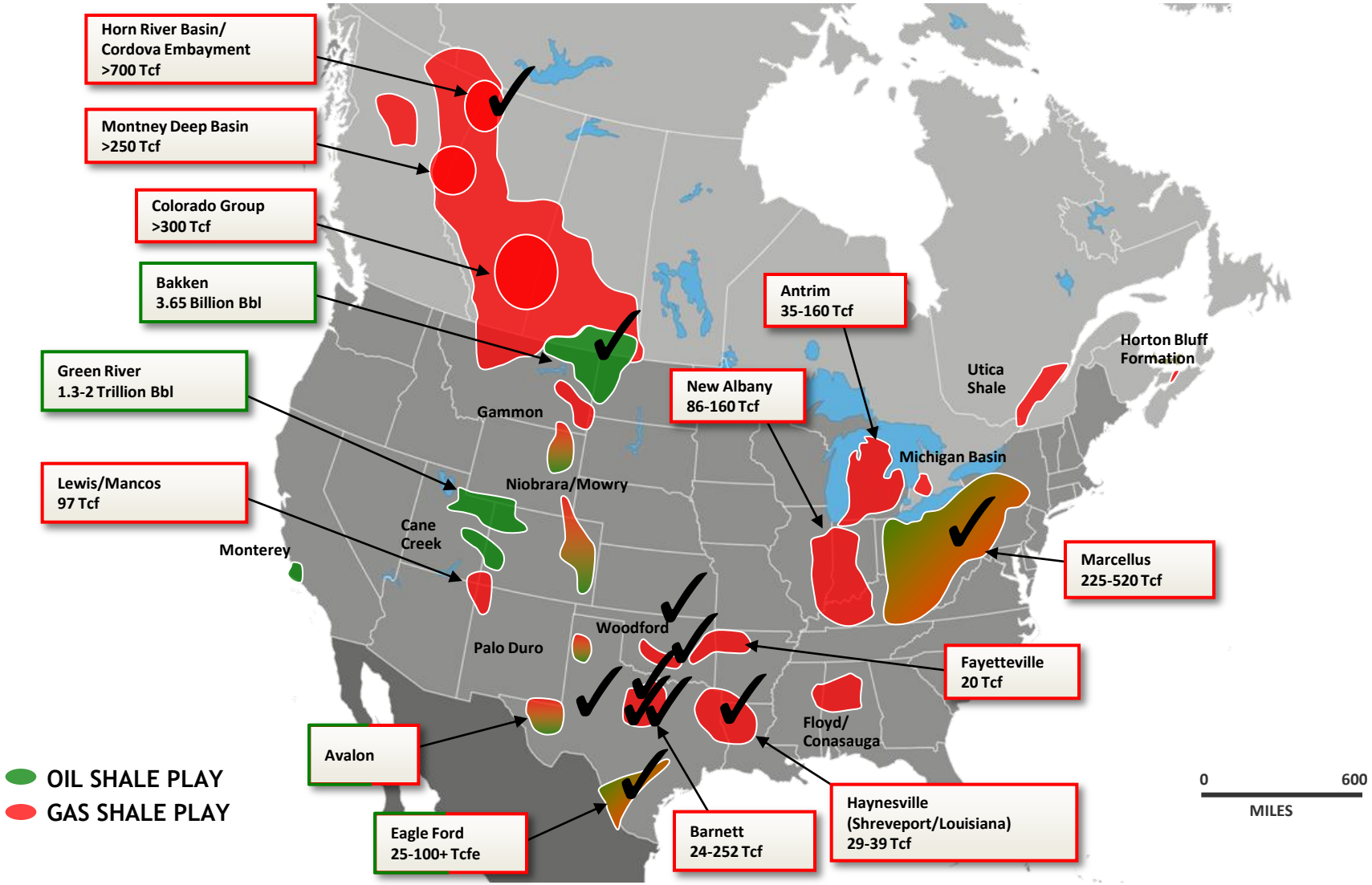
Induced and Triggered Seismicity in Exploration and Exploitation of Unconventional Reservoirs

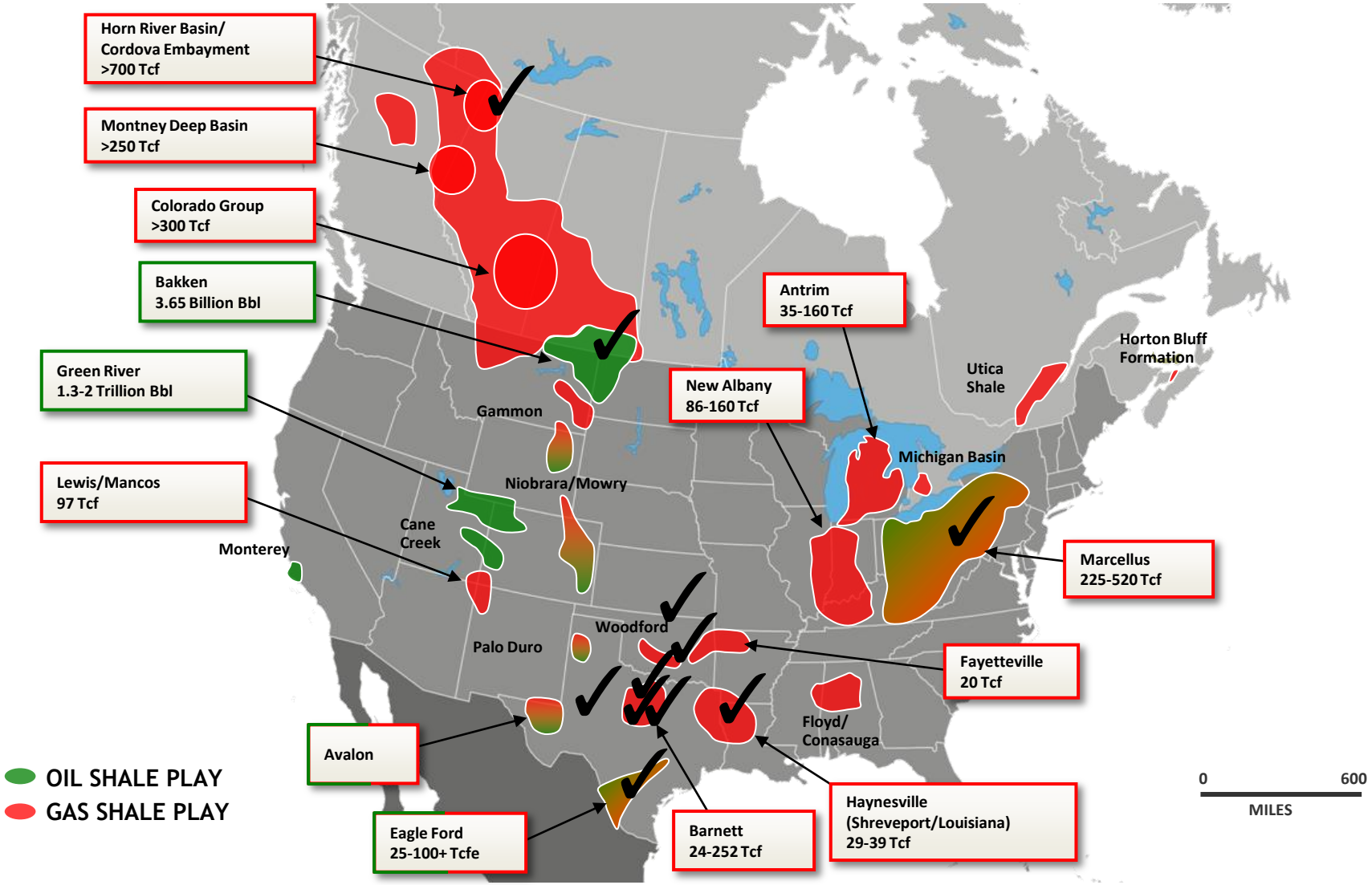
Mark D. Zoback
Professor of Geophysics
Stanford University

Stanford Center for Induced and Triggered Seismicity

Unconventional Gas, NG Liquids and Oil Development



After 150,000 Wells in North America…



Shale Gas RF ~25%, NG Liquids and Oil RF ~5%

Secretary of Energy Advisory Board

Shale Gas Production Subcommittee 90-Day Report

August 18, 2011

U.S. DEPARTMENT OF ENERGY

Secretary of Energy Advisory Board

Shale Gas Production Subcommittee Second Ninety Day Report

November 18, 2011

U.S. DEPARTMENT OF ENERGY

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

Douglas J. Arent

Mark D. Zoback and
Douglas J. Arent

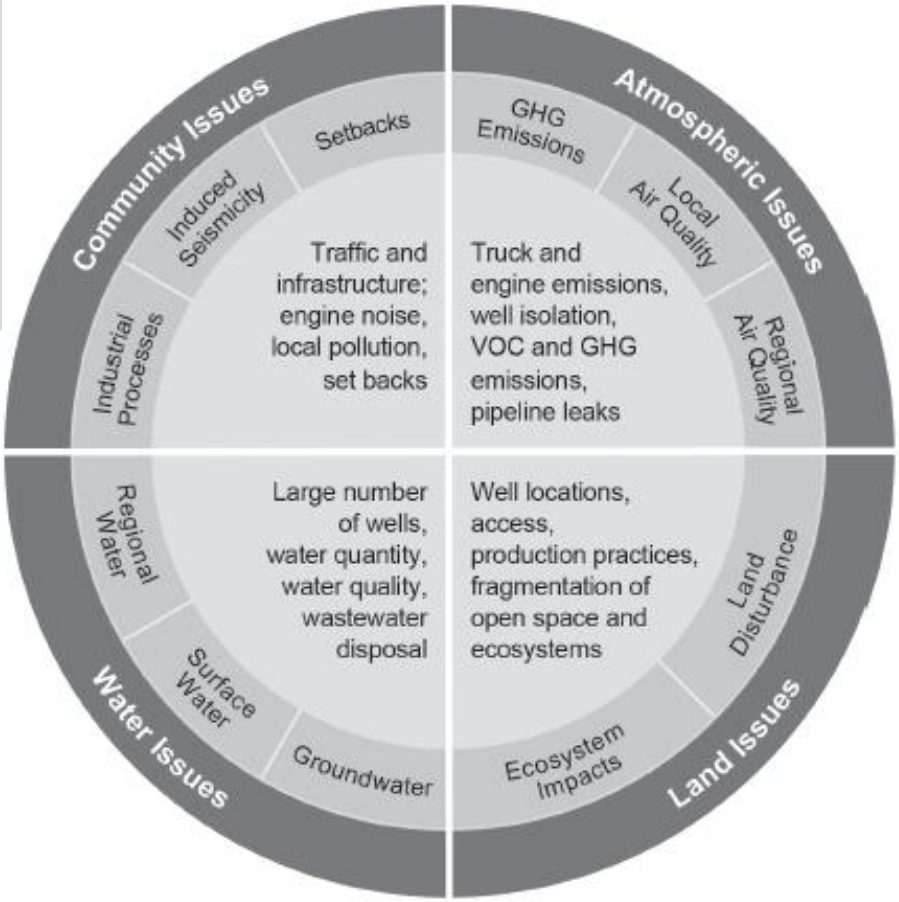
The use of horizontal drilling and multistage hydraulic fracturing technologies has enabled the production of immense quantities of natural gas, to date principally in North America but increasingly in other countries around the world. The global availability of this resource creates both opportunities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

There seems 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.

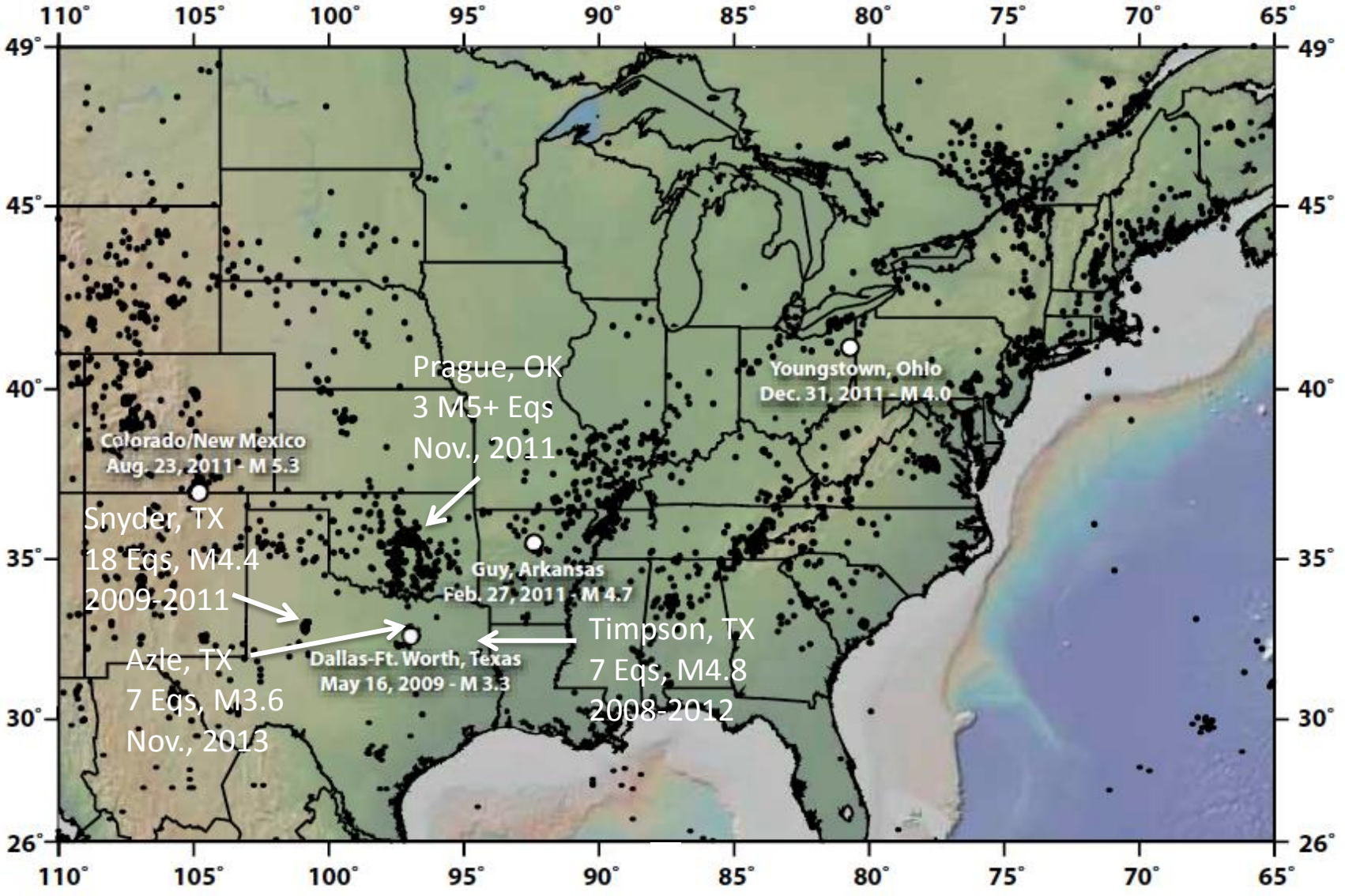
Background

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

Mark D. Zoback (NAE) is a professor of geophysics at Stanford University. Douglas J. Arent is executive director of the Joint Institute for Strategic Energy Analysis at the National Renewable Energy Laboratory.

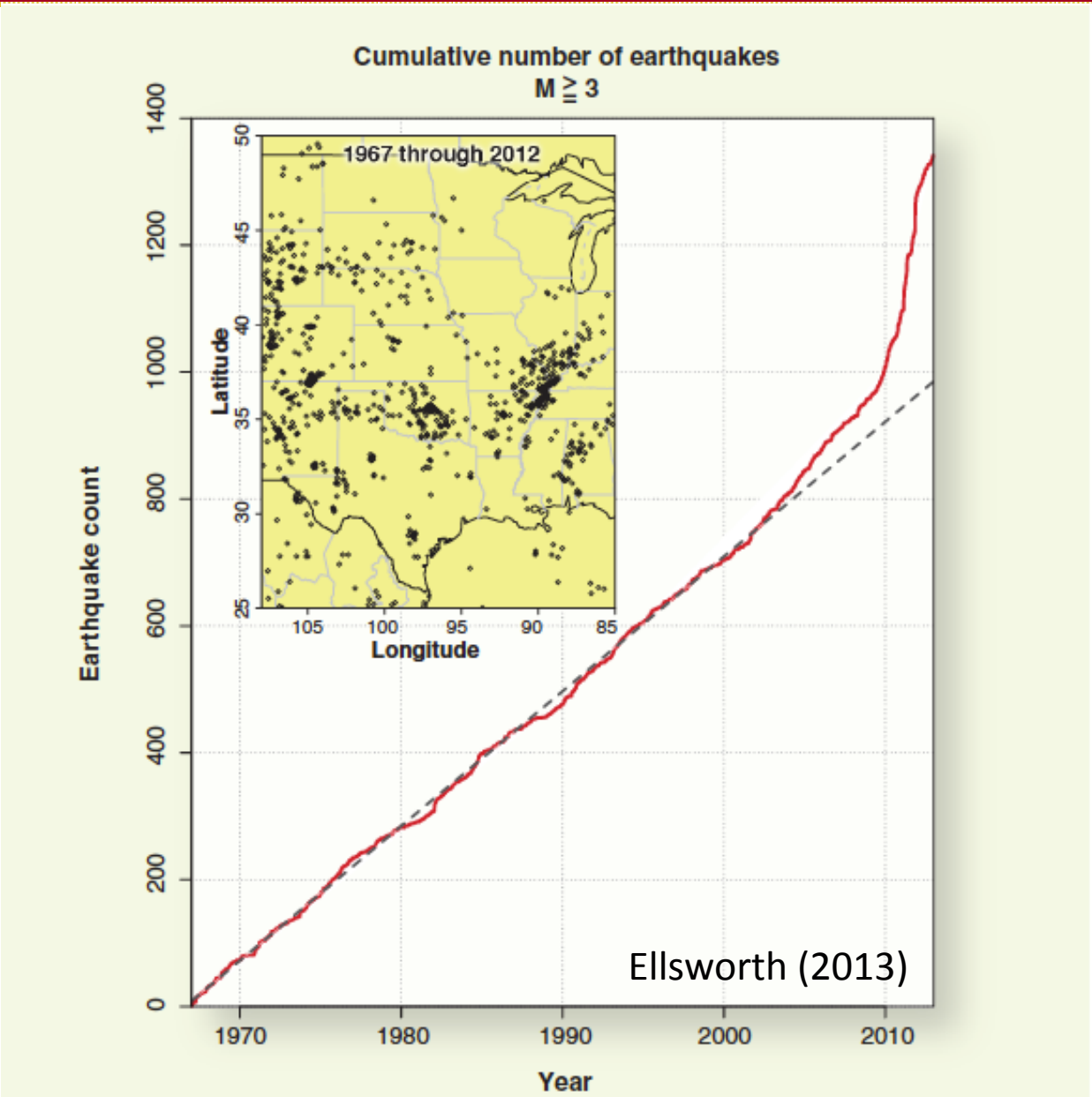


Injection Triggered Seismicity

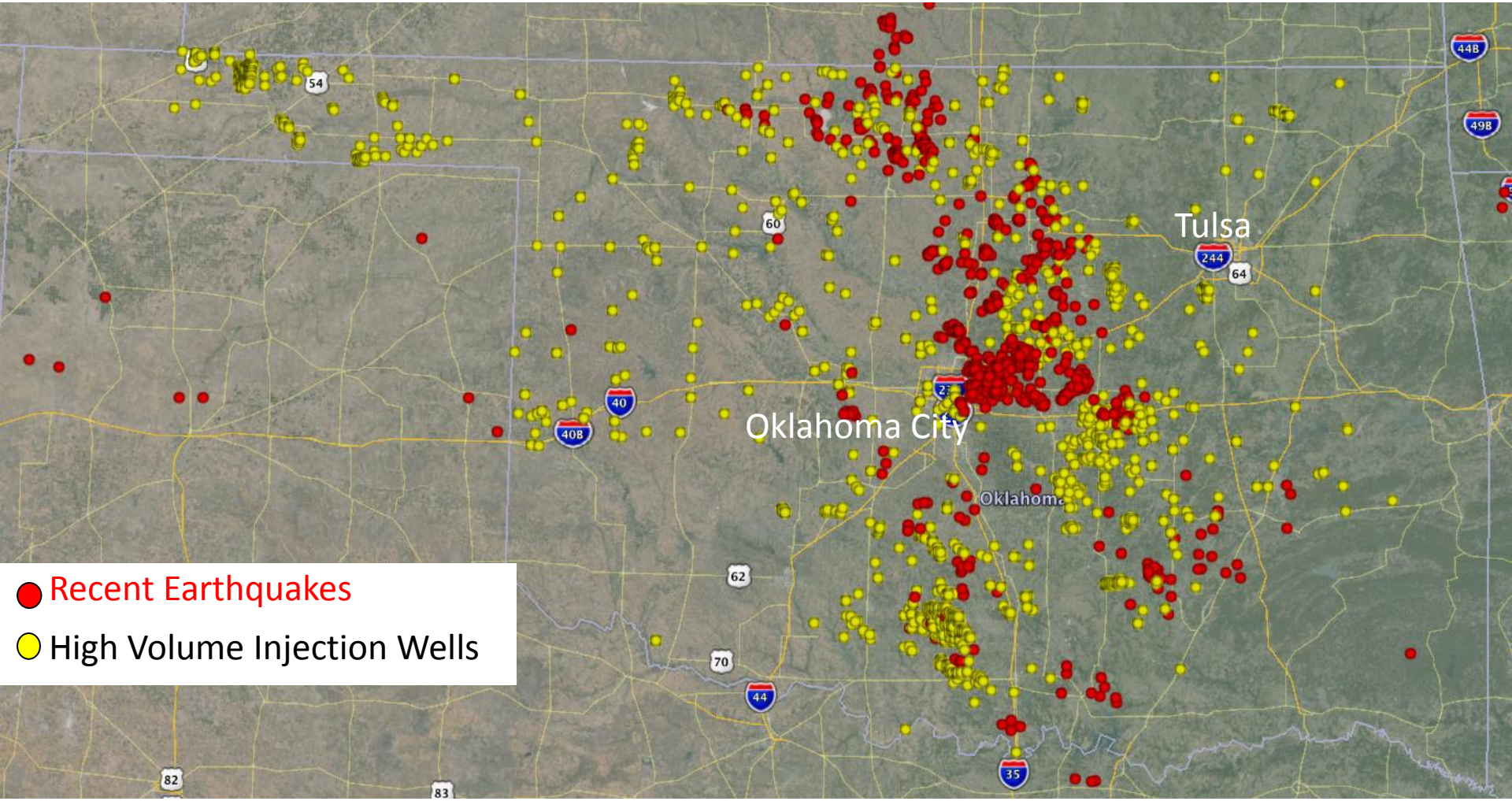


M.D. Zoback, Managing the seismic risk of wastewater disposal, *EARTH*, April, 2012, 38-43 (2012).

A Marked Recent Increase in Intraplate Seismicity

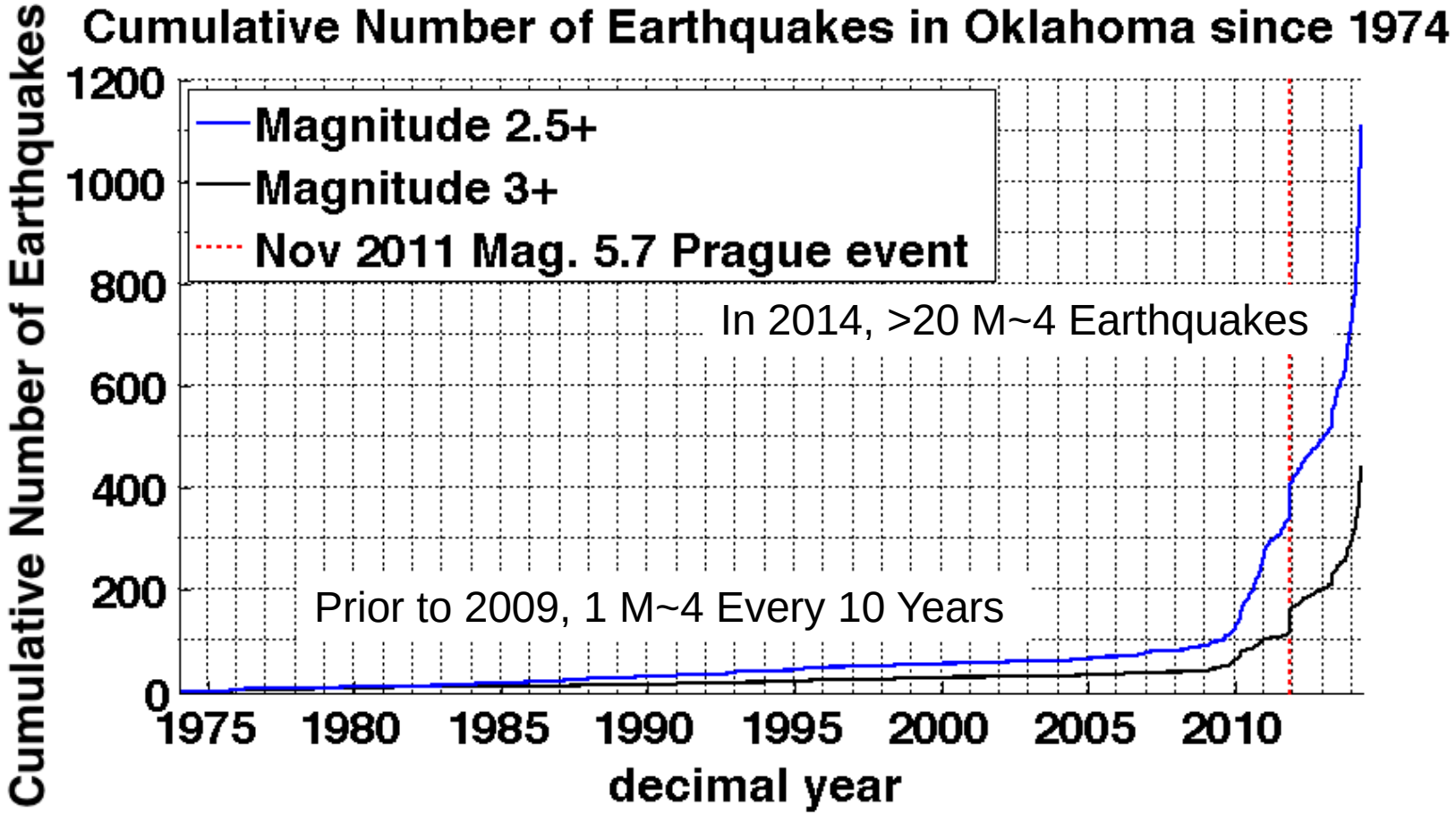


The Curious Case of Oklahoma Seismicity

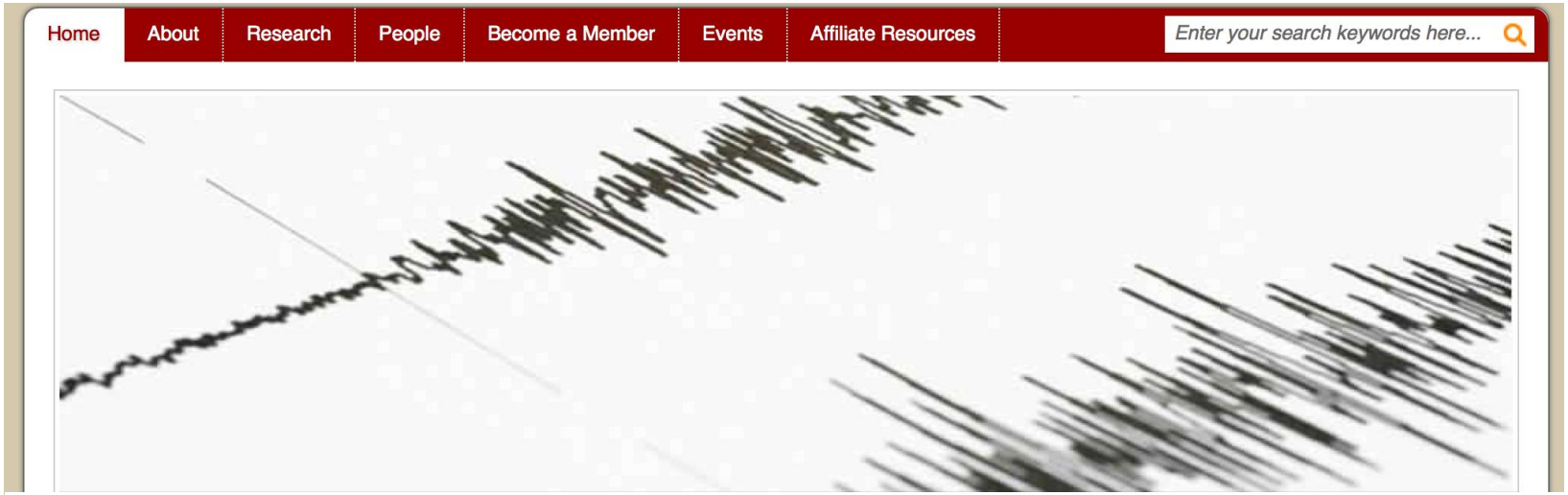


Walsh and Zoback (in preparation)

Seismicity Increase Since 2009



- The increase in seismicity is not because of better detection
- The recent earthquakes are broadly distributed
- Seismicity continues to this day



SCITS

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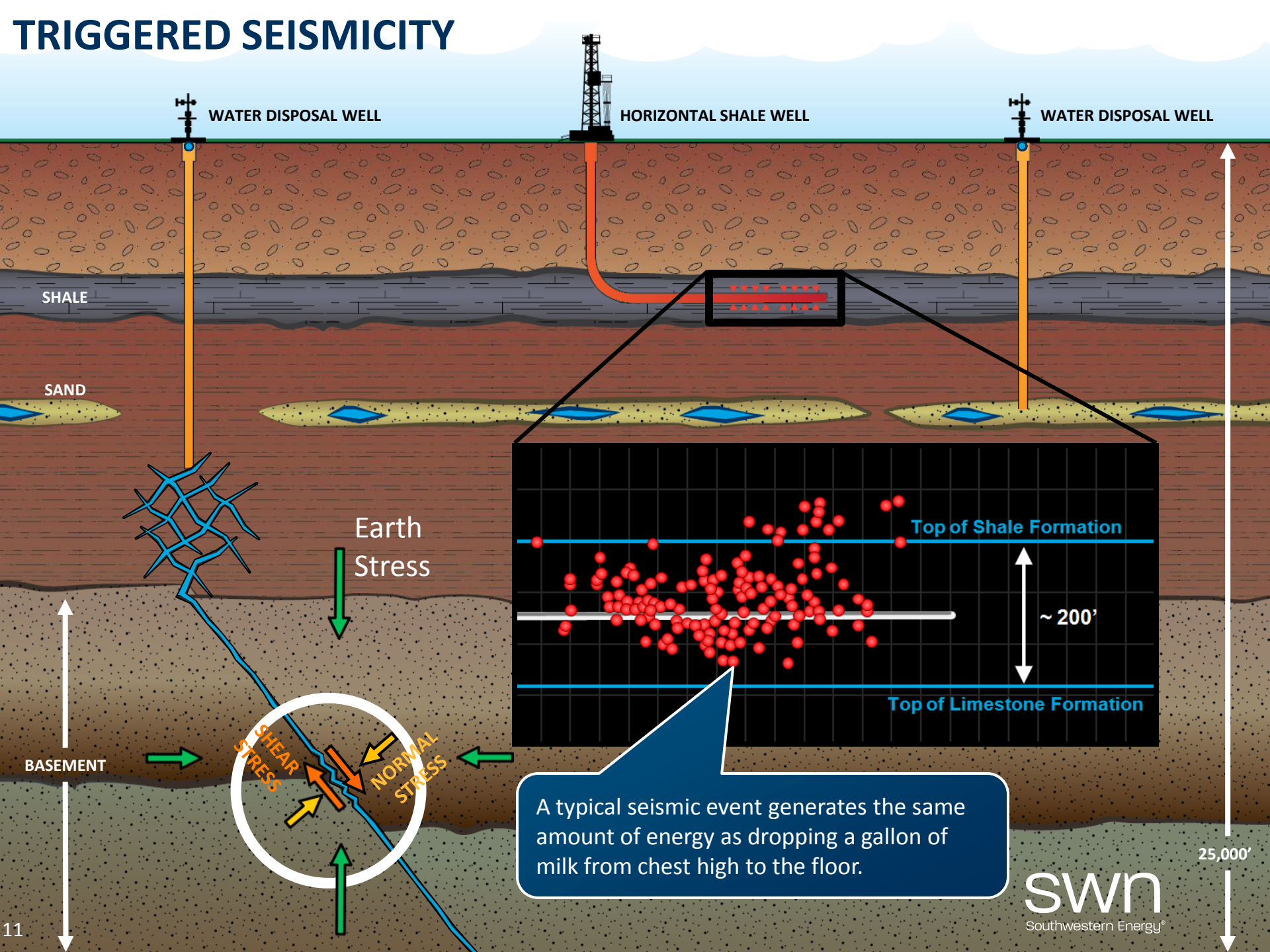
Nine Stanford Professors in Geophysics, Petroleum Engineering and Civil Engineering

Twenty-three Industrial Affiliates

TRIGGERED SEISMICITY



A typical seismic event generates the same amount of energy as dropping a gallon of milk from chest high to the floor.

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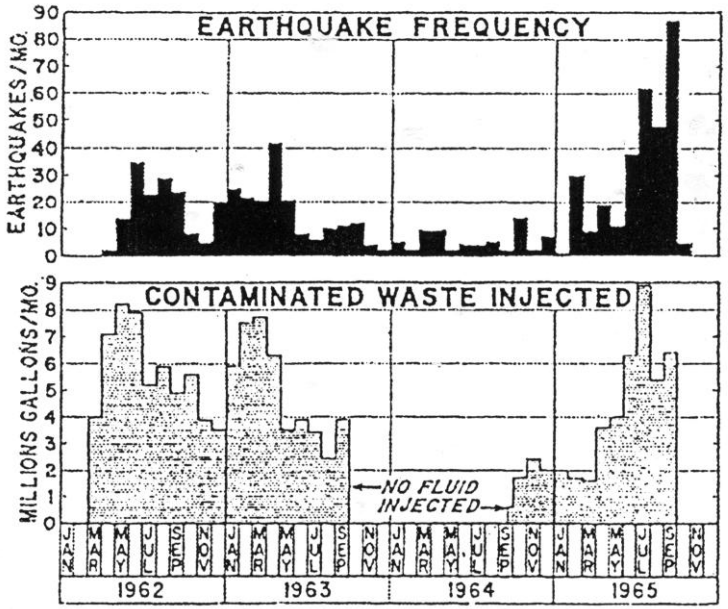
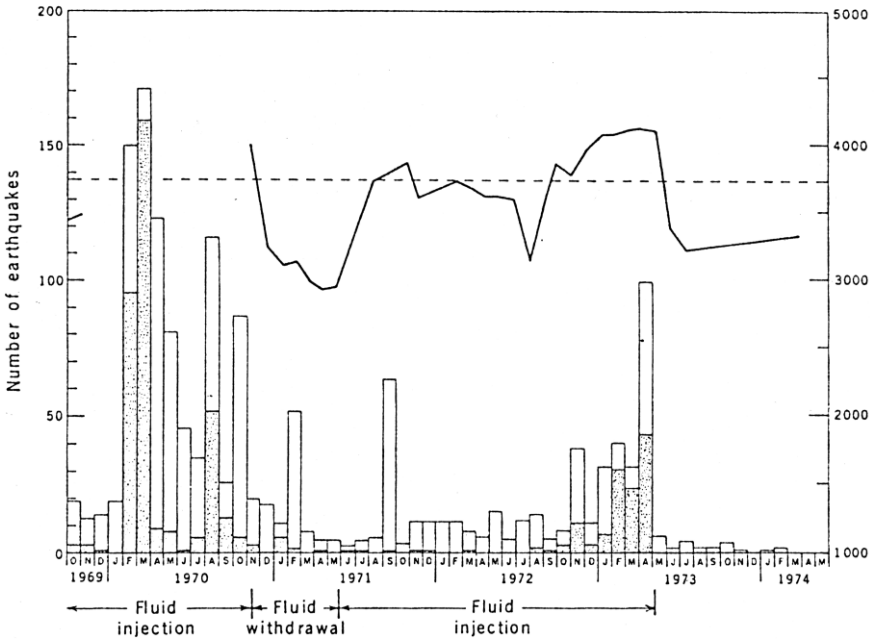
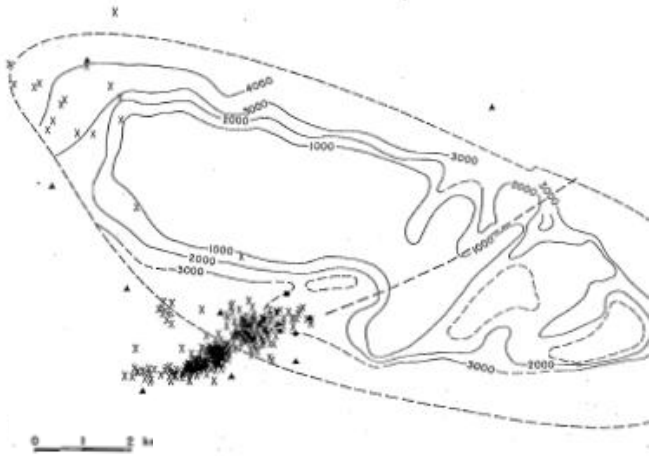
Waste Injection
Denver Arsenal

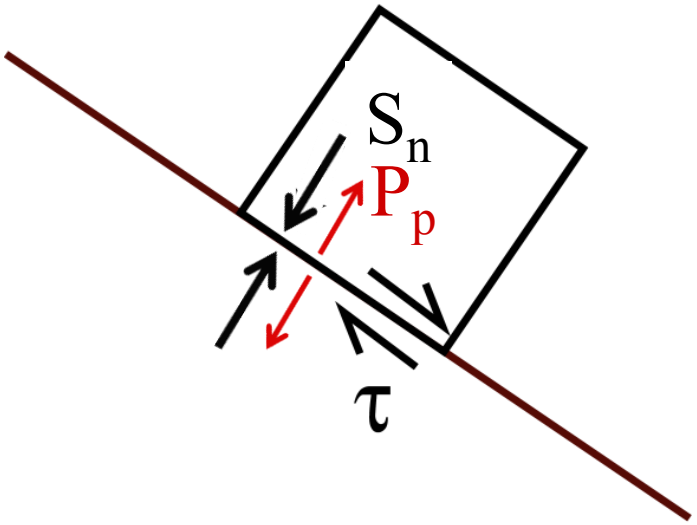


Fluid Injection
Rangely Oil Field





How Fluid Pressure Affects Frictional Sliding

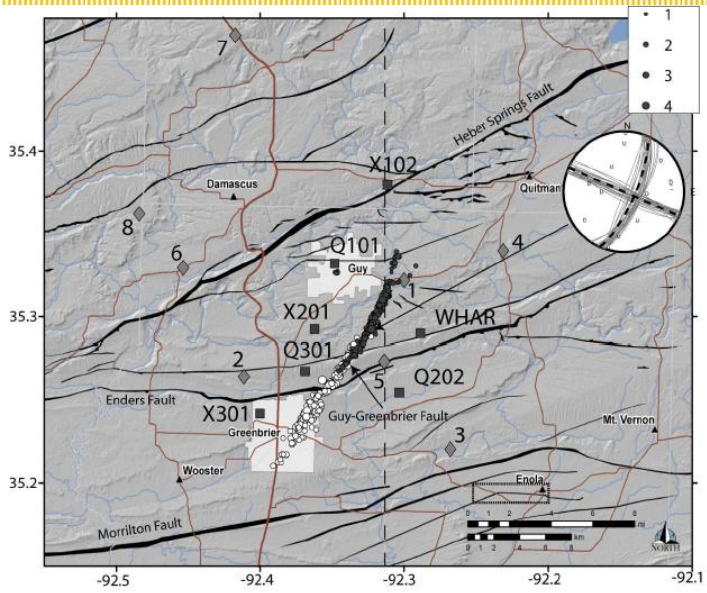


Sliding occurs when
Amonton's Law is satisfied:

$$\frac{t}{S_n - P_p} = \eta$$

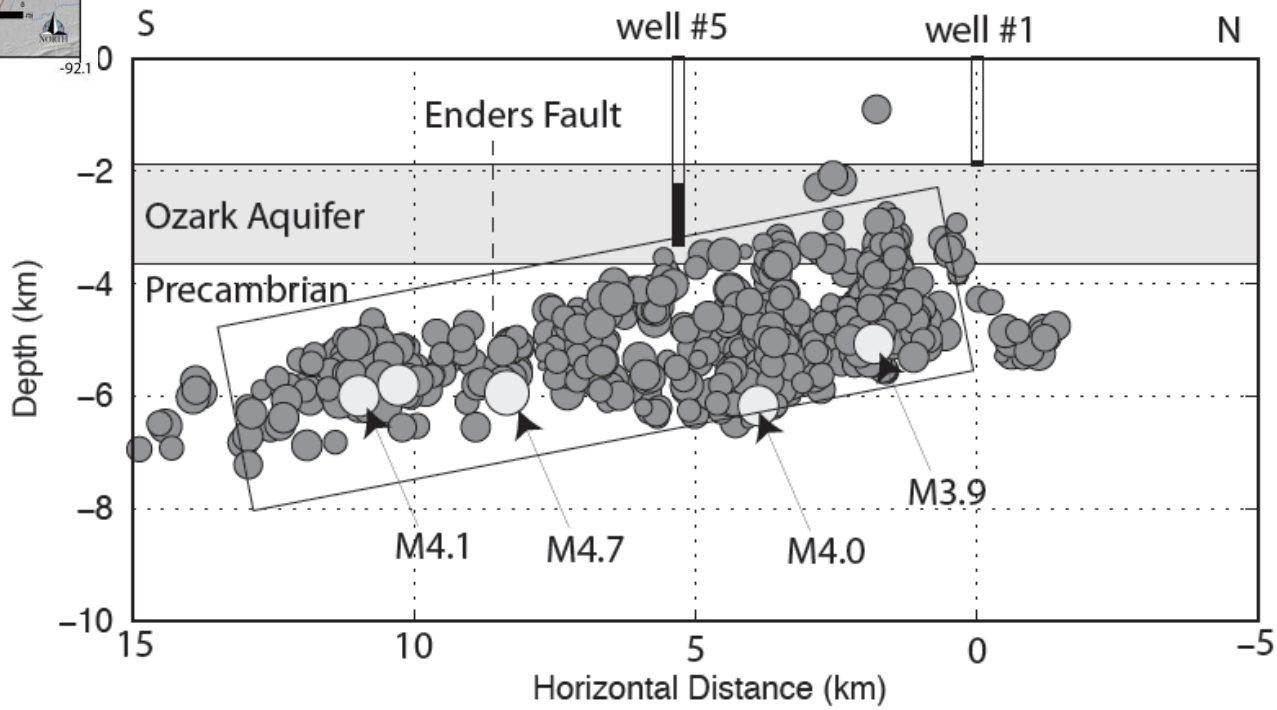
Coefficient of Friction

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

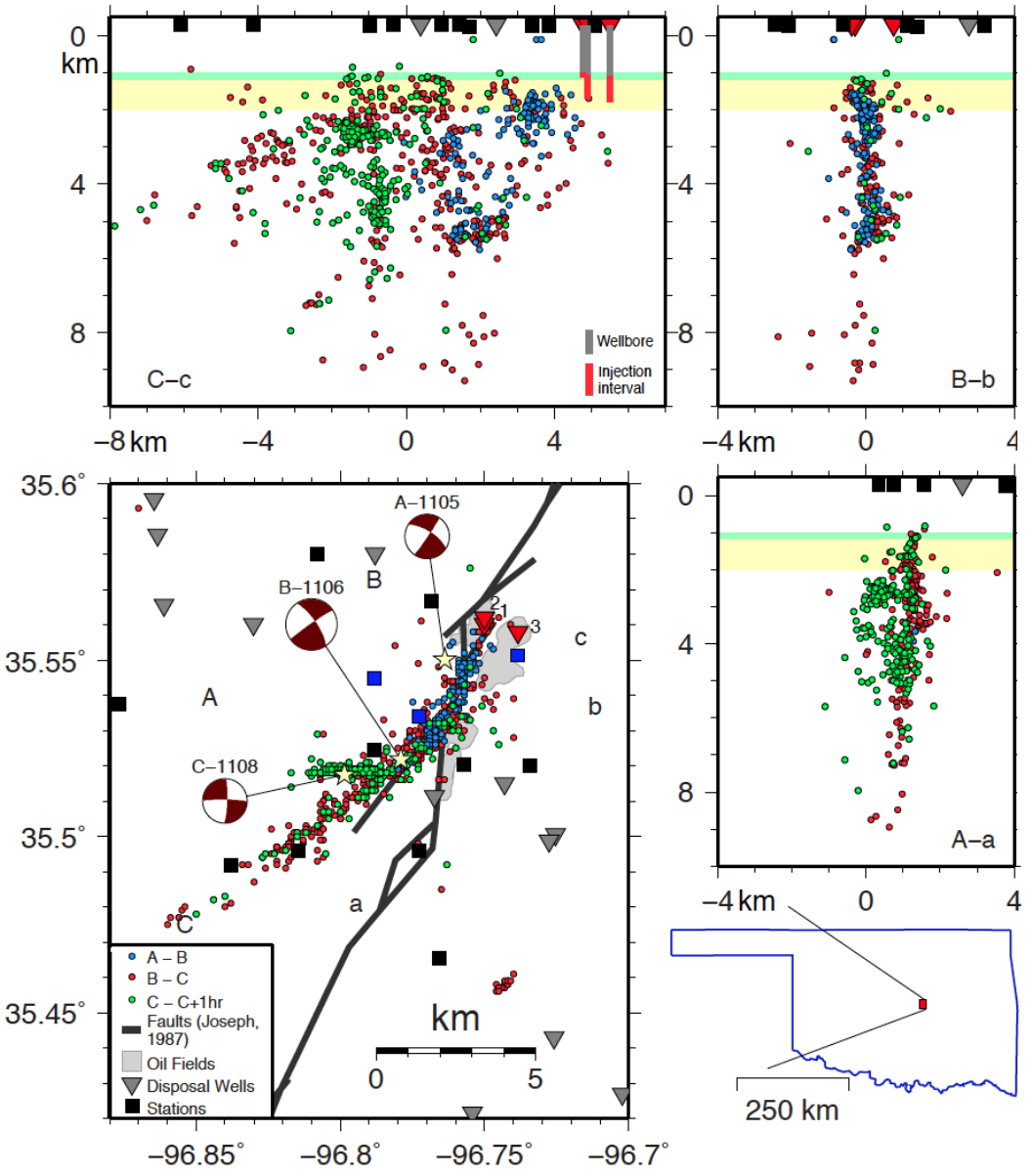


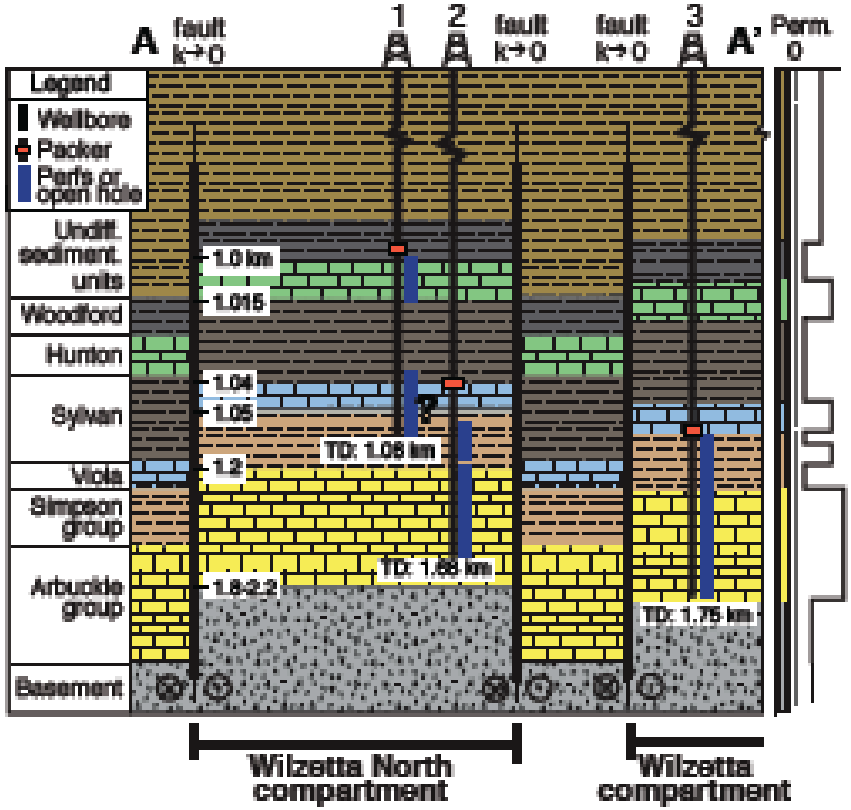
Horton (2012)

Earthquake Risk 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

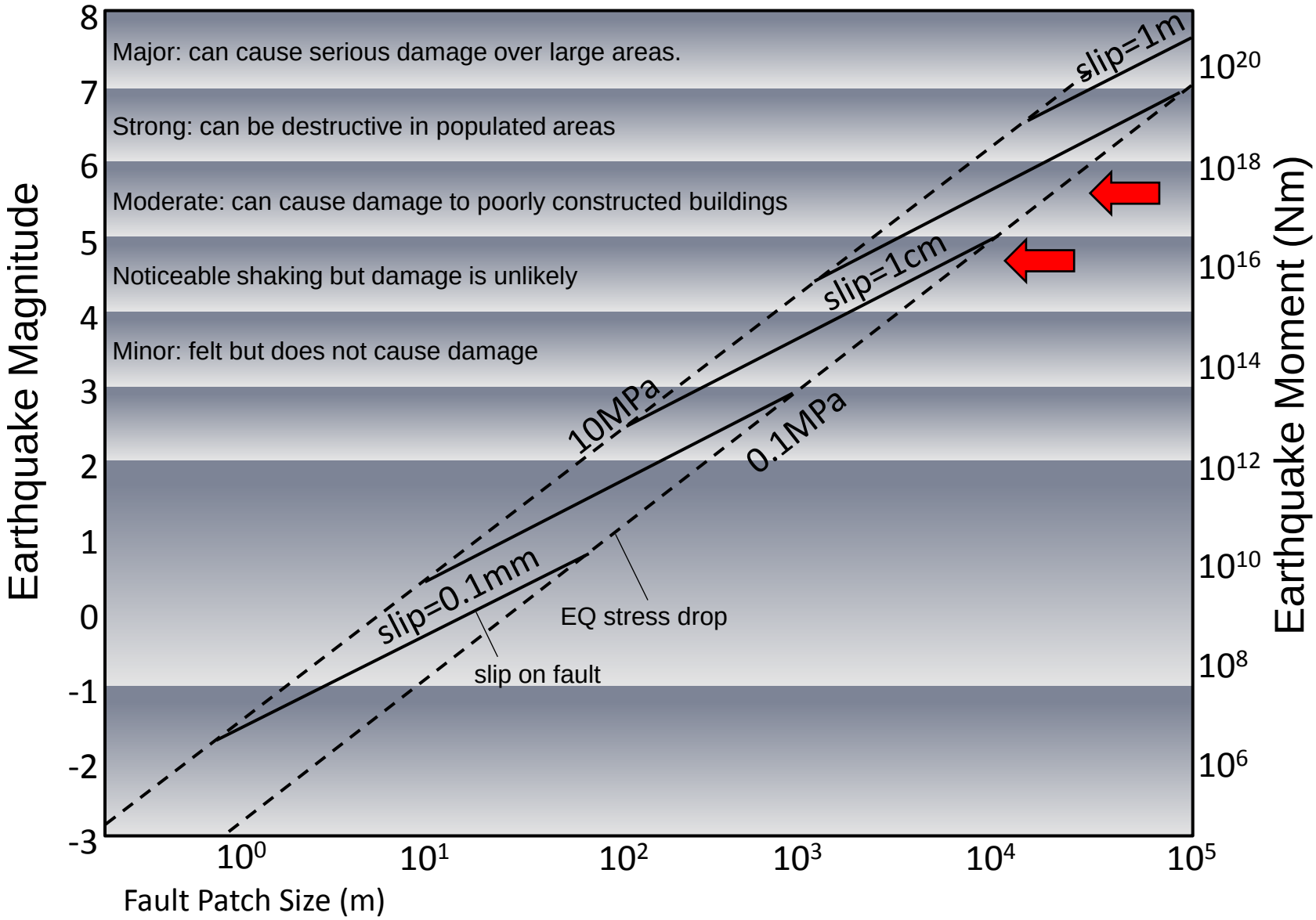




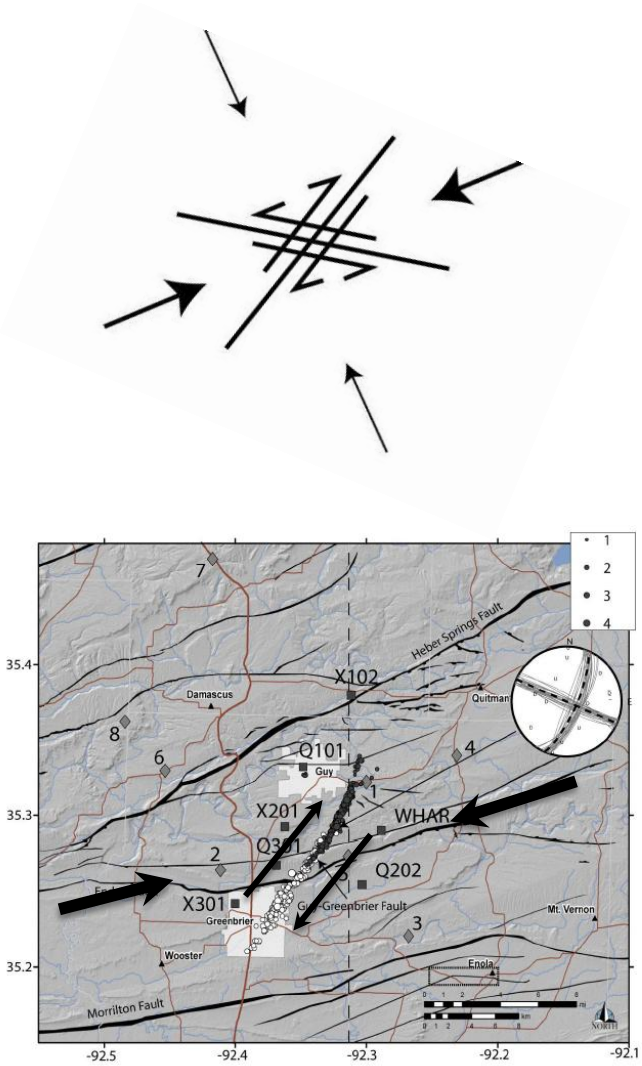
Prague Earthquakes

Keranen et al. (2013)

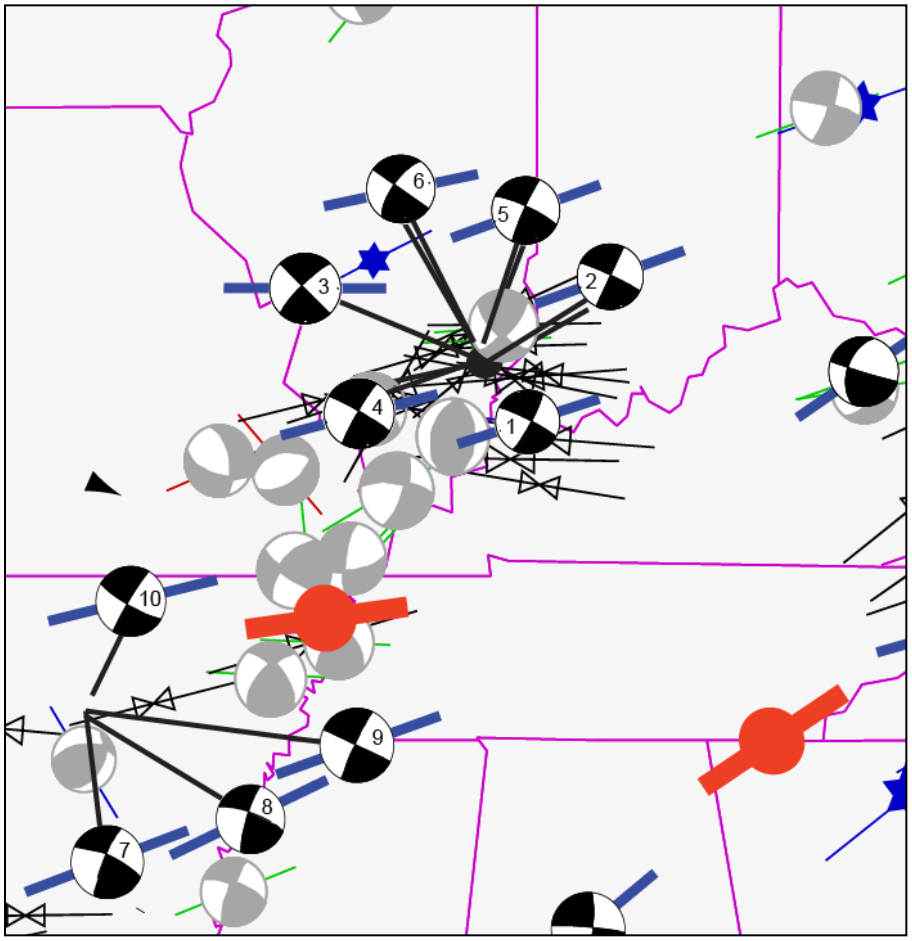
Fault Dimension and Earthquake Magnitude



Potentially Active Fault Could Have Been Identified Prior to Injection



Horton (2012)



Hurd and Zoback (2012)

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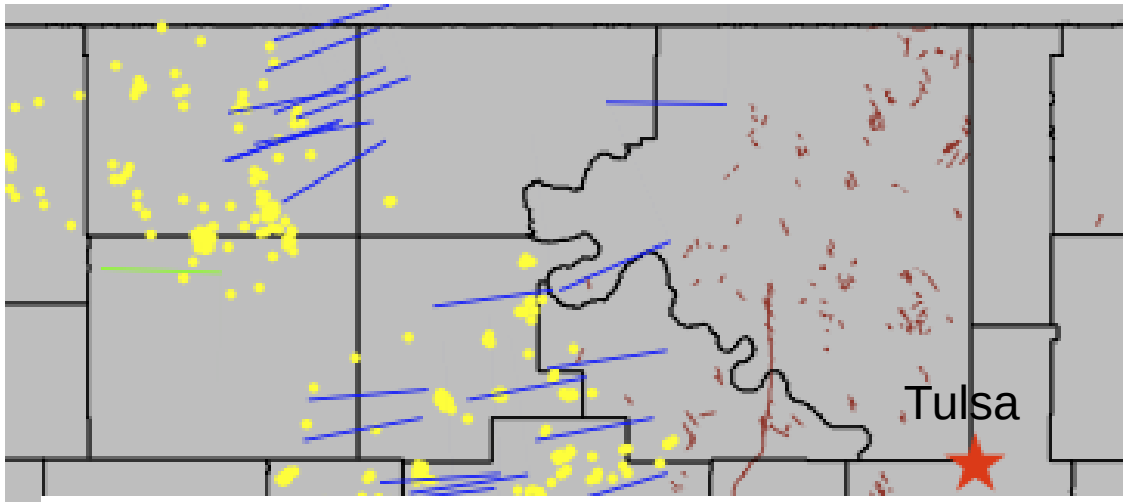
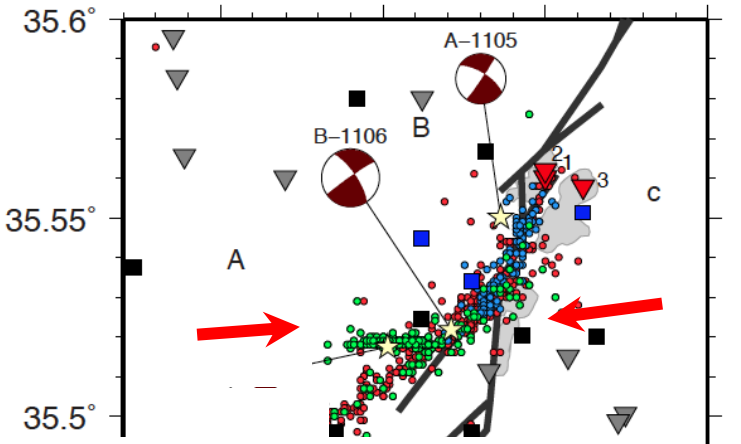
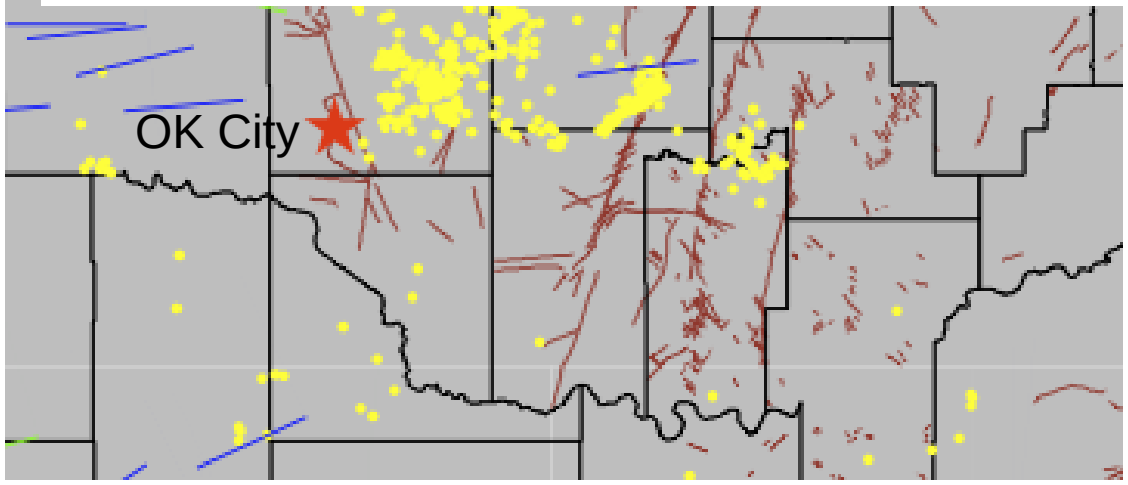
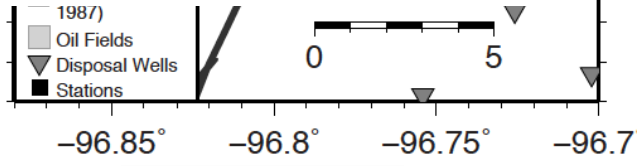
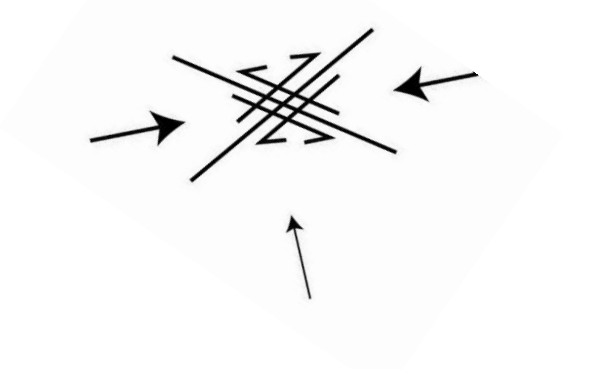




Avoid Locating Injection Wells Near Potentially Active Faults

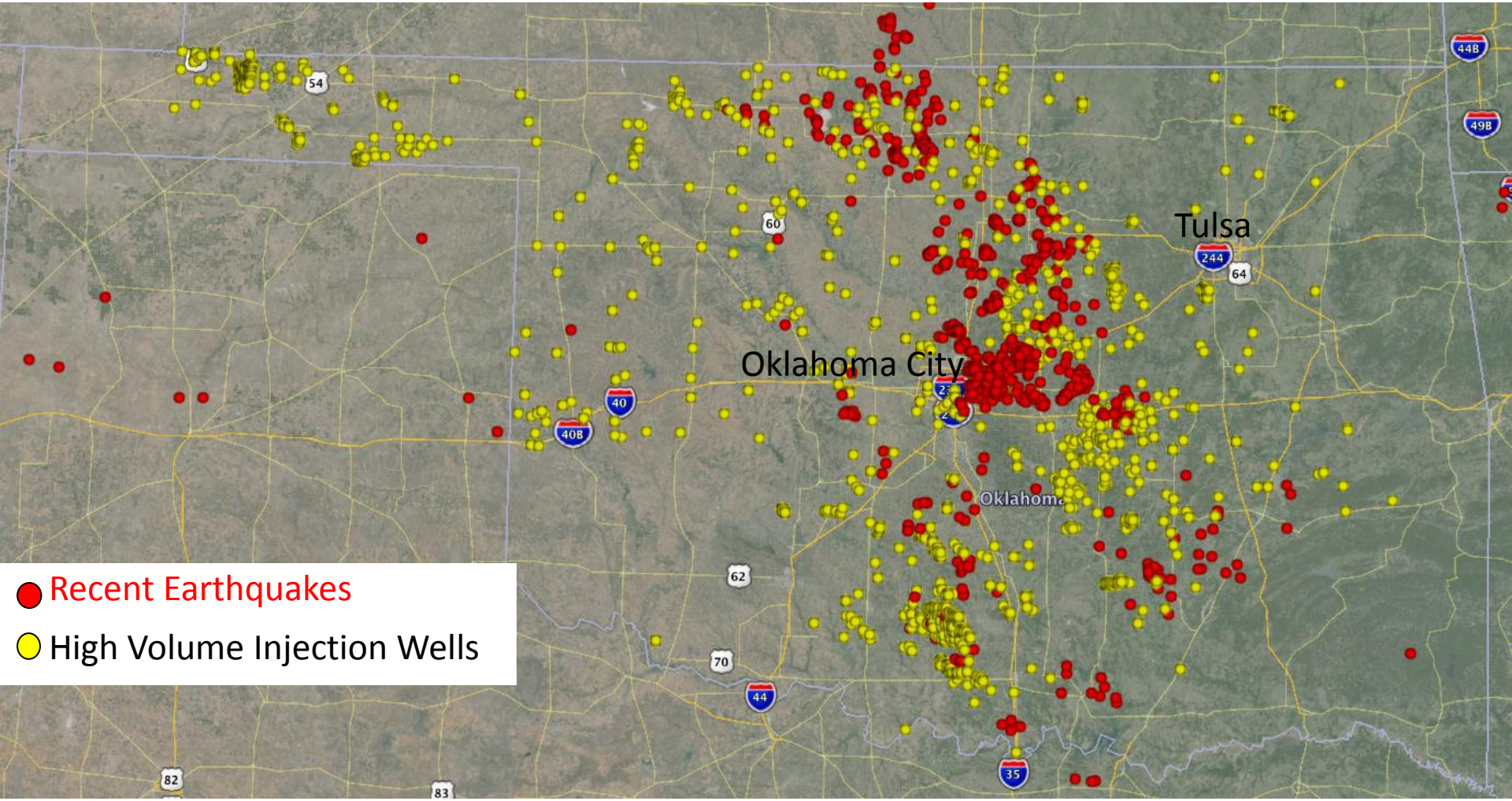






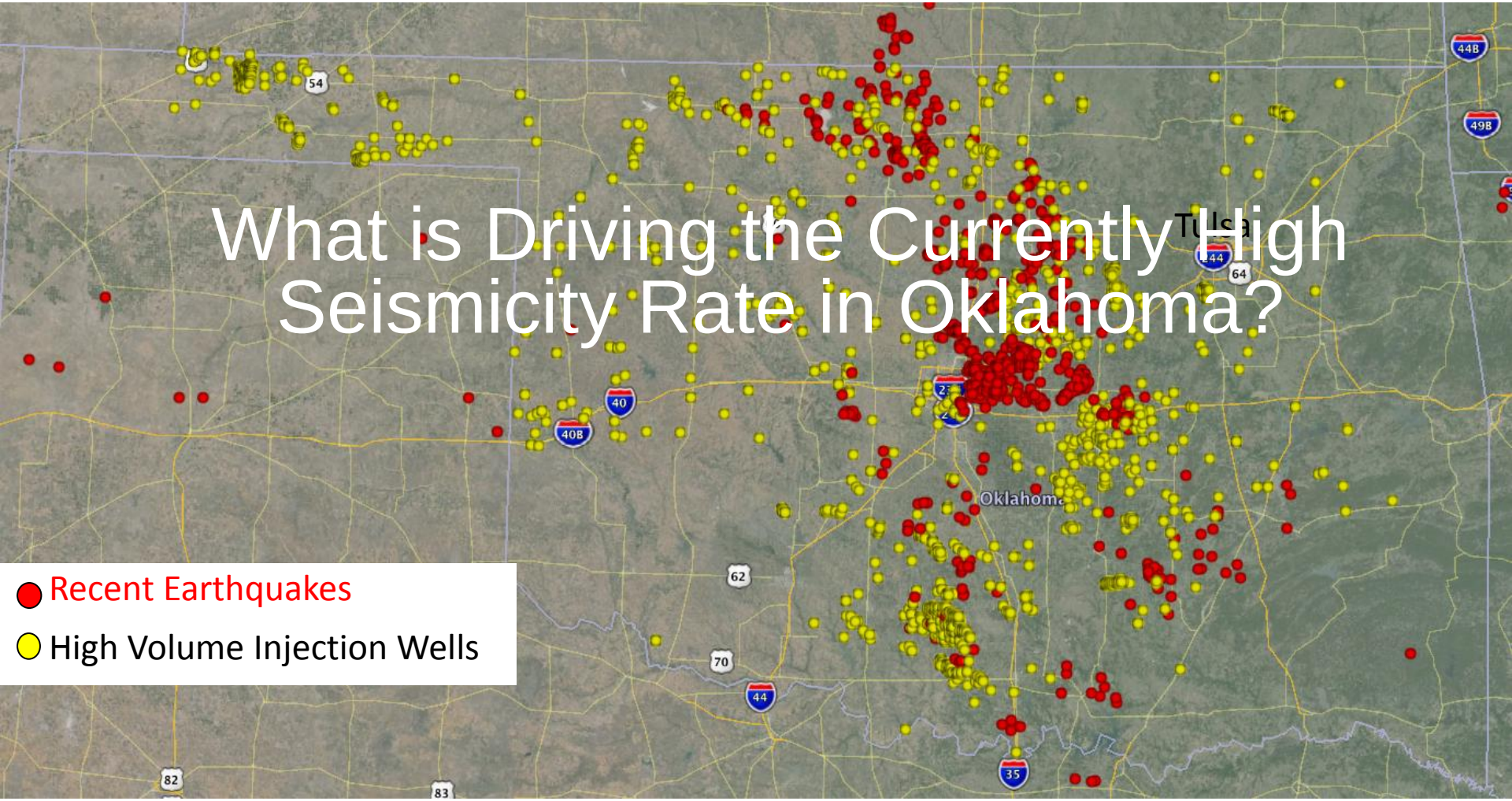
Water Recycling – Western Pennsylvania

The Curious Case of Oklahoma Seismicity



Walsh and Zoback (in preparation)

The Curious Case of Oklahoma Seismicity



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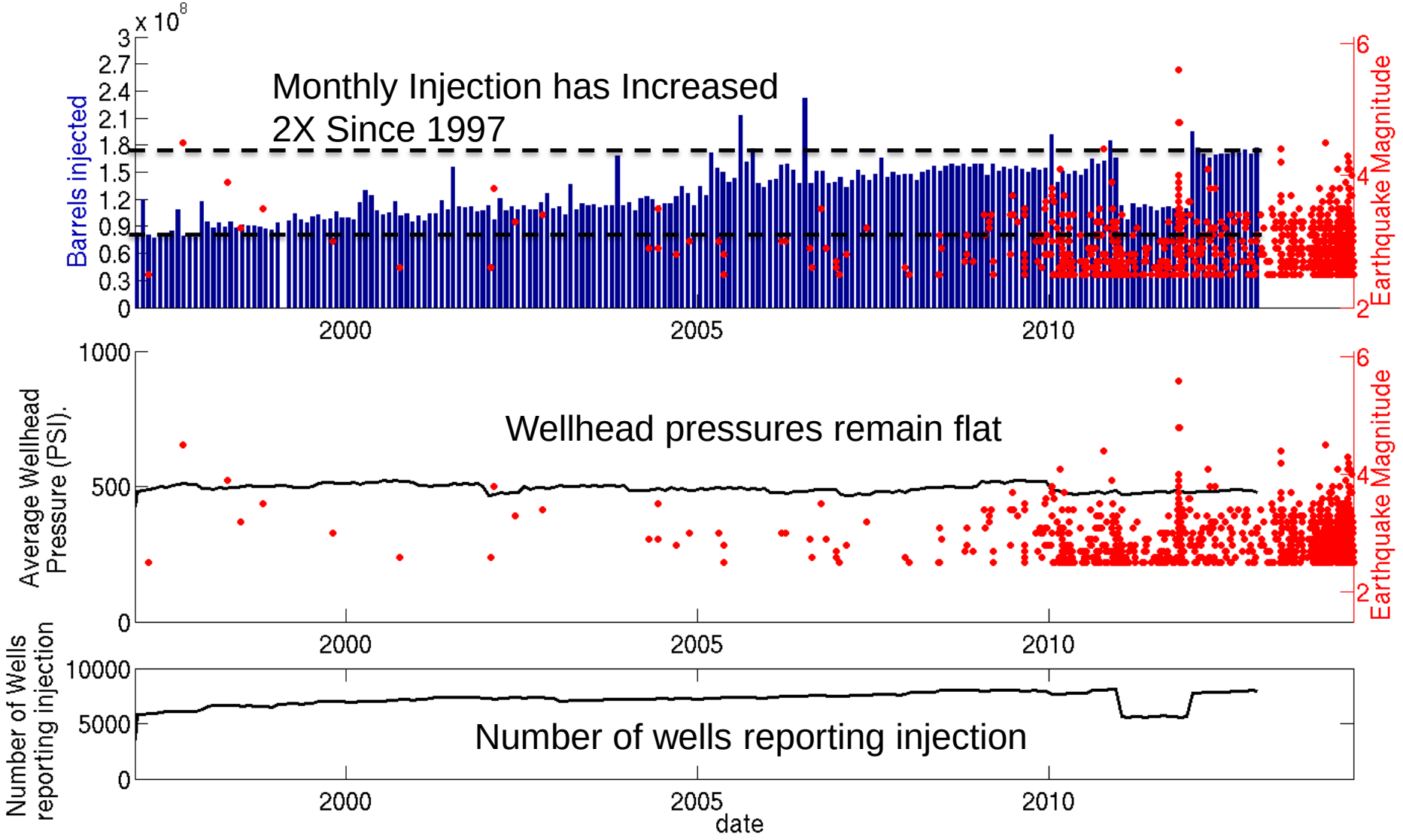
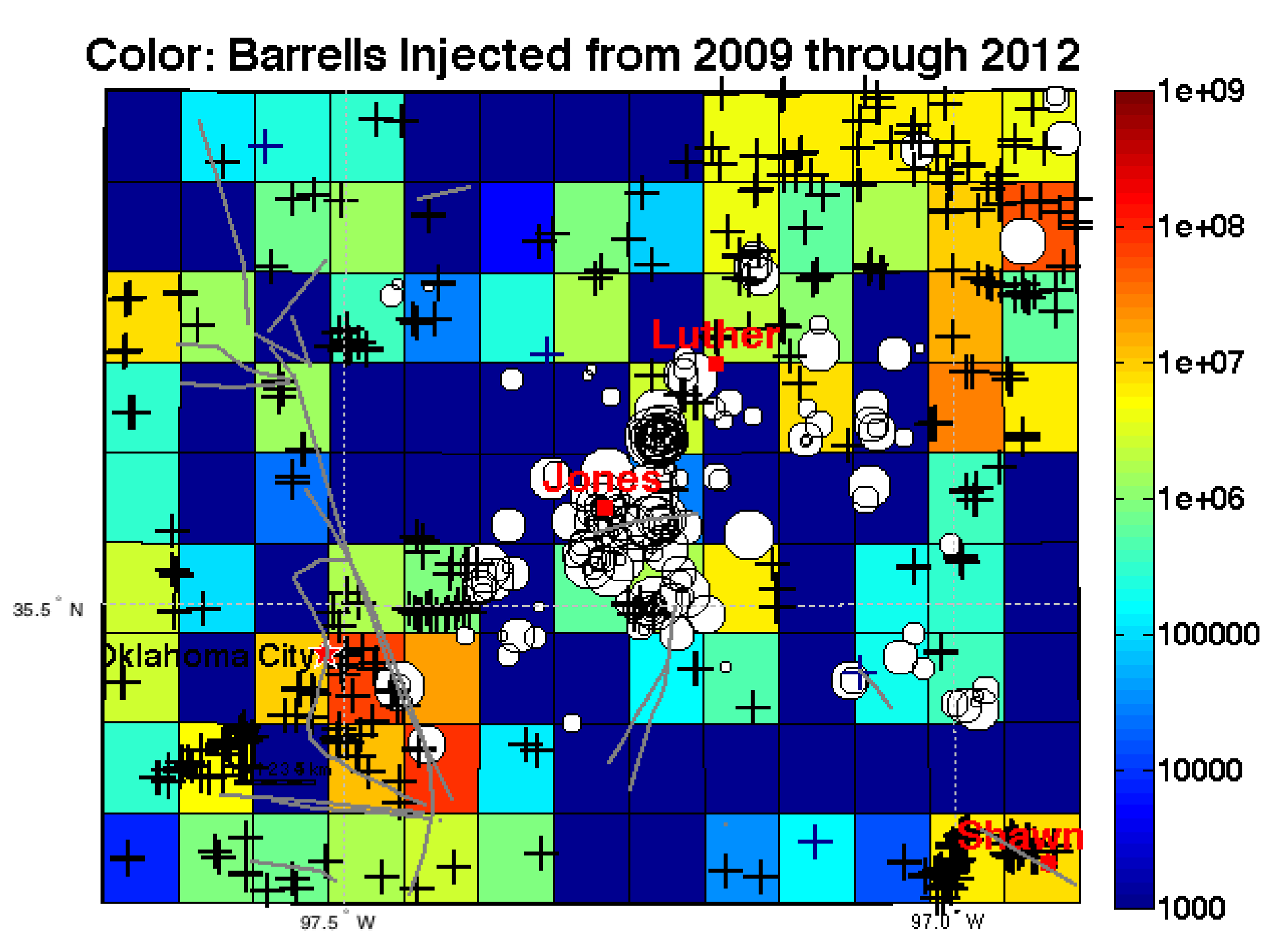
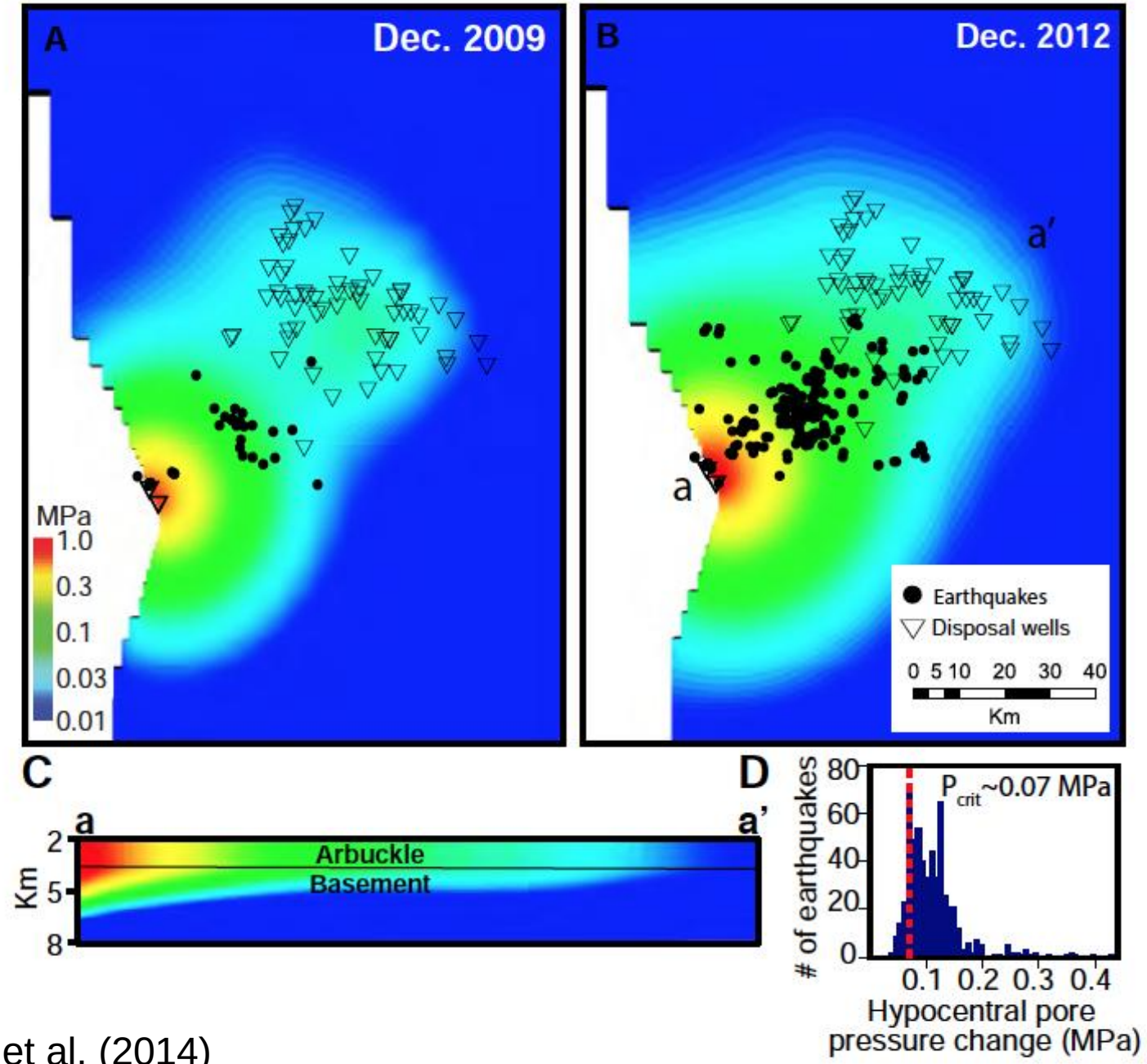
Statewide Monthly Injection Rates

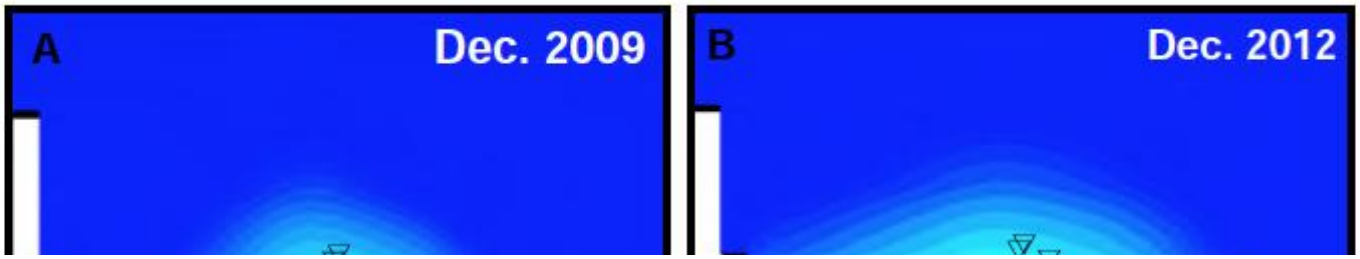



Color: Barrells Injected from 2009 through 2012
Luther
Jones
Oklahoma City
Shawn
35.5 ° N
97.5 ° W
97.0 ° W
1e+09
1e+08
1e+07
1e+06
100000
10000
1000

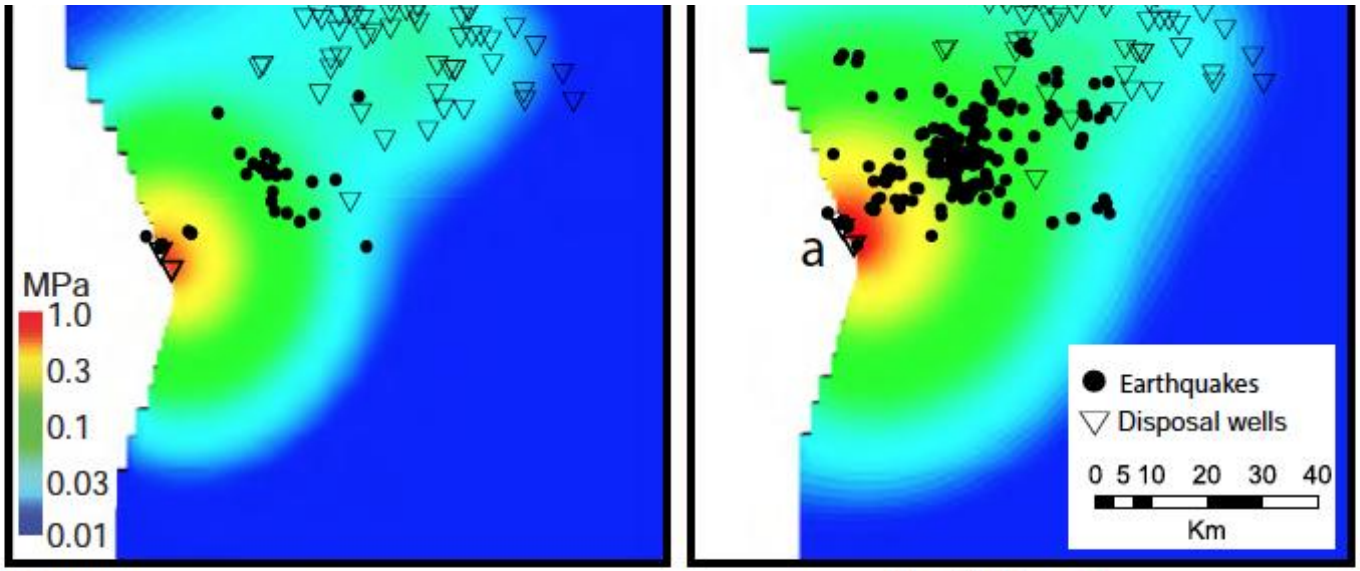


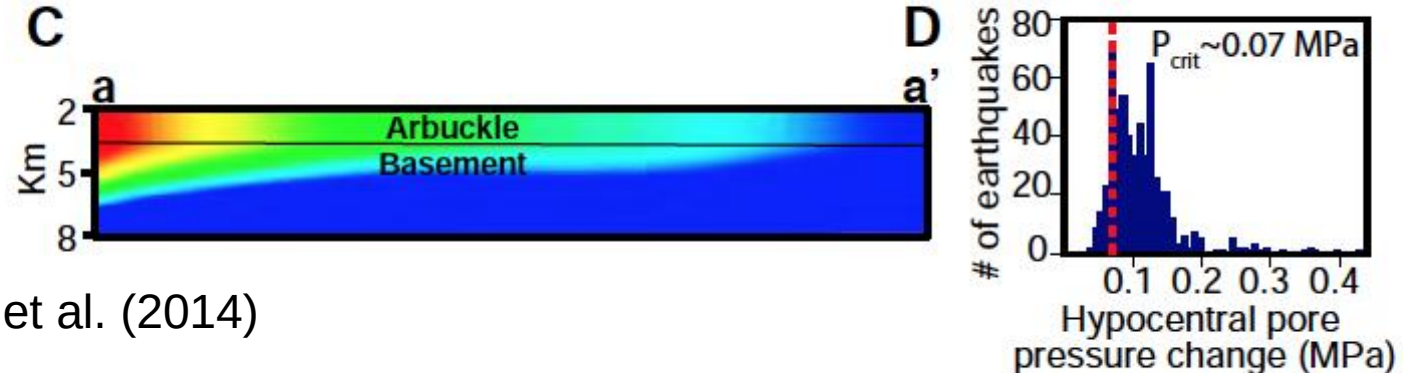
Keranen et al. (2014)

Why Are There Very Large Injection Wells?



Not Waste Water Associated with Hydraulic Fracturing

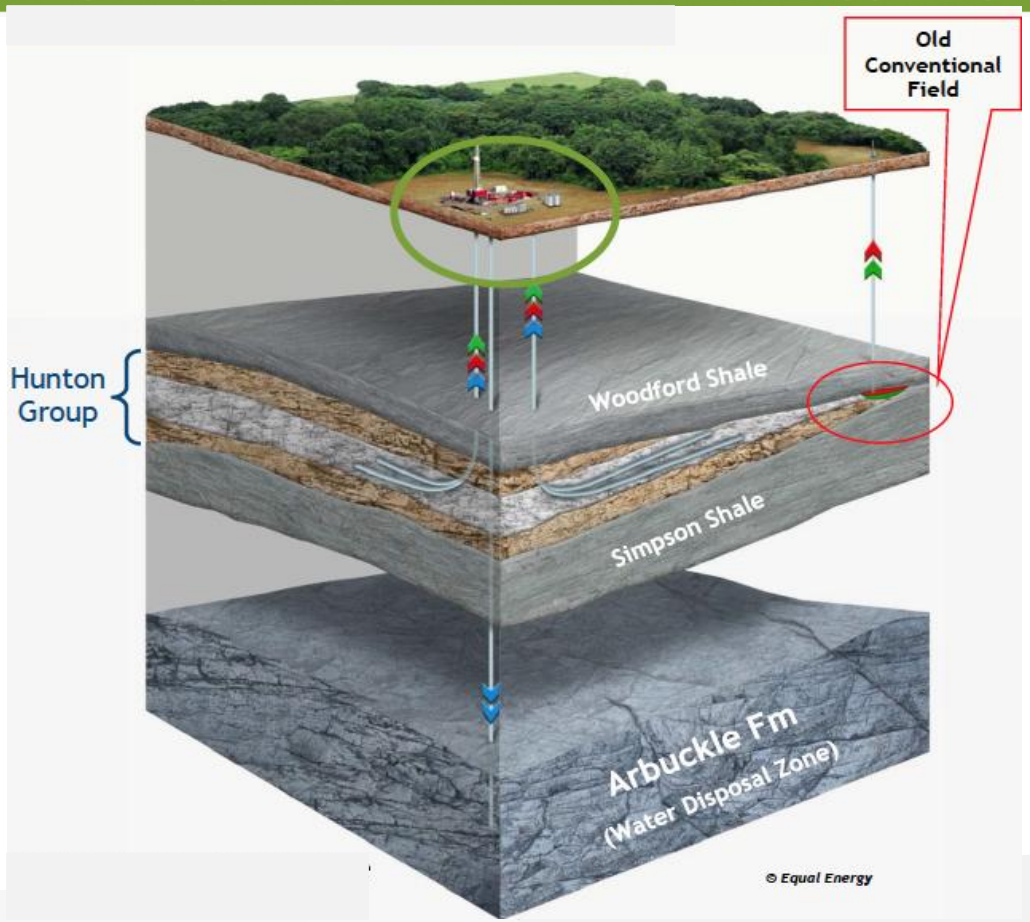




Keranen et al. (2014)

The Hunton Play - How it Works

The Hunton Group is a dual porosity carbonate system that contains oil-wet primary porosity and water-saturated secondary porosity

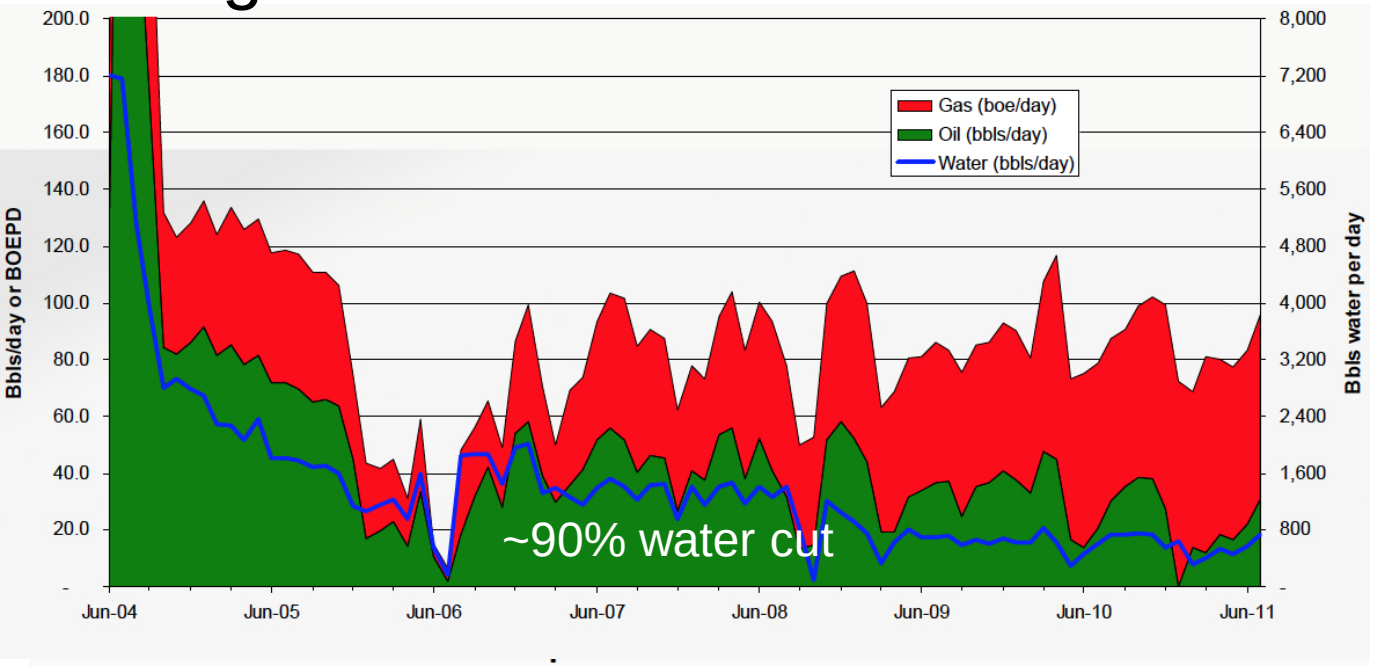


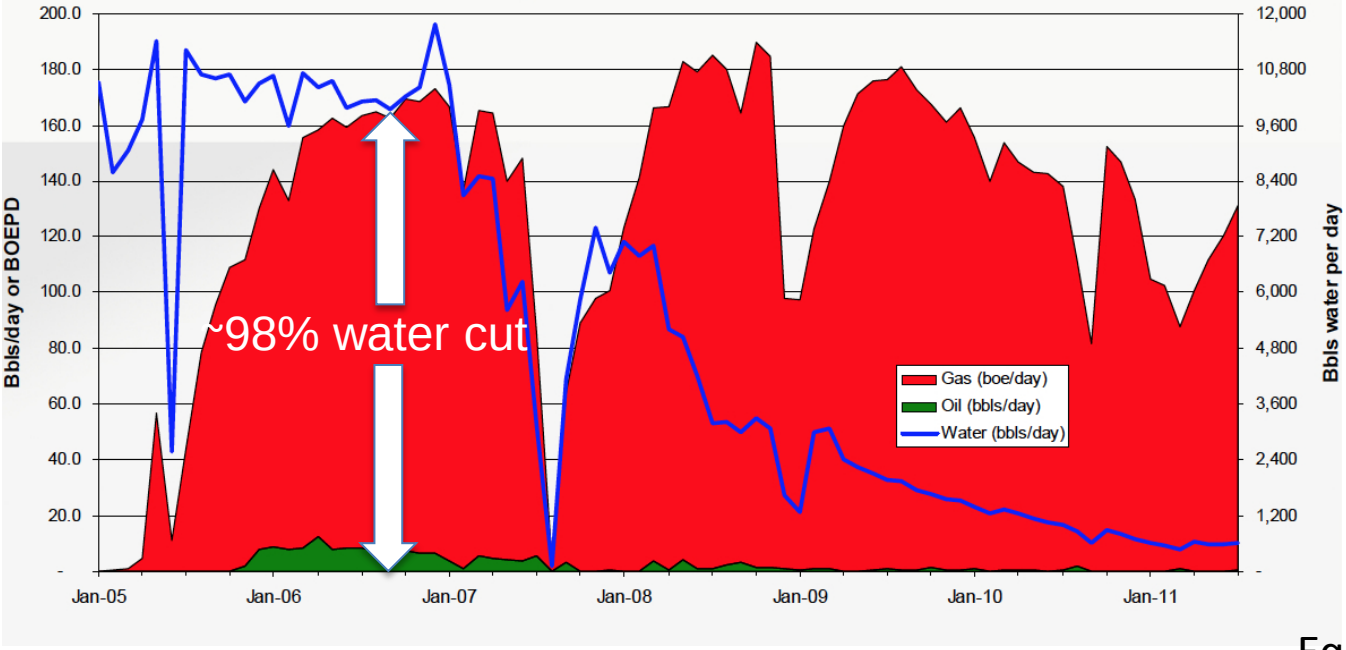
Equal Energy Method

- Multi-well pads exploit up to four square miles of resource
- Multi-lateral horizontal wells
- Deep water disposal wells service up to 12 producers and 65,000 bbls of water per day

Flow Rate of the Macondo well

Dewatering Wells Produce a Lot of Water Per BOE:





Equal Energy

Induced Seismicity Potential in Energy Technologies

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2012

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Risk Associated with Injection and Triggered Seismicity

Microseismic Events Associated with Hydraulic Fracturing

- Very Low Risk to Public
  - Limited rock volume, limited pumping volume/time
  - Very few events > M 2 in 100,000's of frac stages

Seismic Events Associated with Wastewater Injection

- Low Risk to Public
  - Much Larger Pumping Volumes
  - Can be Effectively Managed by Effective Site Characterization, Monitoring and Proactive Planning
  - Minimize Injection by Water Recycling

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