Saltwater Disposal and Triggered Earthquakes in Oklahoma: Implications for Large Scale CO_2 Storage

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Large-Scale CCS?

PNAS

PERSPECTIVE

Earthquake triggering and large-scale geologic storage of carbon dioxide

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Edited by Pamela A. Matson, Stanford University, Stanford, CA, and approved May 4, 2012 (received for review March 27, 2012)

Despite its enormous cost, large-scale carbon capture and storage (CCS) is considered a viable strategy for significantly reducing CO_2 emissions associated with coal-based electrical power generation and other industrial sources of CO_2 [Intergovernmental Panel on Climate Change (2005) IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, eds Metz B, et al. (Cambridge Univ Press, Cambridge, UK); Szulczewski ML, et al. (2012) *Proc Natl Acad Sci USA* 109:5185–5189]. We argue here that there is a high probability that earthquakes will be triggered by injection of large volumes of CO_2 into the brittle rocks commonly found in continental interiors. Because even small- to moderate-sized earthquakes threaten the seal integrity of CO_2 repositories, in this context, large-scale CCS is a risky, and likely unsuccessful, strategy for significantly reducing greenhouse gas emissions.

carbon sequestration | climate change | triggered earthquakes

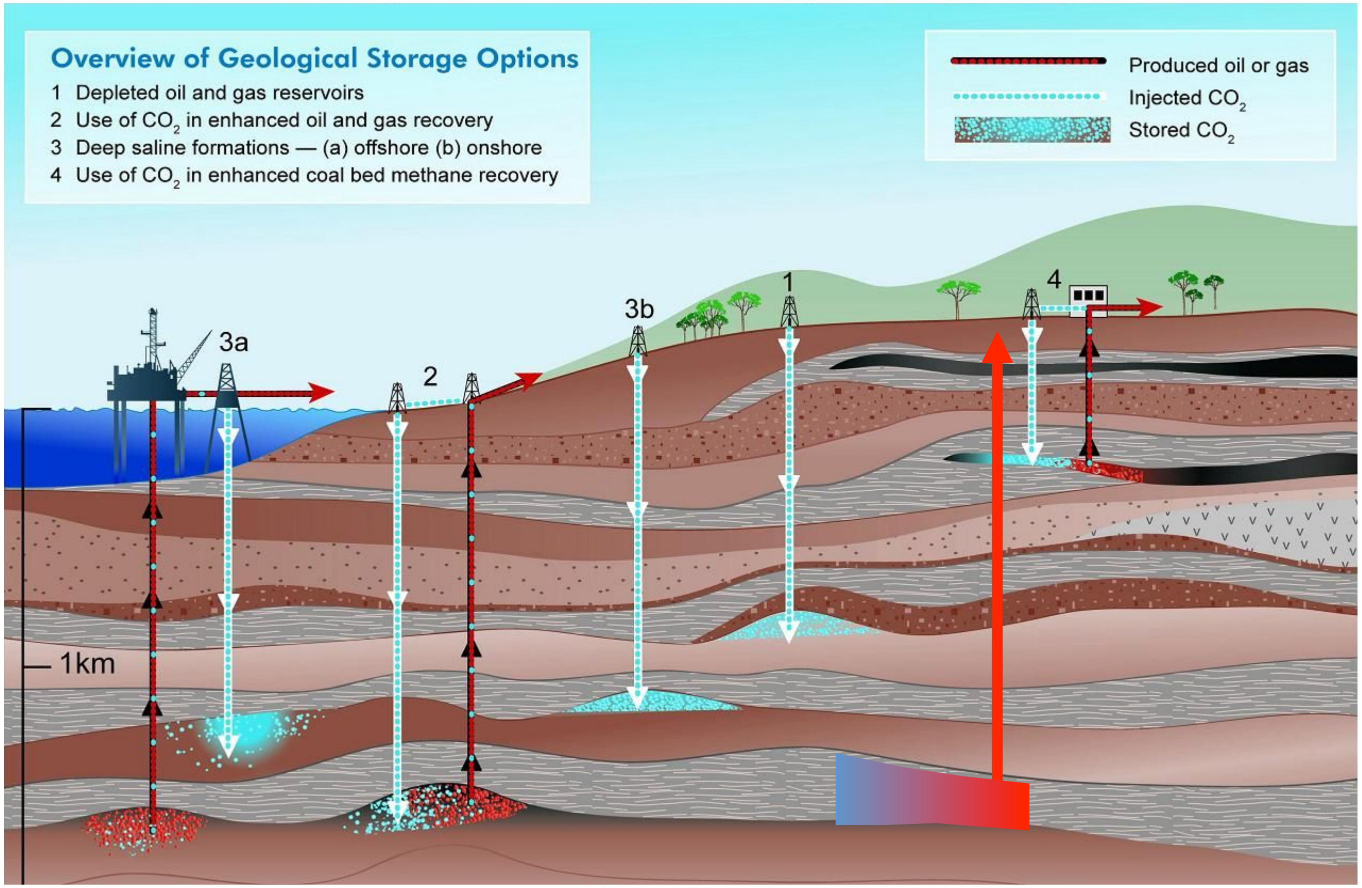
The combustion of coal for electrical power generation in the United States generates approximately 2.1 billion metric tons of CO_2 per year, ~36% of all US emissions. In 2011, China generated more than three

corded intraplate earthquakes in south and east Asia (4). The seismicity catalogs are complete to magnitude (M) 3. The occurrence of these earthquakes means that nearly everywhere in continental interiors a subset of the preexisting faults in

March, where the largest earthquake was M 4.7. In the Trinidad/Raton area near the border of Colorado and New Mexico, injection of produced water associated with coalbed methane production seems to have triggered a number of earth-

Proc. National Academy of Sciences, June 18, 2012

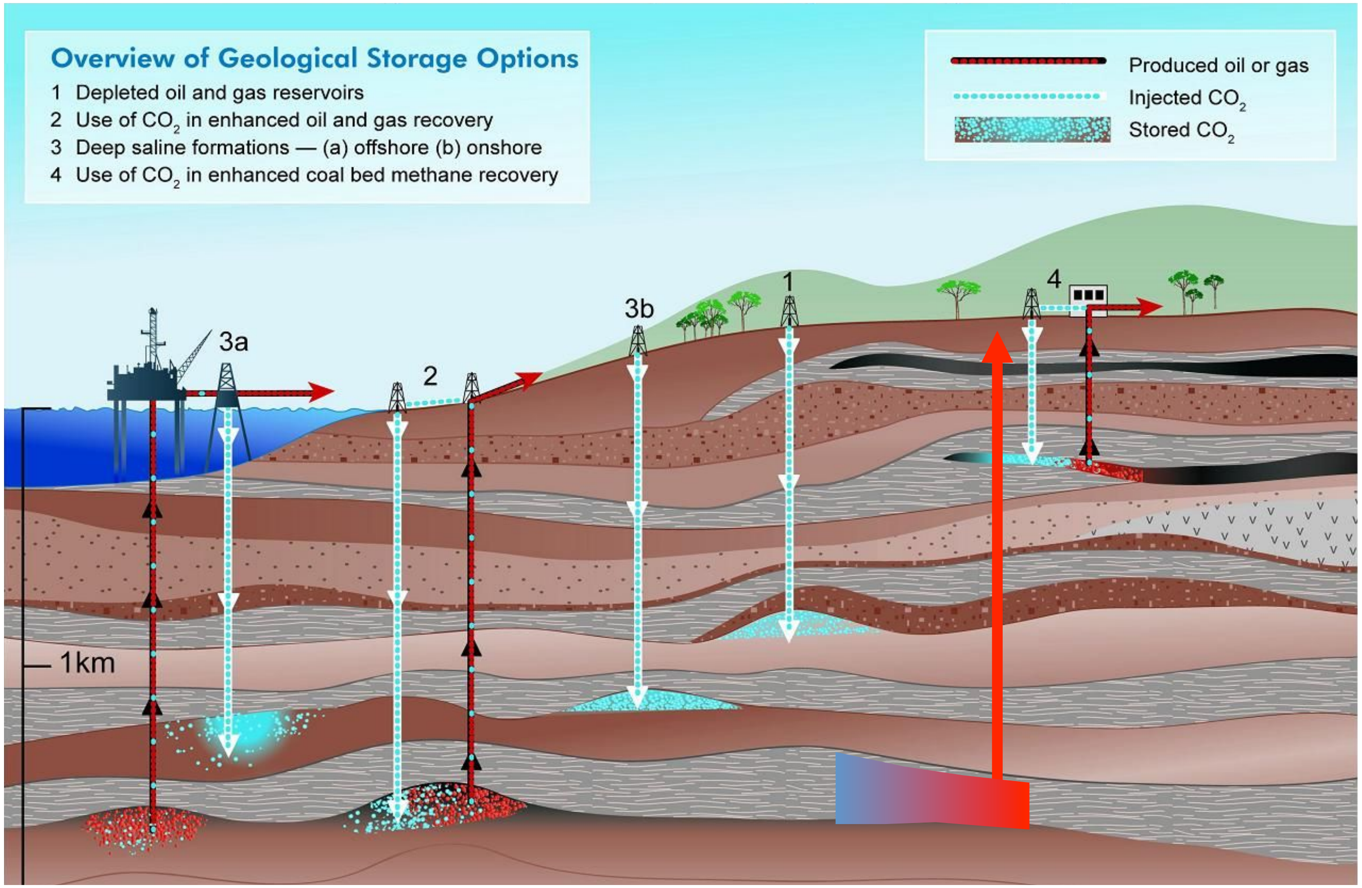
Most Common Objections to CO_2 Sequestration



HUGE COSTS – Carbon capture, pipelines, injection wells, monitoring systems … Roughly $0.5 Trillion/Year

LONG TIME TO IMPLEMENT – Many decades to implement at the required scale

Potential for Triggered Seismicity



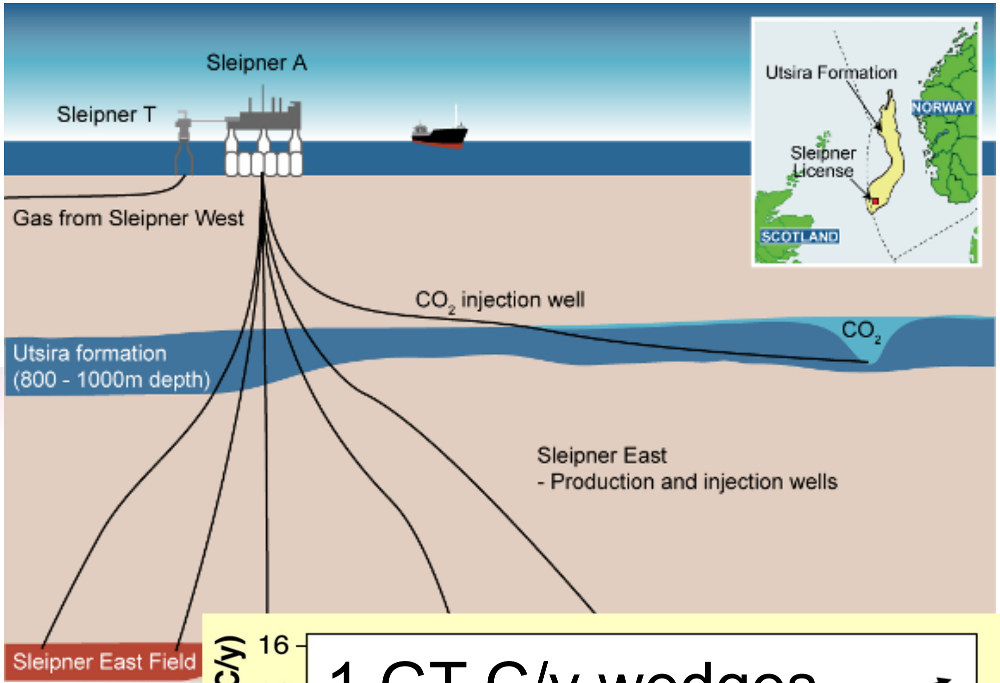
PORE SPACE IS OCCUPIED – Injection Causes Pressure to Increase

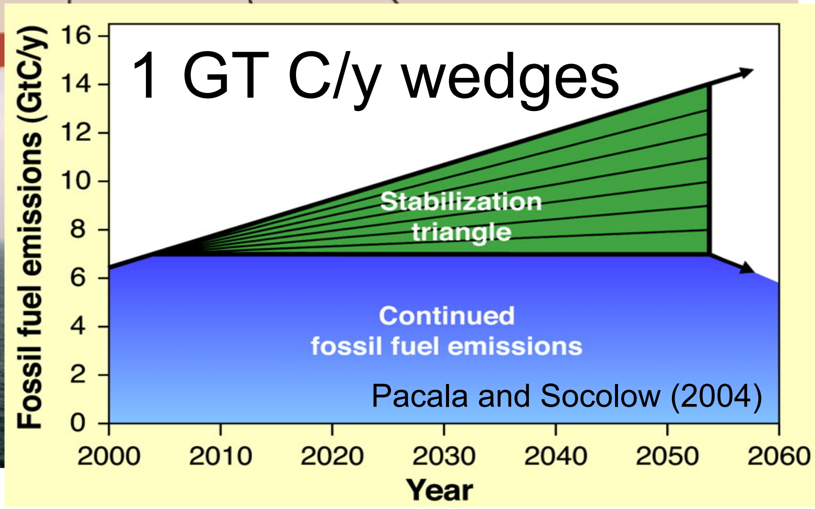
LIMITED INJECTIVITY – Many Sites in Intraplate Areas Have Low Permeability

BRITTLE ROCK – In Frictional Equilibrium

Sleipner Works - Why Not Just Do It?

- 1996 to present
- 1 Mt CO_2 injection/yr
- Seismic monitoring





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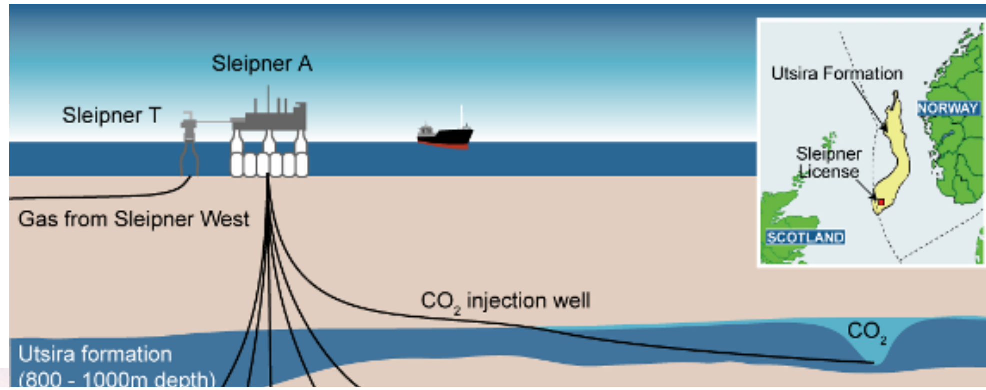
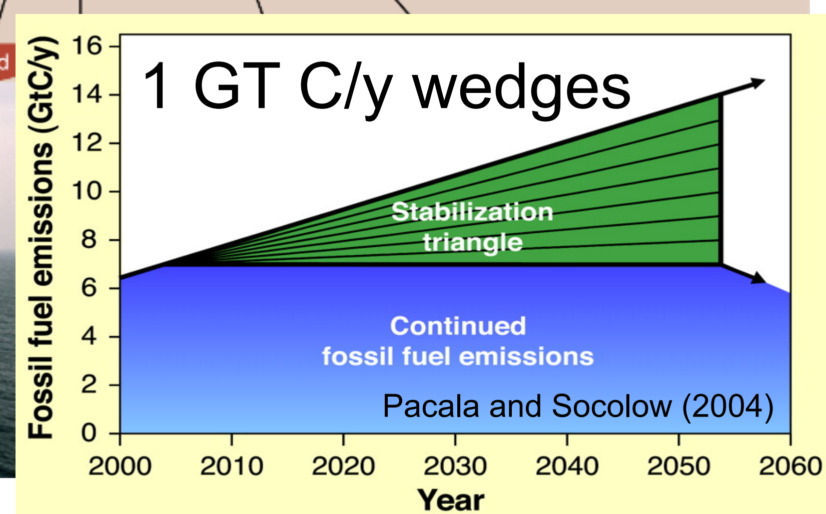


27 Billion Barrels/Year



Earthquake triggering and large-scale geologic storage of carbon dioxide

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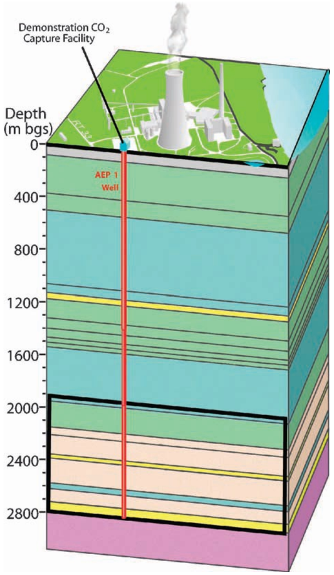
- The issue is not whether CO_2 can be safely stored at a given site; the issue is whether the capacity exists for sufficient volumes of CO_2 to be stored geologically for it to have the desired beneficial effect on climate change.

- Can it operate at a scale that makes it one of the principal mechanisms to reduce GHG emission and justify expenditures of ~$0.5 T/y ?

- In this context, it must be recognized that large-scale CCS will be an extremely expensive and risky strategy for achieving significant reductions in greenhouse gas emissions.

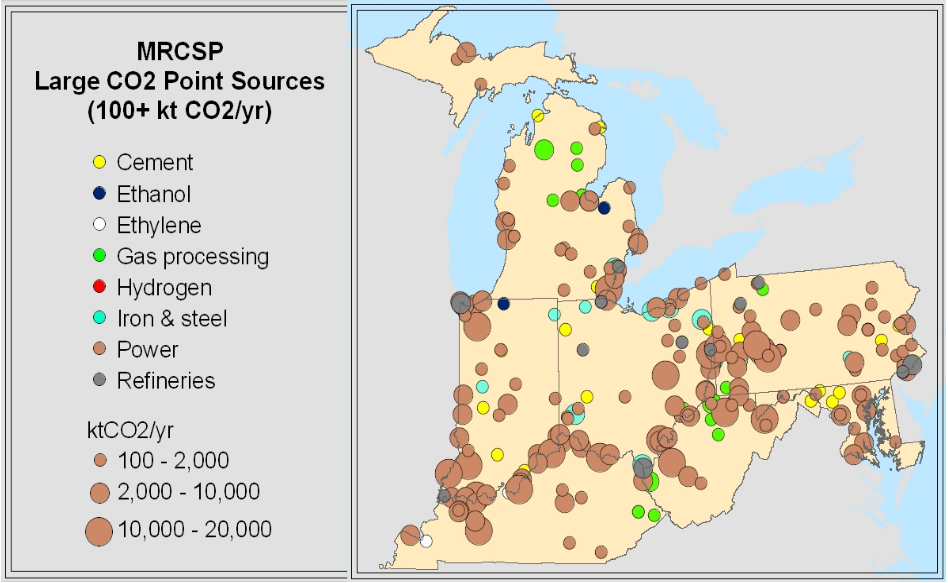
CO_2 Type 1 - AEP Mountaineer Project



183 Coal burning plants in Ohio River Valley

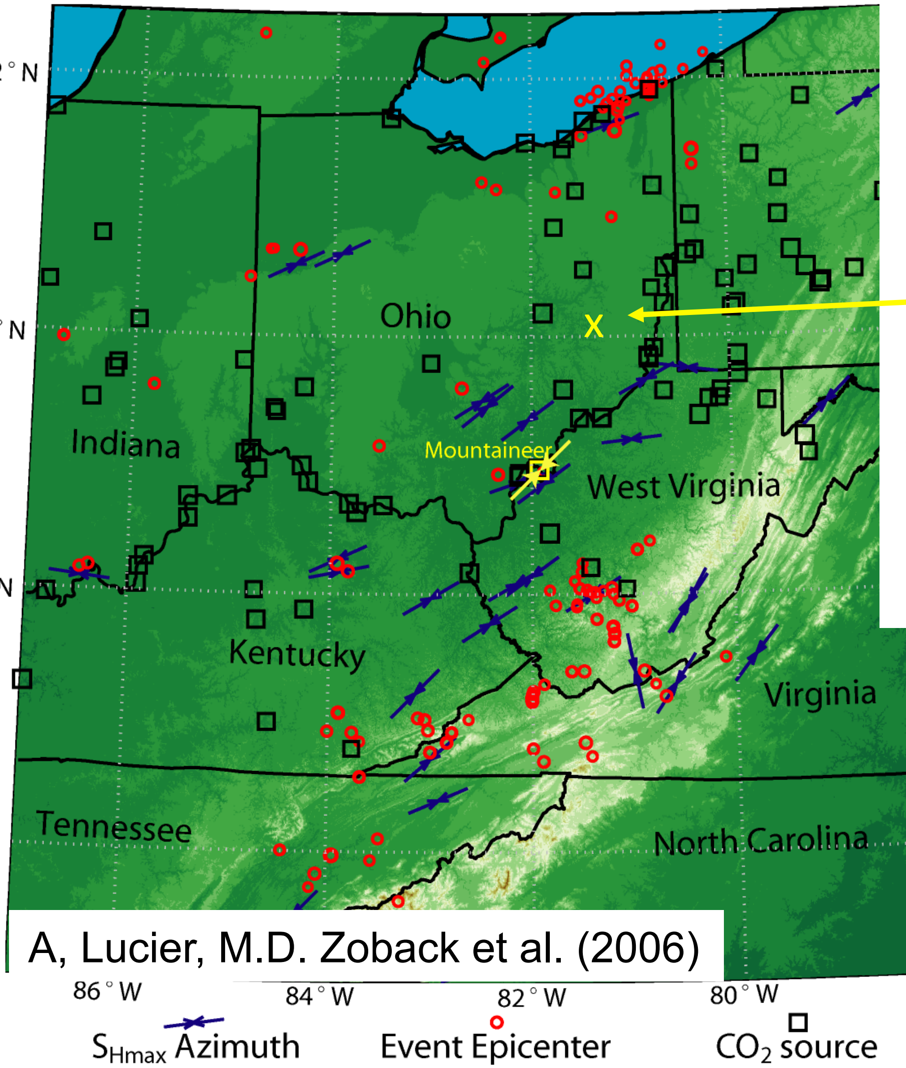
Emissions ~700 million tonnes of CO_2/year)

AEP Mountaineer CO_2 Emissions ~7 Mton/year



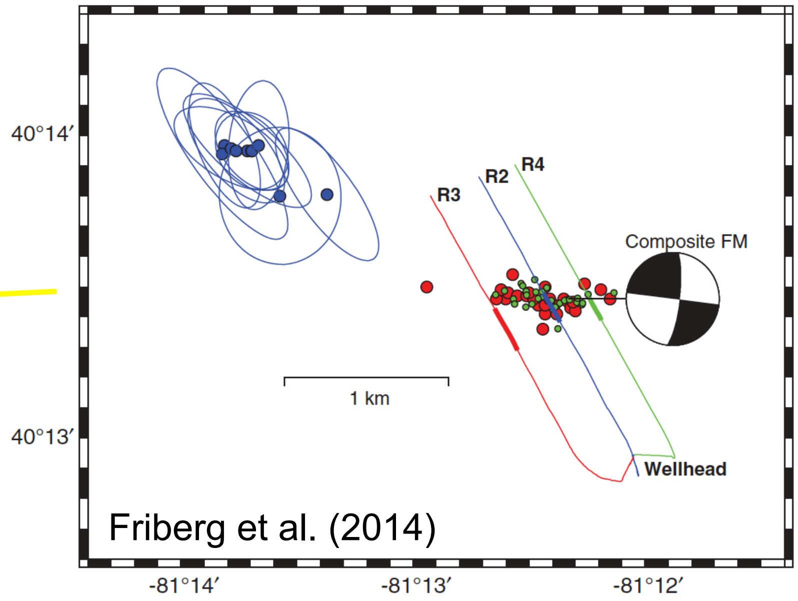
A, Lucier, M.D. Zoback et al. (2006)

Local and Regional Stress

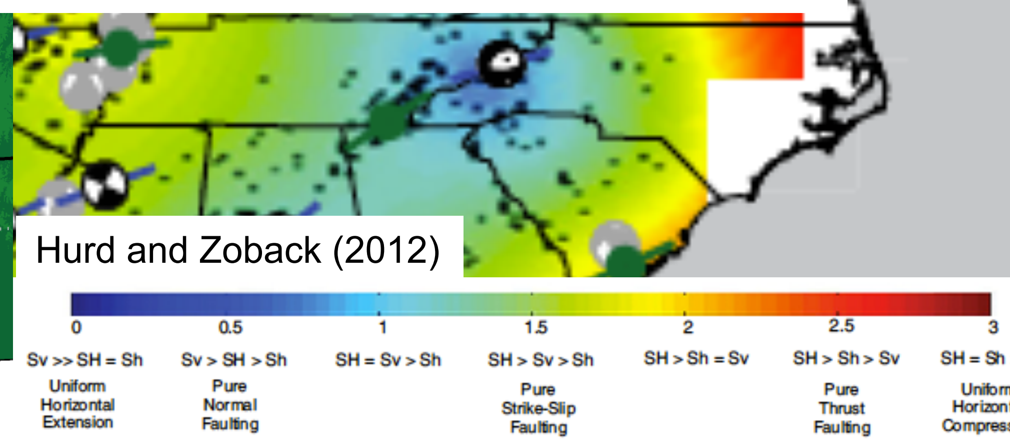


A, Lucier, M.D. Zoback et al. (2006)

Mountaineer Power Plant Site

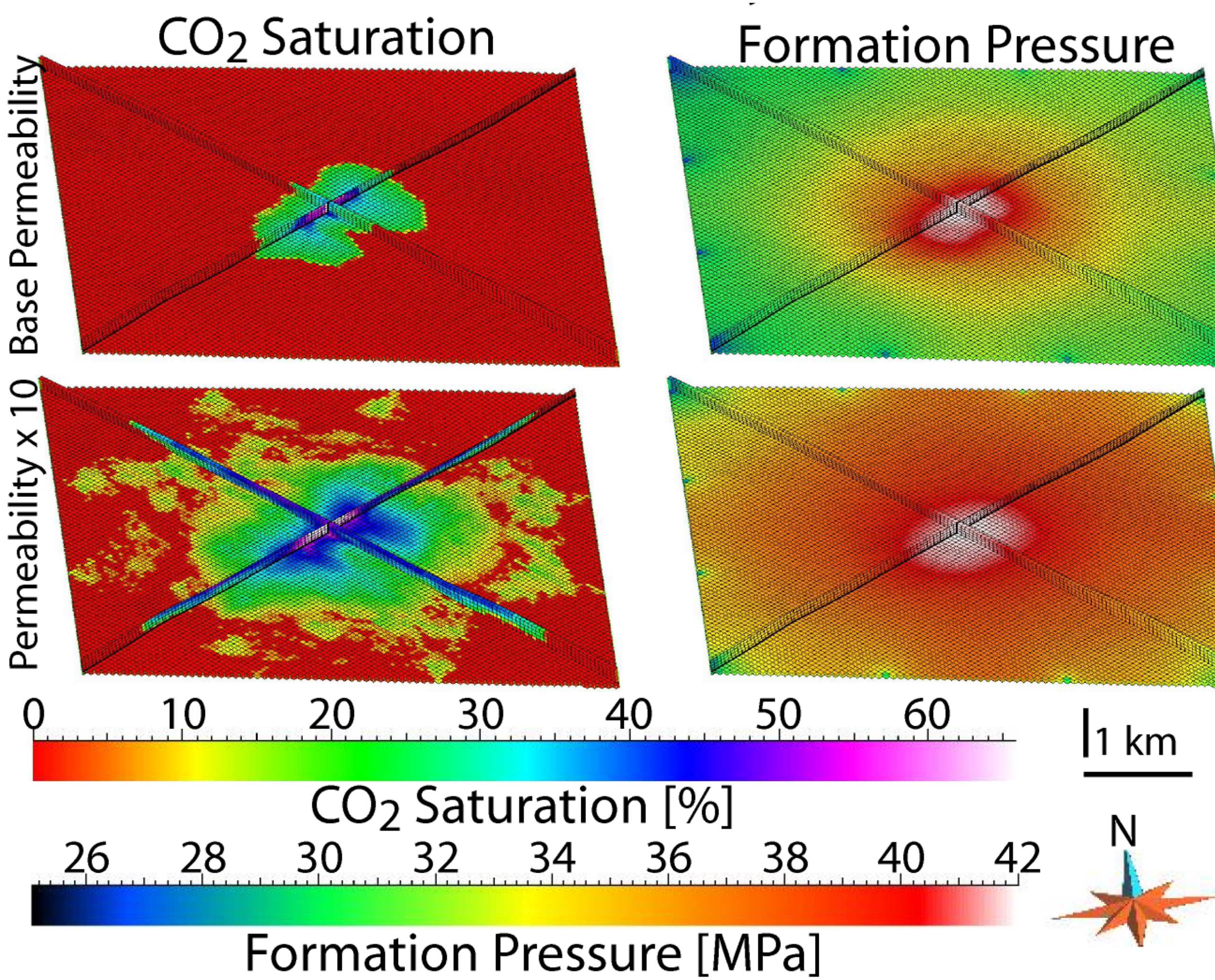


Friberg et al. (2014)



Hurd and Zoback (2012)

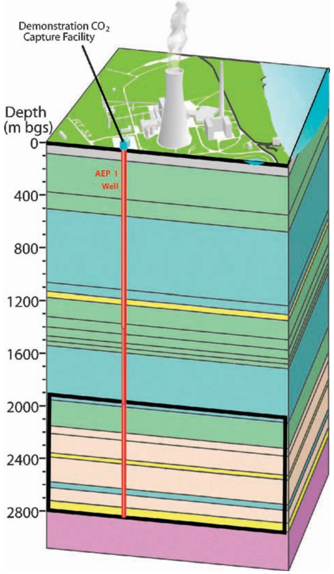
Geomechanically-Constrained Simulation*



A, Lucier, M.D. Zoback et al. 2006)

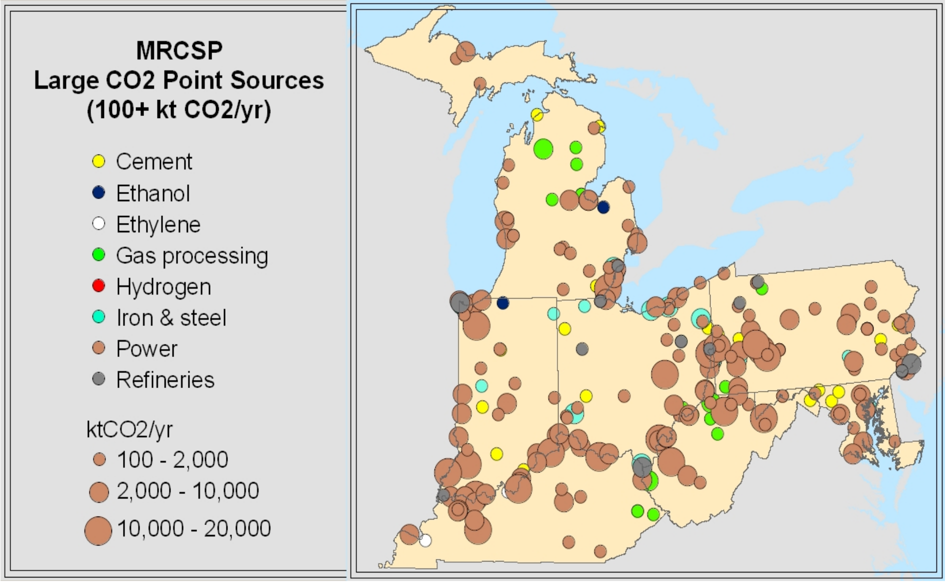
At What Injection Rate Does Injection Not Cause Observed Faults to Slip?

CO_2 Type 1 - AEP Mountaineer Project



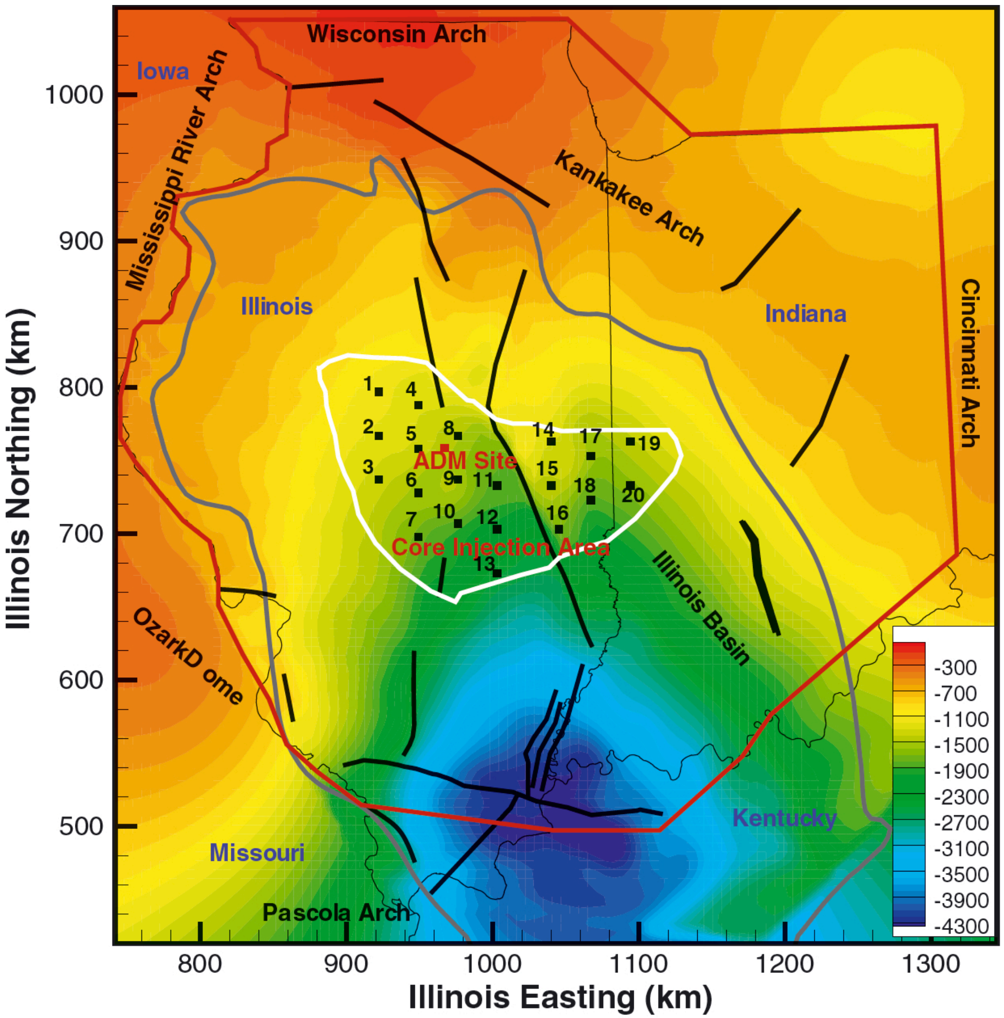
AEP Mountaineer CO_2 Emissions ~7 Mton/year

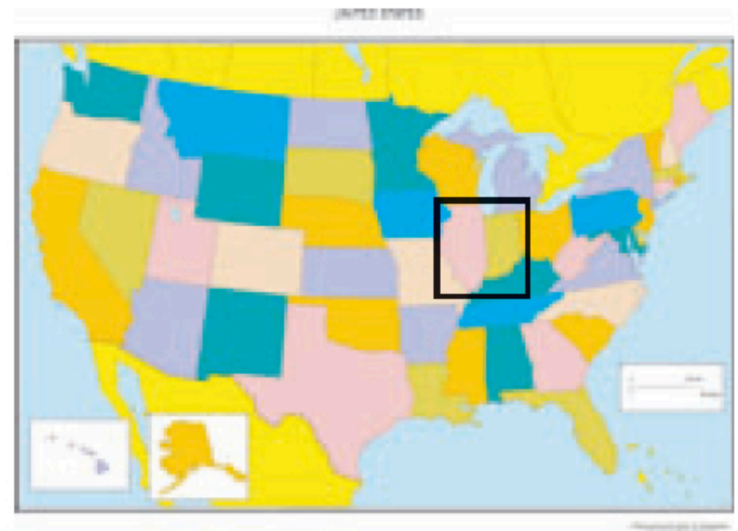
- Maximum Injection Rate Must be Less Than <u>~ 35 kton/year per injection zone</u> to Avoid Triggering Fault Slip
- 200 injection zones required!



CO_2 Type 2 - Large Scale CO_2 Sequestration
The Mt. Simon Sandstone, Illinois Basin

(Zhou et al. GROUND WATER 48, no. 4: 494–514, 2010)

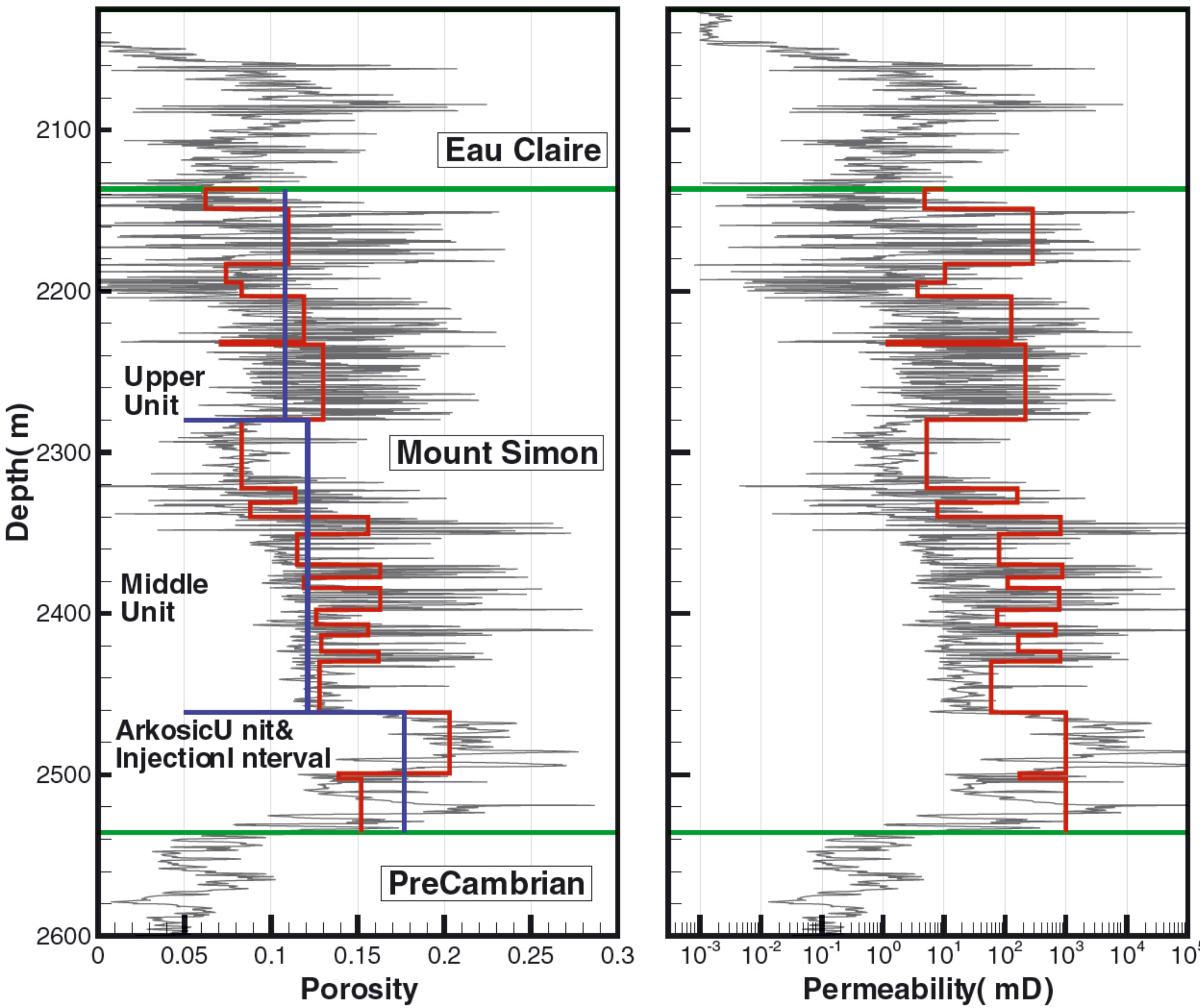




- 100 Million Tonnes/Year for 50 years
- US generates 2000 Million Tonnes/ Year of CO_2
- 100 Million Tonnes/Year is 1/7 of Emissions from Coal Burning Power Plants inJust the Ohio River Valley

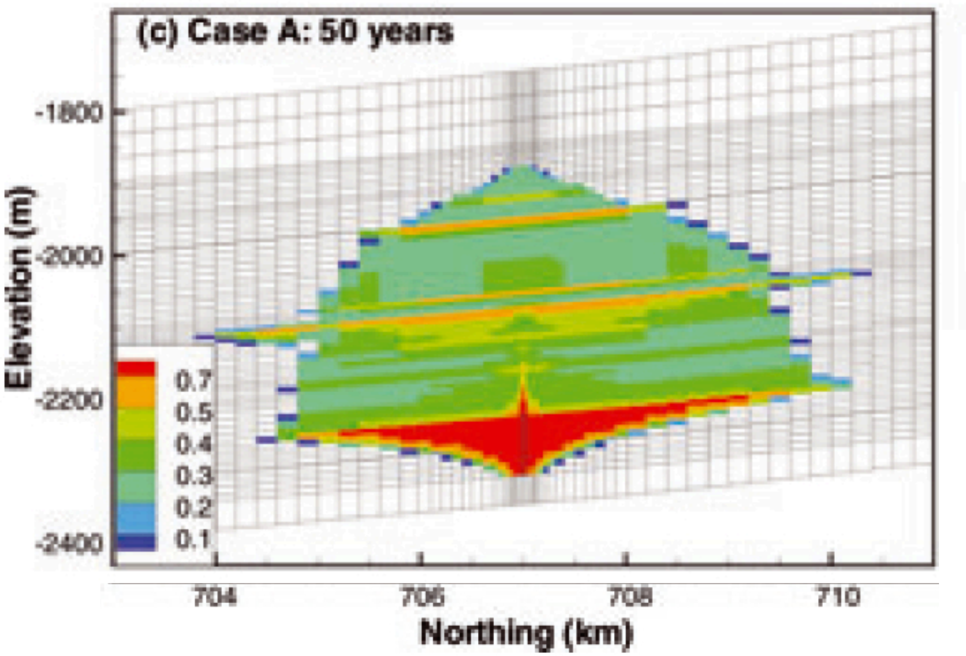
Mt. Simon Sandstone, Illinois Basin

(Zhou et al. GROUND WATER 48, no. 4: 494–514, 2010)



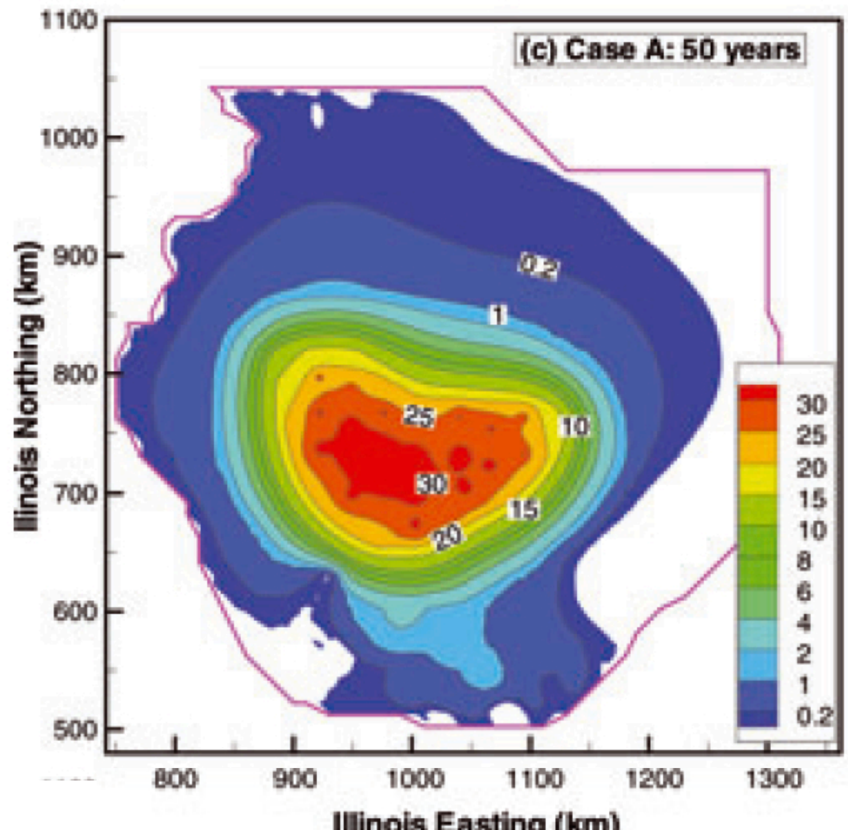
Modeling Large Scale CO_2 Sequestration In the Mt. Simon Sandstone, Illinois Basin

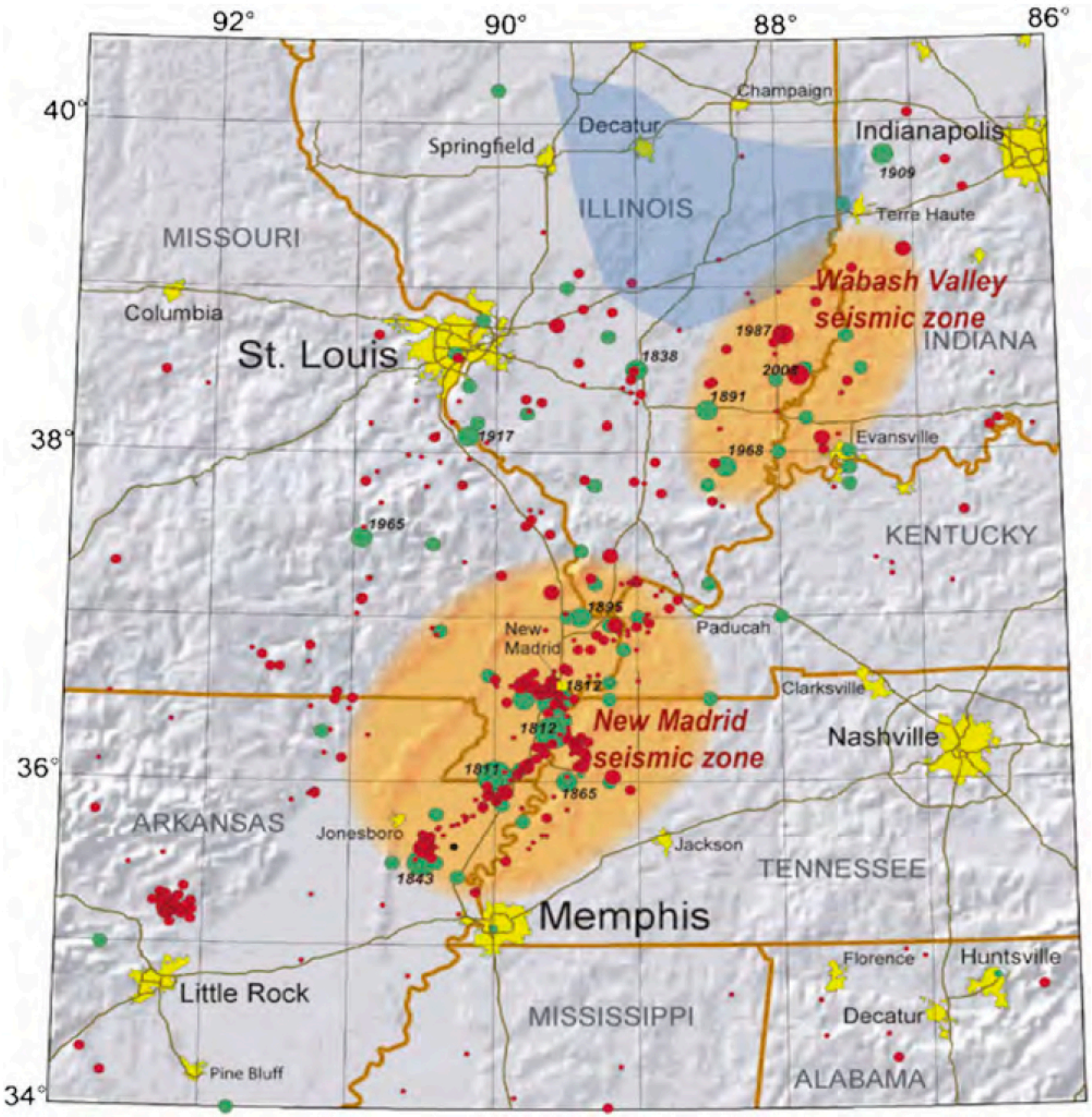
(Zhou et al. GROUND WATER 48, no. 4: 494–514, 2010)



CO_2 Saturation Extends Only a Few km From Each Injection Well

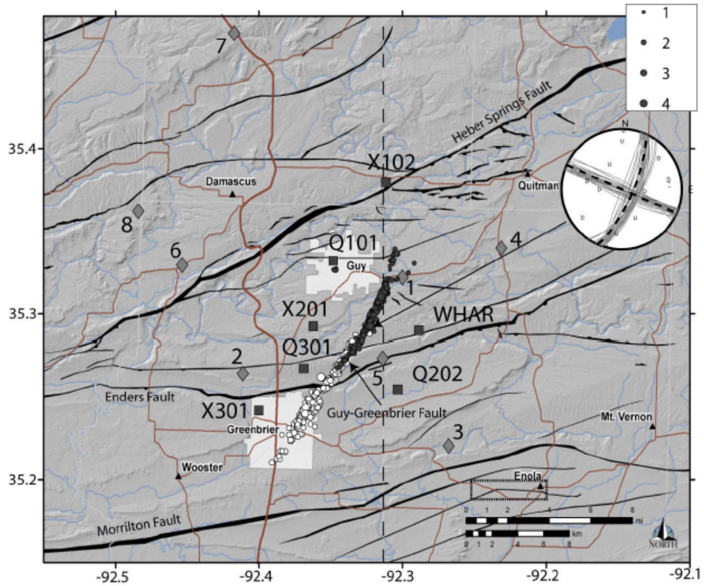
Pressure Perturbation Extends a 100's of km From Injection Area





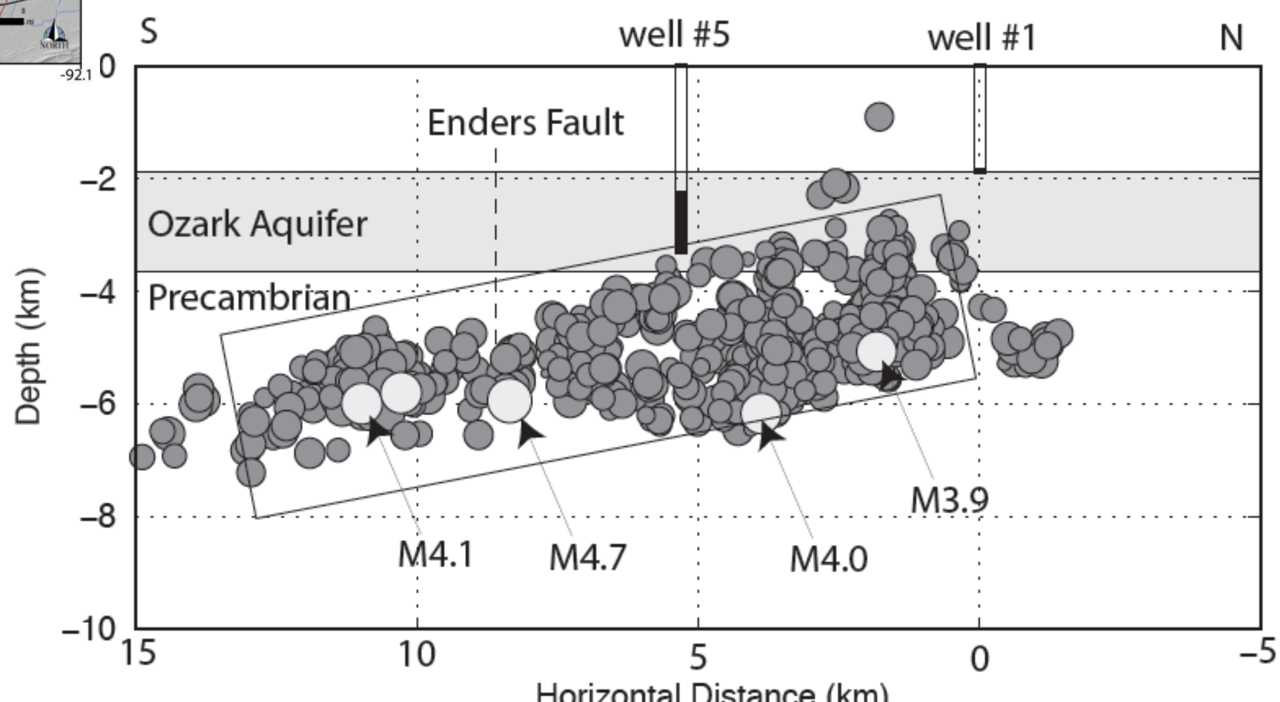
Zoback and Gorelick (2012)

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

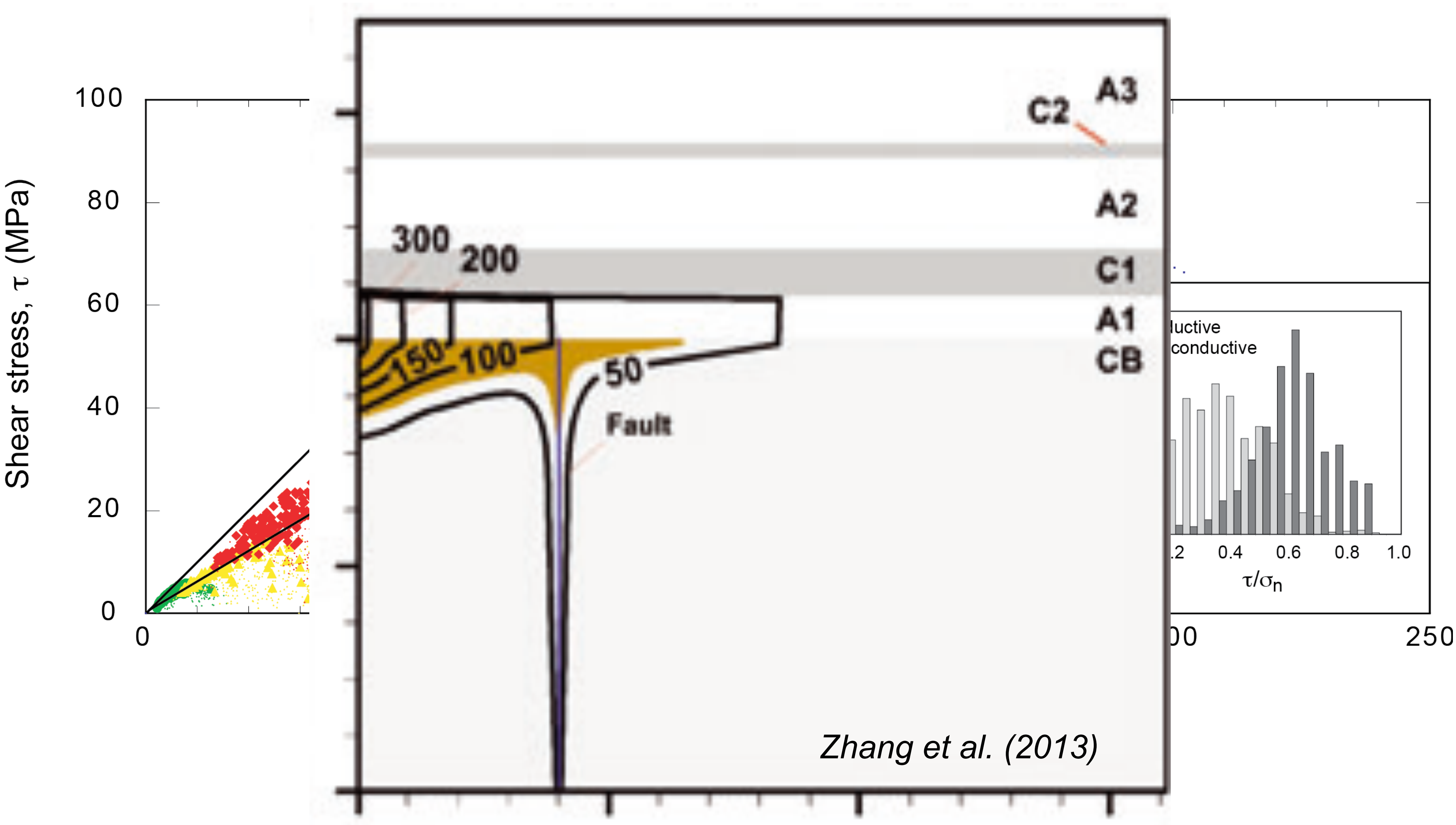


Horton *(2012)*

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

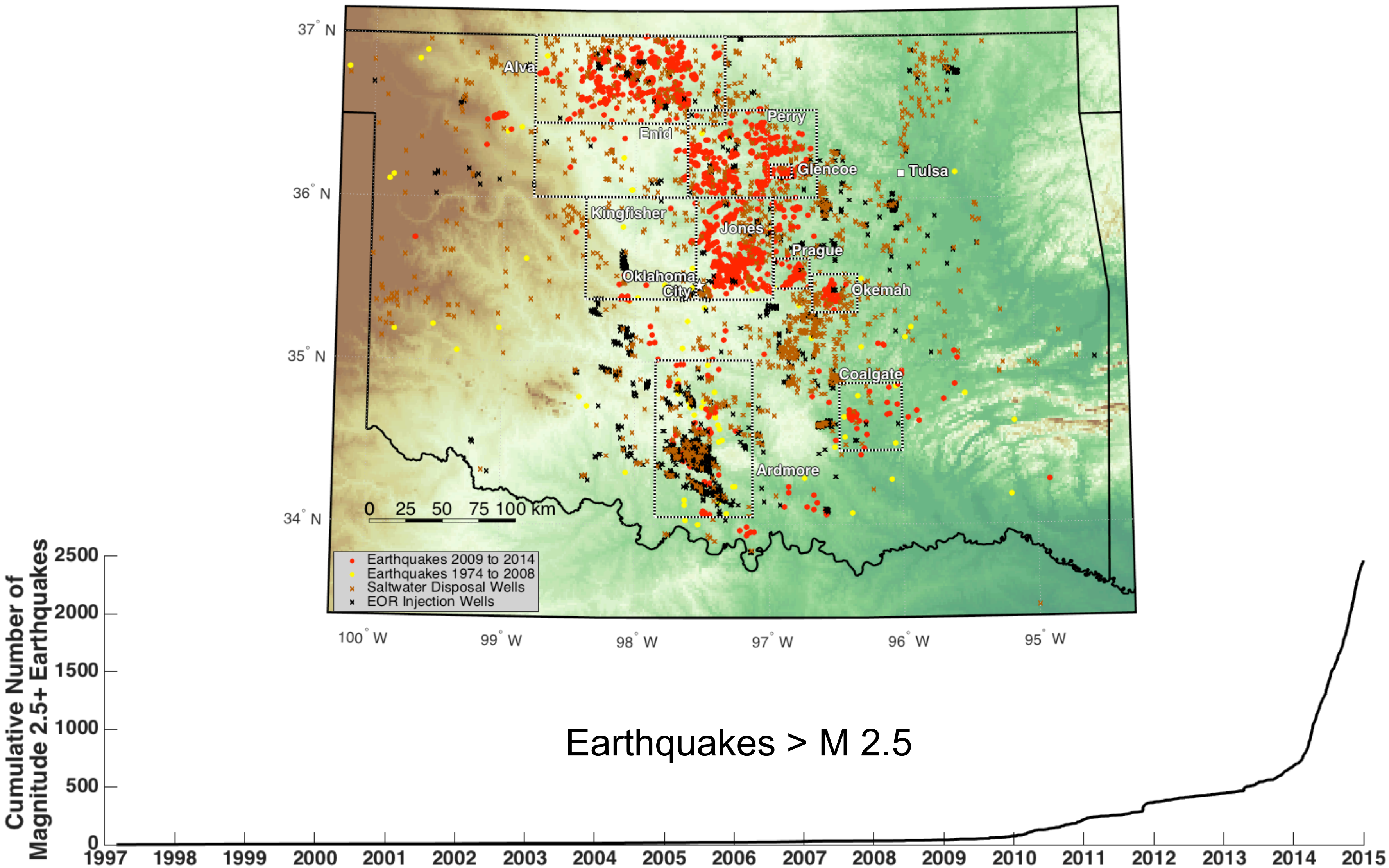


Basement Faults That are *Potentially Active* in the Current Stress Field Are Also *Hydraulically Conductive*



Zoback and Townend (2001)

Recent Oklahoma Seismicity



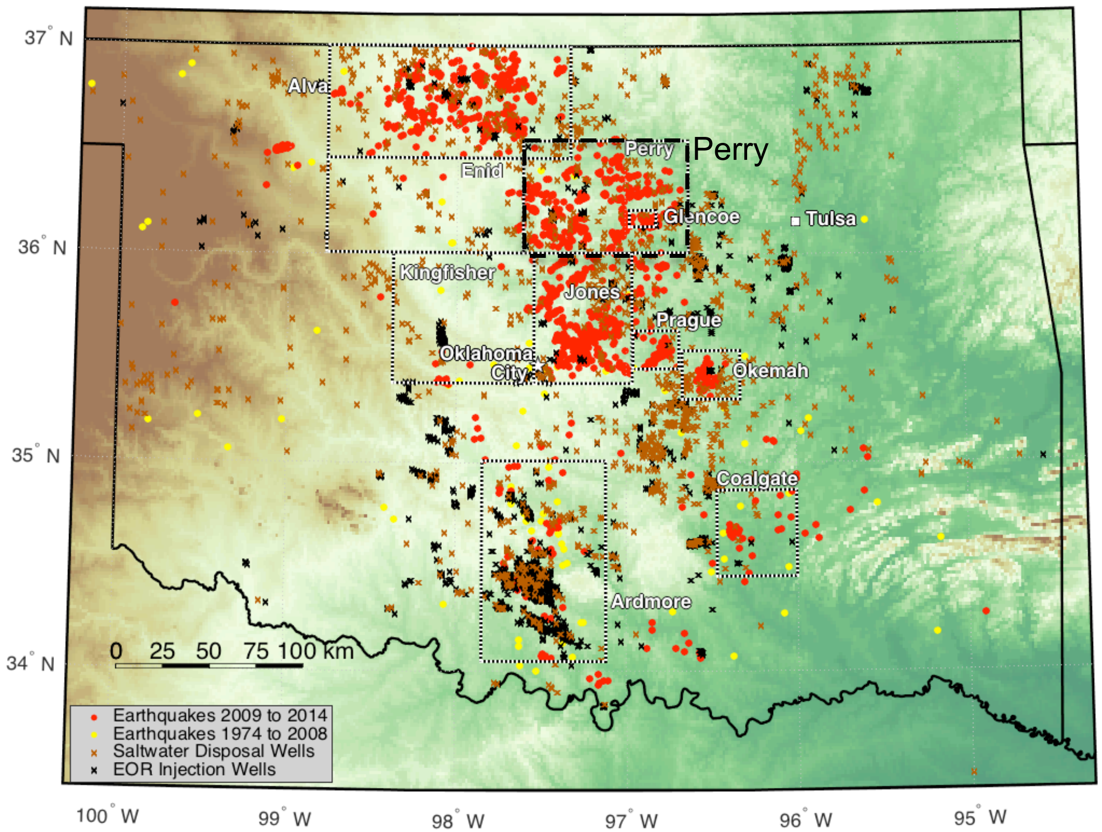
Oklahoma's Recent Earthquakes and Saltwater Disposal

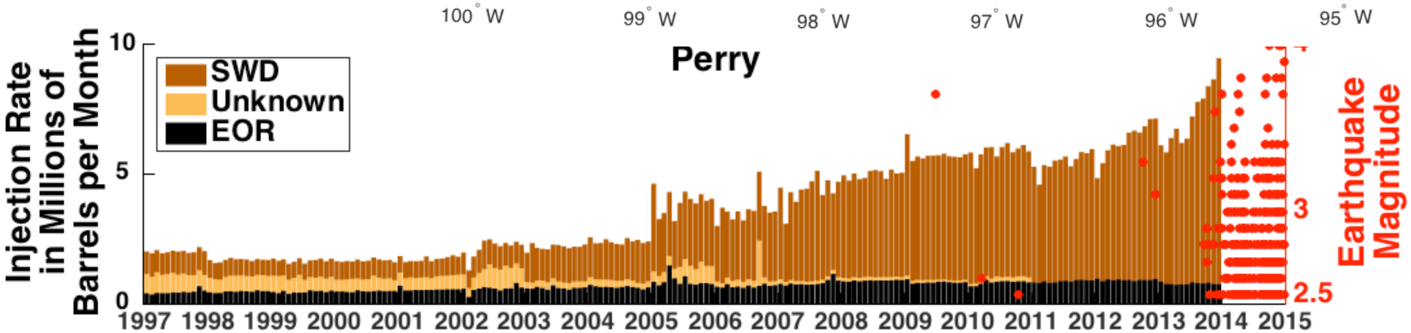
By Rall Walsh and Mark Zoback, submitted to *Science Advances*

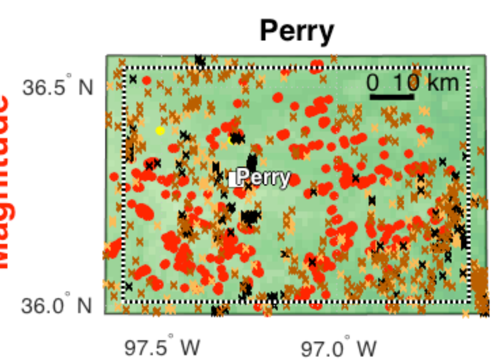
Abstract

Over the past five years, parts of Oklahoma have experienced marked increases in the number of small-to-moderate sized earthquakes. In five study areas that encompass nearly all of the recent seismicity, we show that the increases in seismicity follow five- to ten-fold increases in the rates of saltwater disposal. Adjacent areas where there is relatively little saltwater disposal have had few recent earthquakes. In the areas of 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. These 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 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 significantly reduce the occurrence of triggered seismicity.

Oklahoma Seismicity in the Perry Area







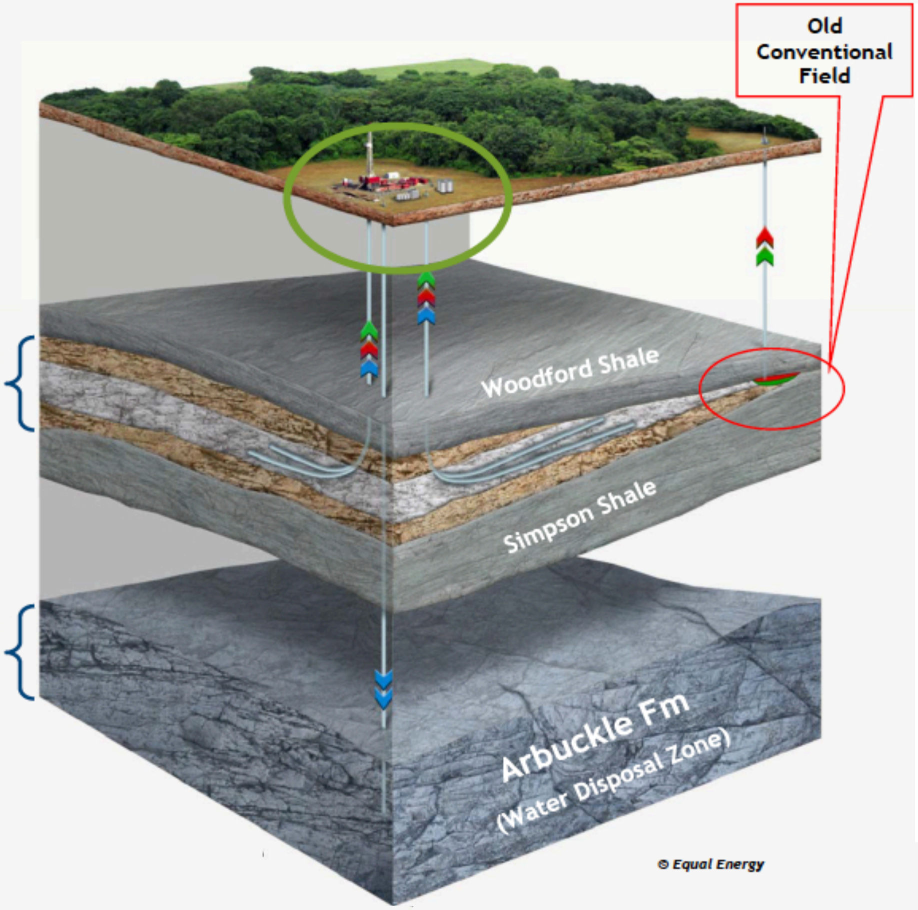
Walsh and Zoback (submitted to Science Advances)

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

Massive Saltwater Production
(~ 50 -100 bbls of water for 1 bbl of oil)

Massive Saltwater Injection
(~120 million bbls/year)

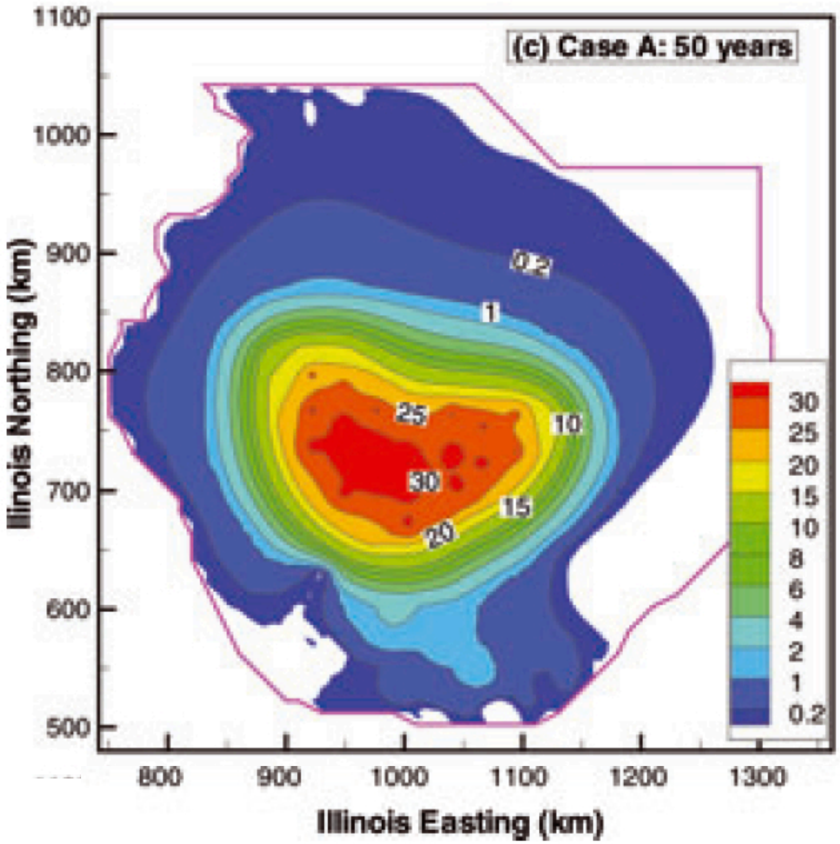


Equal Energy Method

- 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

Equal Energy OKLAHOMA PLAYS BACKGROUNDER October 2011

Flow Rate of the Macondo well



Mt. Simon (simulation)

100 Million Tonnes/Year Injected into 11,000 km^2

Mt. Simon ~400 m thick

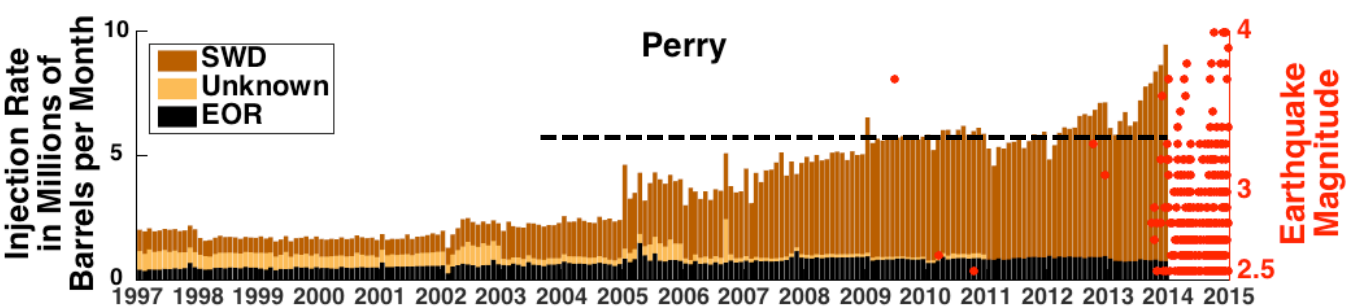
75,000 bbls/year per km^2
(6.3 bbl = 1 m^3, ~8.2 bbls = 1 tonne)

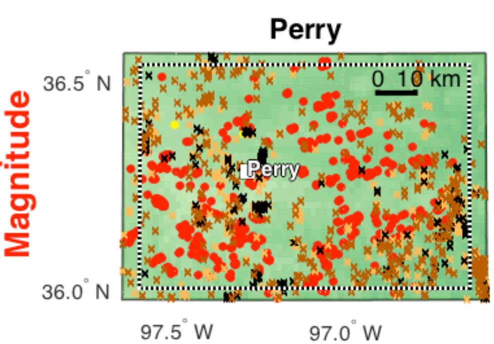
Perry Area (actual)

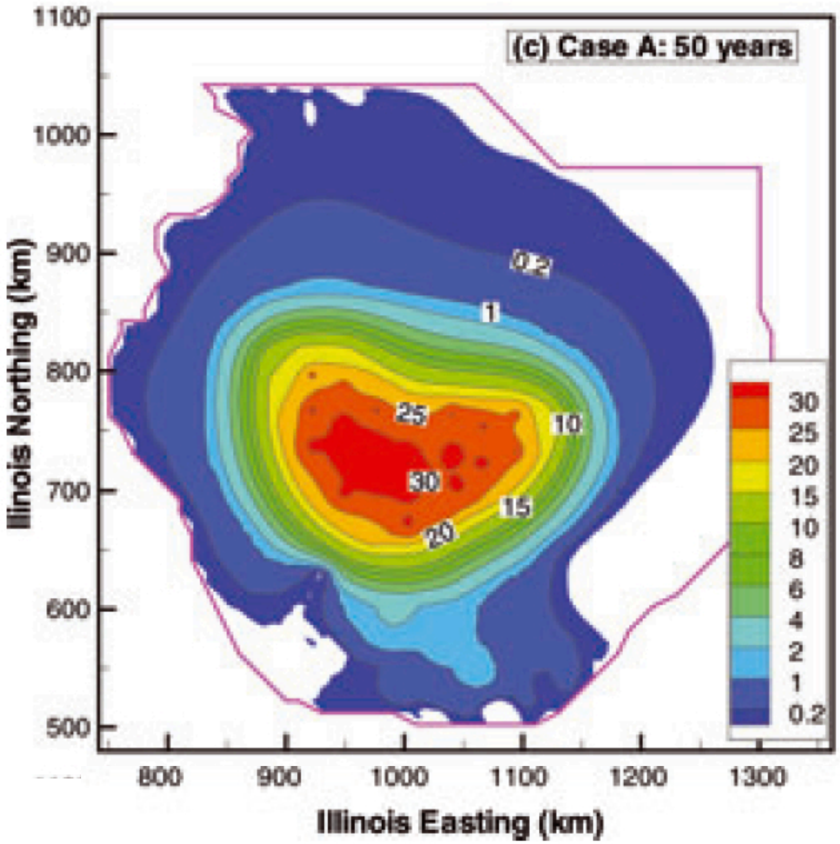
72 Million bbls/year Injected into 5,000 km^2

Arbuckle ~300 m thick

24,000 bbls/year per km^2







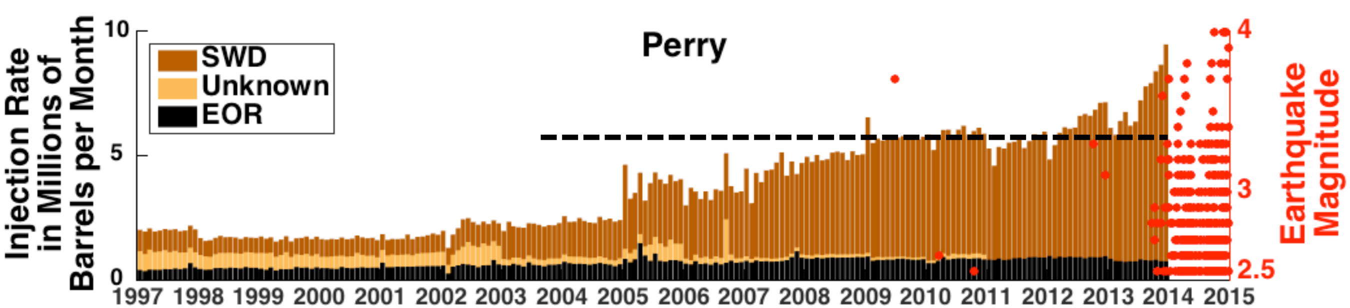
Mt. Simon (simulation)

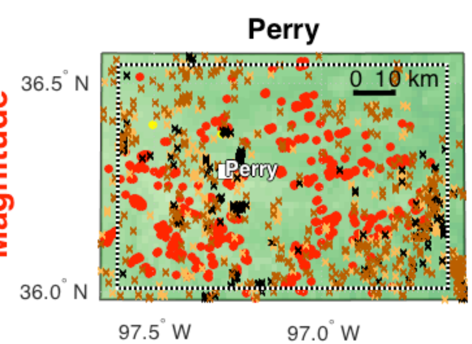
75,000 bbls/year per km^2

Perry Area (actual)

24,000 bbls/year per km^2

At approximately 1/3 of the injection rate assumed by Zhou et al (2010) - which is only 5% of US emissions from coal burning power plants – appreciable seismicity is being triggered by saltwater injection in OK





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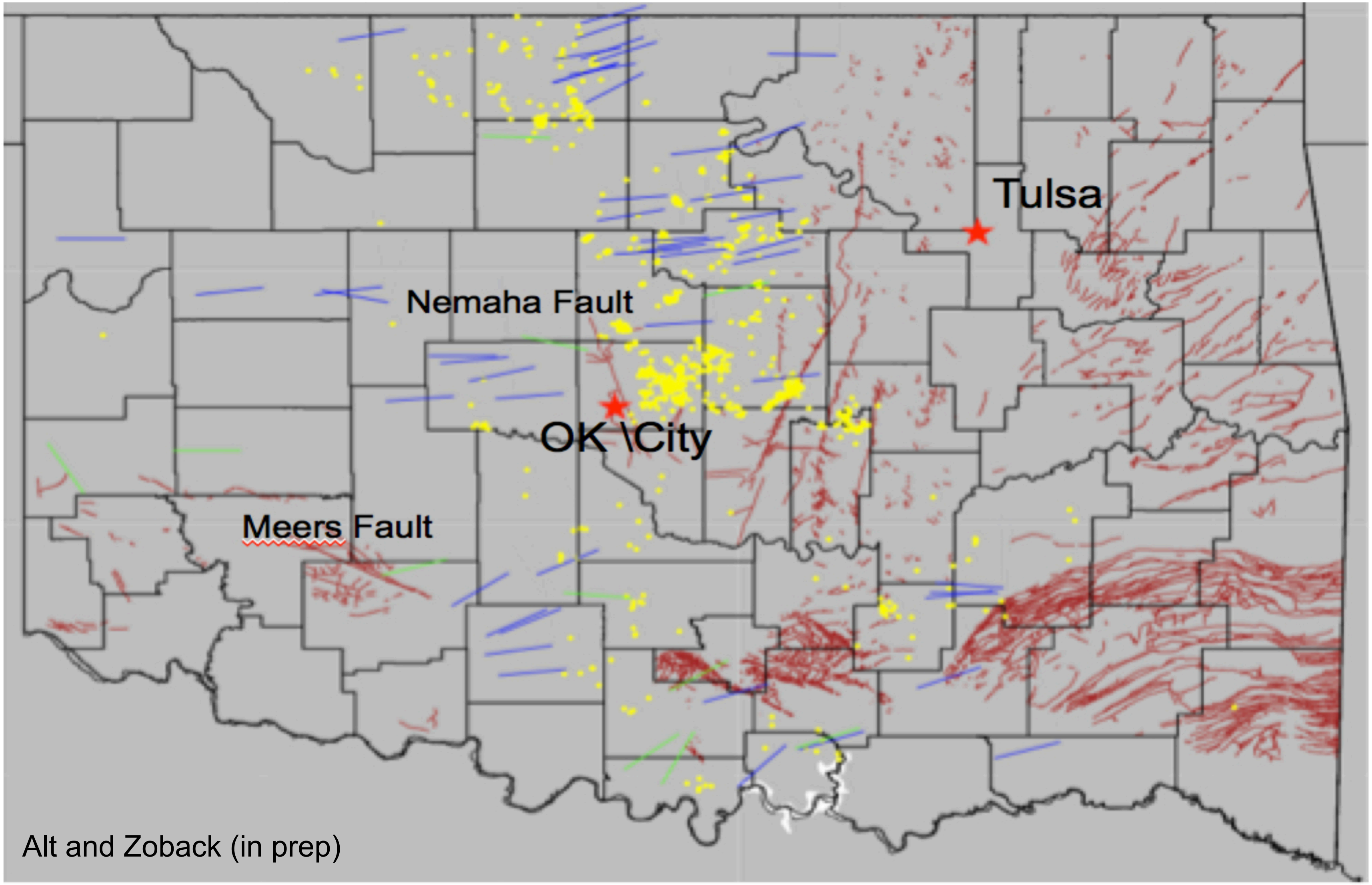
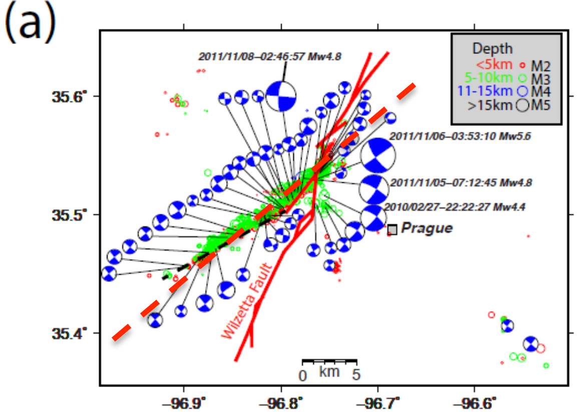
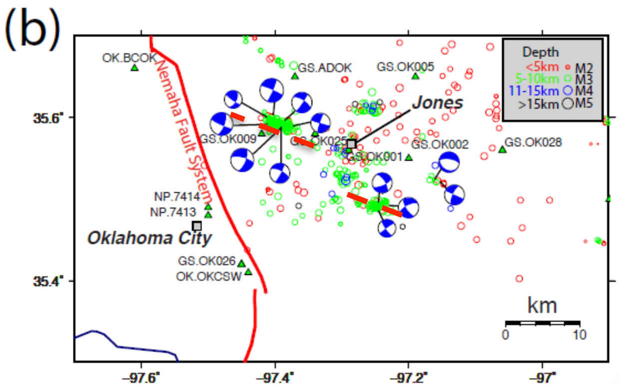
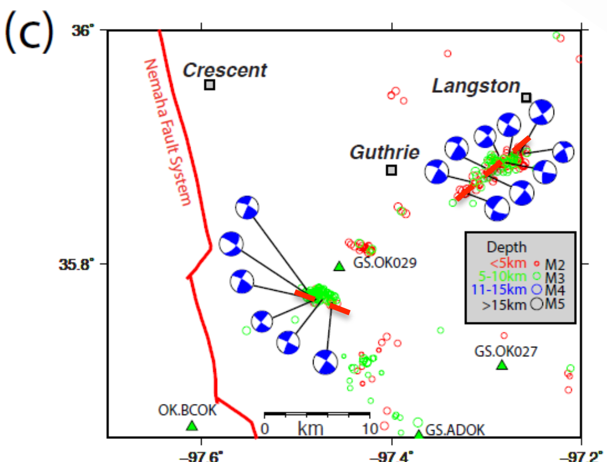
State of Stress in Oklahoma




(a)
Depth
<5km M2
5-10km M3
11-15km M4
>15km M5
2011/11/08-02:46:57 Mw4.8
2011/11/06-03:53:10 Mw5.6
2011/11/05-07:12:45 Mw4.8
2010/02/27-22:22:27 Mw4.4
Prague
Wilzetta Fault
0 km 5
35.6°
35.5°
35.4°
-96.9°
-96.8°
-96.7°
-96.6°


(b)
Depth
<5km M2
5-10km M3
11-15km M4
>15km M5
OK.BCOK
GS.ADOK
GS.OK005
Jones
Nemaha Fault System
GS.OK009
GS.OK025
GS.OK001
GS.OK002
GS.OK028
NP.7414
NP.7413
Oklahoma City
GS.OK026
OK.OKCSW
km
0
10
35.6°
35.4°
-97.6°
-97.4°
-97.2°
-97°


(c)
36°
Crescent
Langston
Guthrie
Nemaha Fault System
GS.OK029
Depth
<5km M2
5-10km M3
11-15km M4
>15km M5
GS.OK027
OK.BCOK
0 km 10
GS.ADOK
35.8°
-97.6°
-97.4°
-97.2°

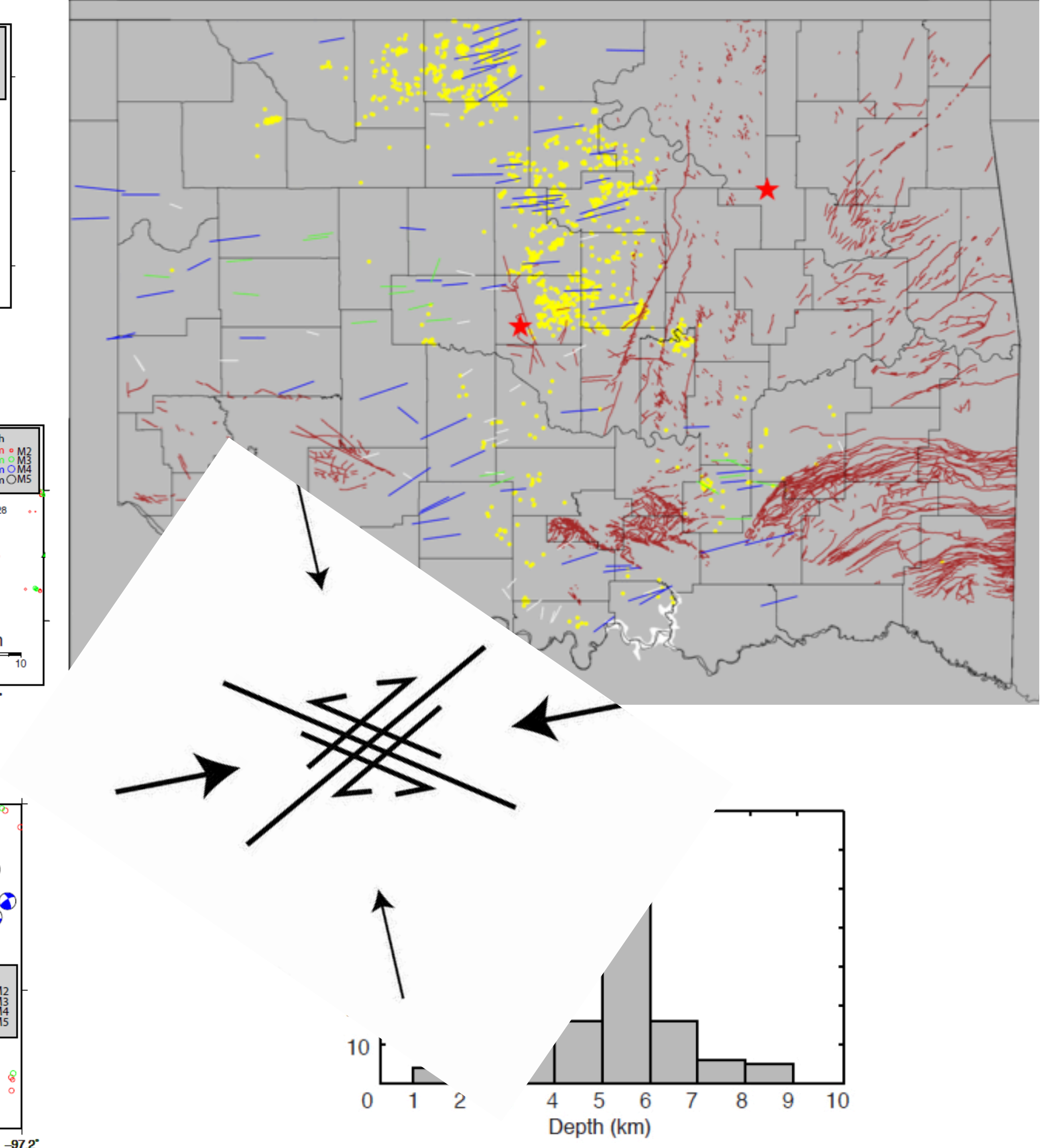

10
0
1
2
4
5
6
7
8
9
10
Depth (km)

Table 1
Model Parameters for the Single-Phase and Two-Phase Flow in the Five Cases of Sensitivity Analysis

Case	Units	ϕ	k_h (10^{-15}m^2)	k_v (10^{-15}m^2)	β_p (10^{-10}Pa^{-1})	α^{-1} (10^5Pa)	m	S_{rb}	S_{rg}
A	EC	0.15	0.001	0.001	7.42	50.0	0.41	0.40	0.30
	CI_MS1	0.062–0.130	4.8–286	4.8–286	3.71	0.064–0.79	0.41	0.30	0.25
	CI_MS2	0.083–0.163	5.2–873	52–873	3.71	0.045–0.41	0.41	0.30	0.25
	CI_MS3	0.139–0.203	174–1000	174–1000	3.71	0.040	0.41	0.25	0.20
	CI_MS4	0.095	22.6	22.6	3.71	0.21	0.41	0.30	0.25
	NF_MS	0.12	100	100	3.71				
	FF_MS	0.16	500	500	3.71				
	PC	0.05	0.0001	0.0001	7.42	100.0	0.41	0.40	0.30

(Zhou et al. GROUND WATER 48, no. 4: 494–514, 2010)