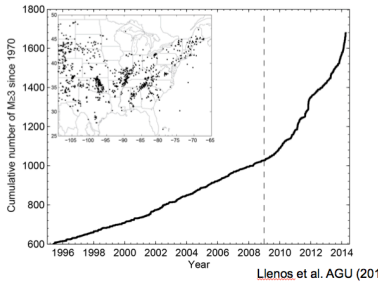
Possible Actions:
- Increase real-time earthquake monitoring and analysis
- Decrease injection rates and volumes

Observations:
- No seismic events detected

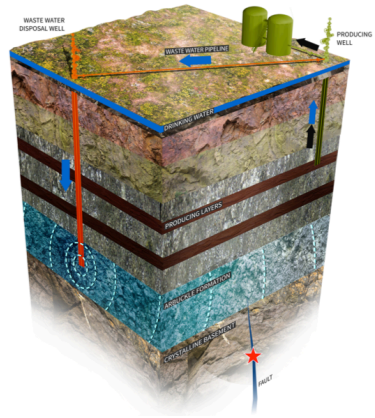
Actions:
- Operations and monitoring continue as planned

Walters et al. 2015

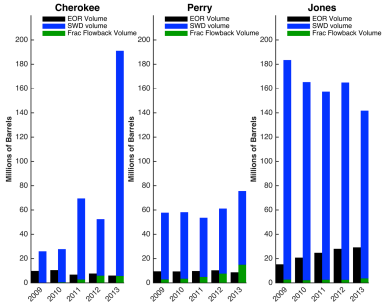
In Summary



- The increase in seismicity is real, and increases hazard.
- The earthquakes are happening because massive increases in saltwater disposal in the Arbuckle formation are pressurizing basement faults.



- It may be possible to inject into shallower formations, ideally back into producing formations, and not pressurize the basement.
- The saltwater is predominantly produced water, not hydraulic fracturing flowback water.



- A framework exists with which we can evaluate and mitigate these risks.

Acknowledgements

- Stanford Center for Induced and Triggered Seismicity for funding this work
- Oklahoma Corporation Commission for well data
- USGS NEIC Earthquake data and helpful conversations
- Oklahoma Geological Survey for research collaborations