Yes.

Humans Really Are Causing Earthquakes…

USGS science for a changing world

Justin Rubinstein | Earthquake Science Center

Yes.

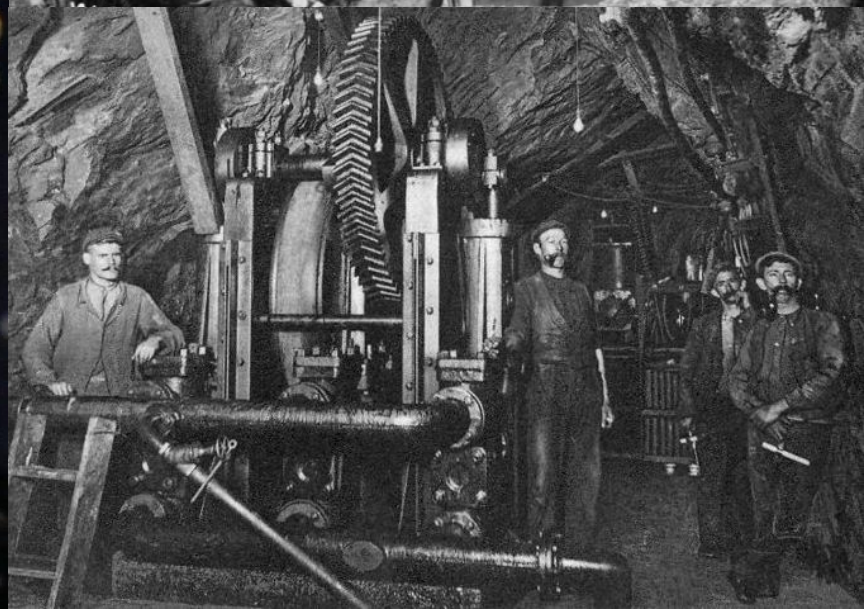
Humans Really Are Causing Earthquakes…

But not in the way you think...

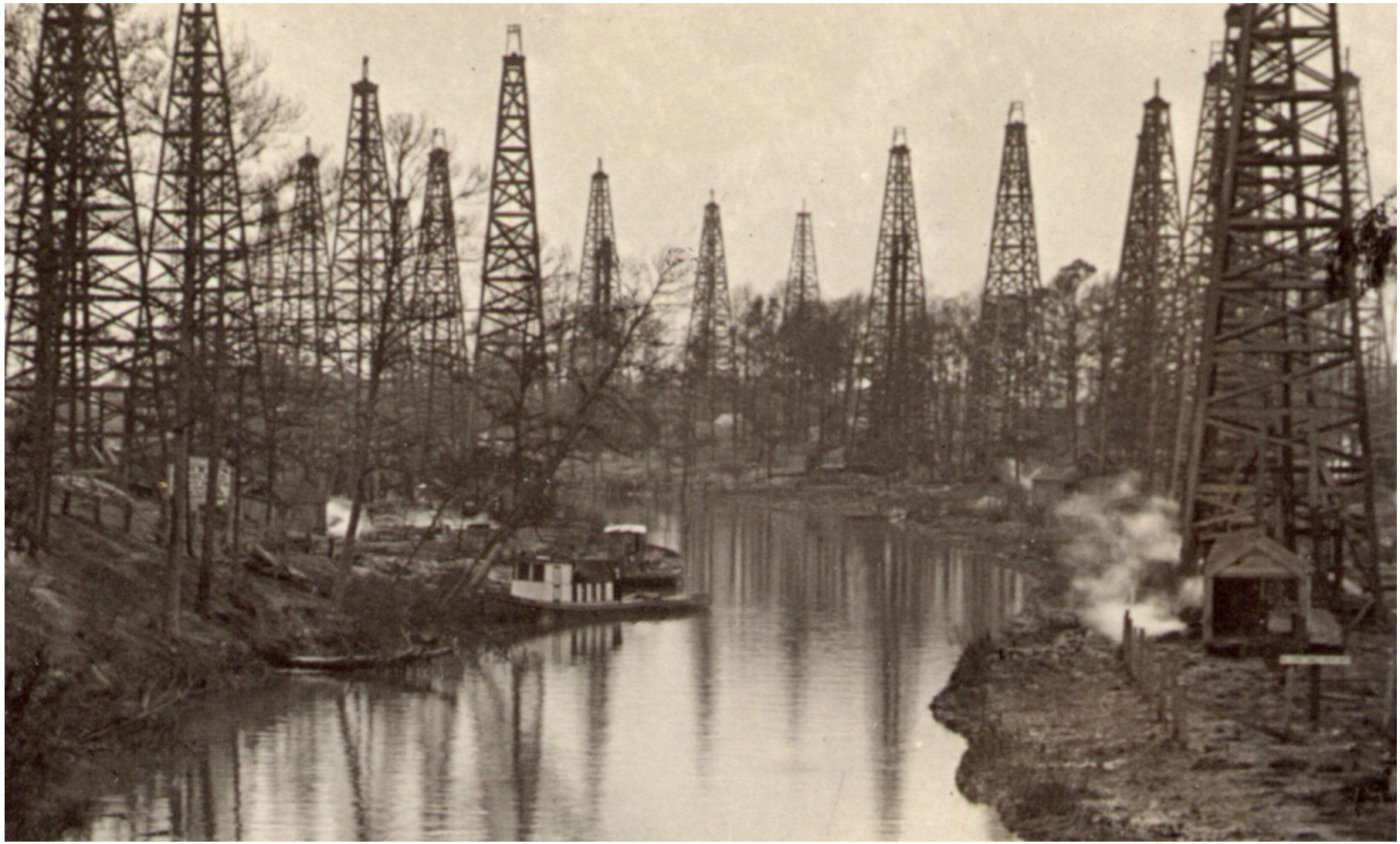
Johannesburg, 1894

First, known, **induced** earthquakes occur

- 1908 Bochum seismological laboratory
- 1920 Silesia Coal Basin seismic monitoring



Goose Creek, Texas (1925)



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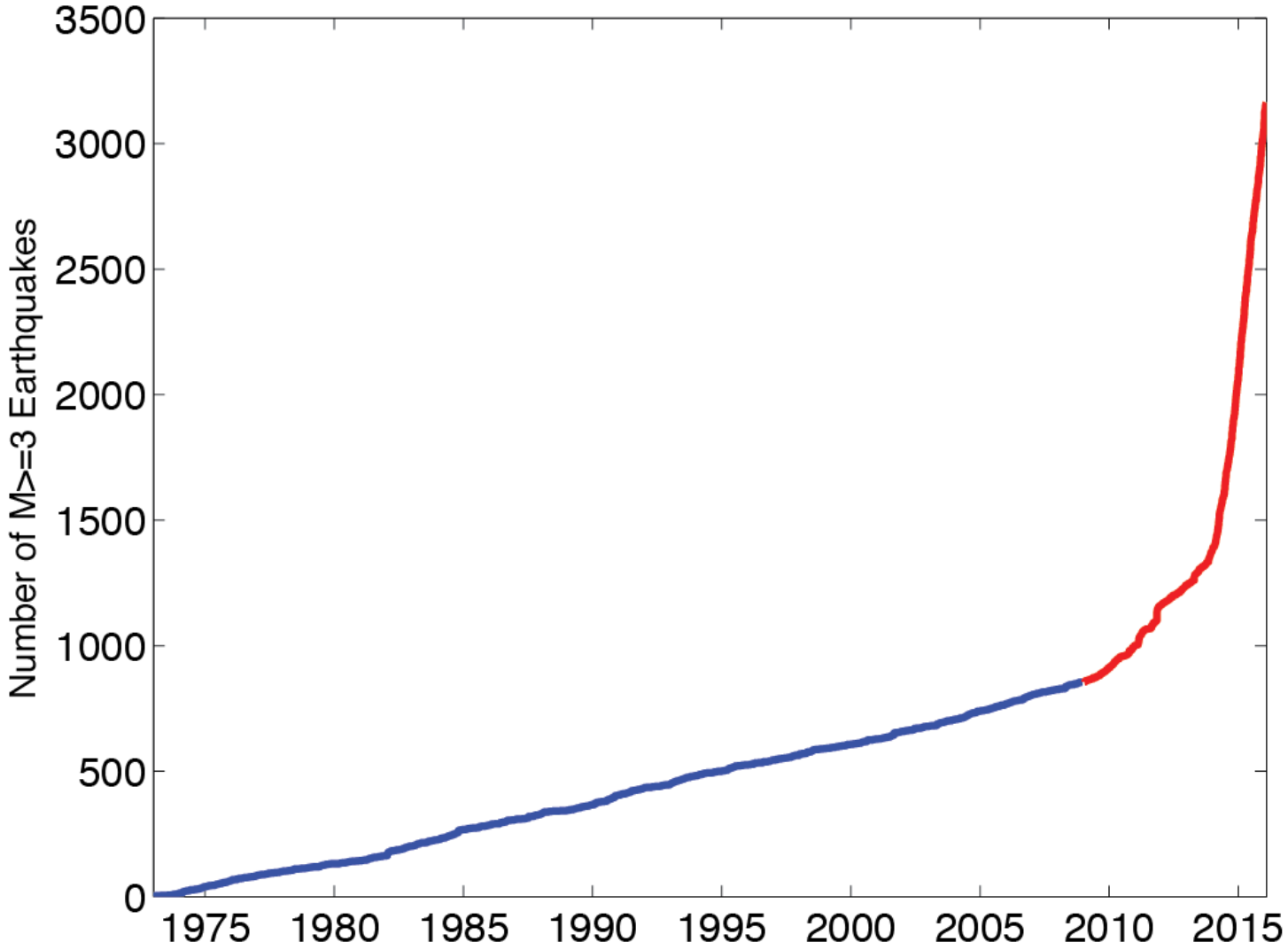
Lake Mead (1935)

Characteristics of Induced EQs

- Spatial Correlation
- Temporal Correlation
- Near surface

NOT HARD AND FAST RULES

Why are Induced Earthquakes Suddenly an Issue?

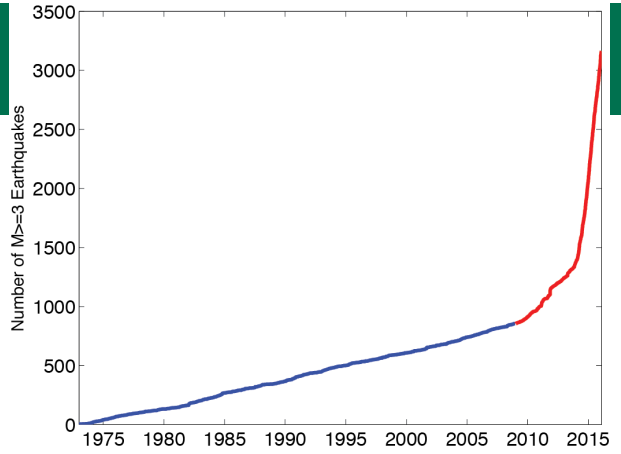


Why are Induced Earthquakes Suddenly an Issue?

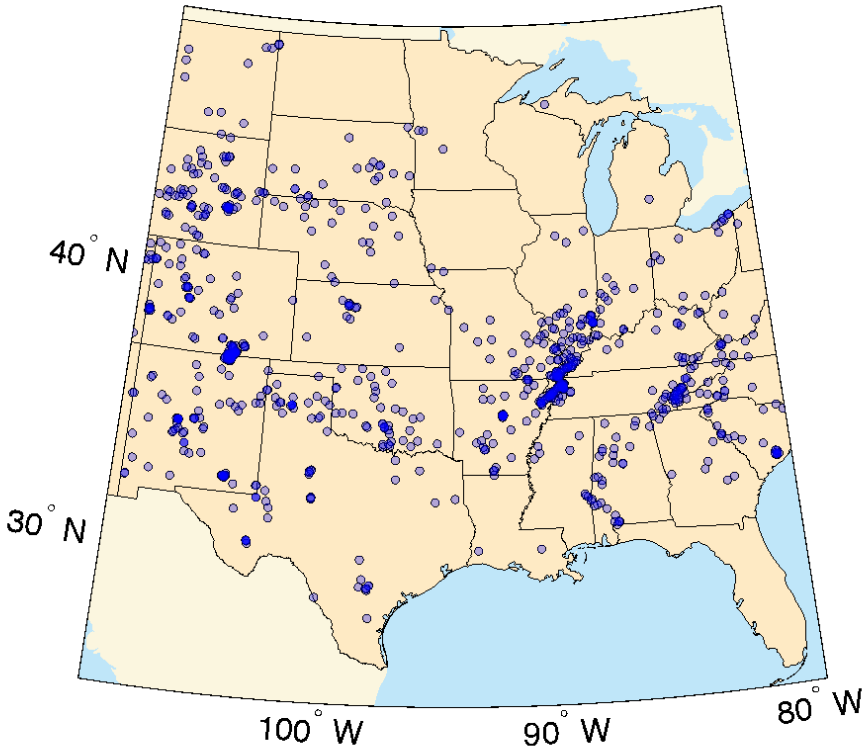
Damage from M5.3 Trinidad, CO Earthquake

Damage from M5.6 Prague, OK Earthquake

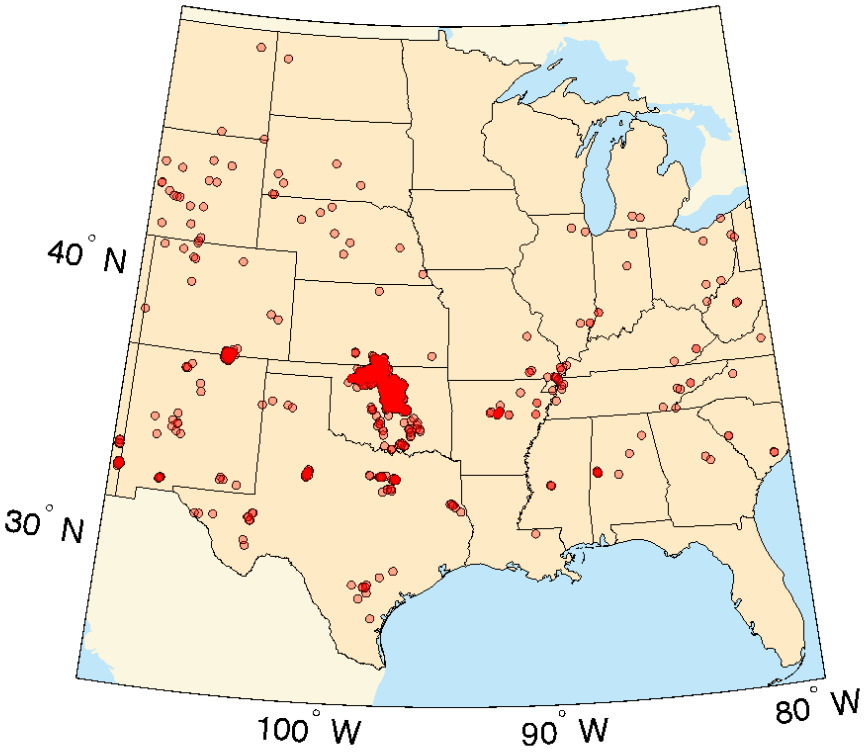
Earthquakes in the Central US



1973 - 2008



2009 – Jan 31, 2016

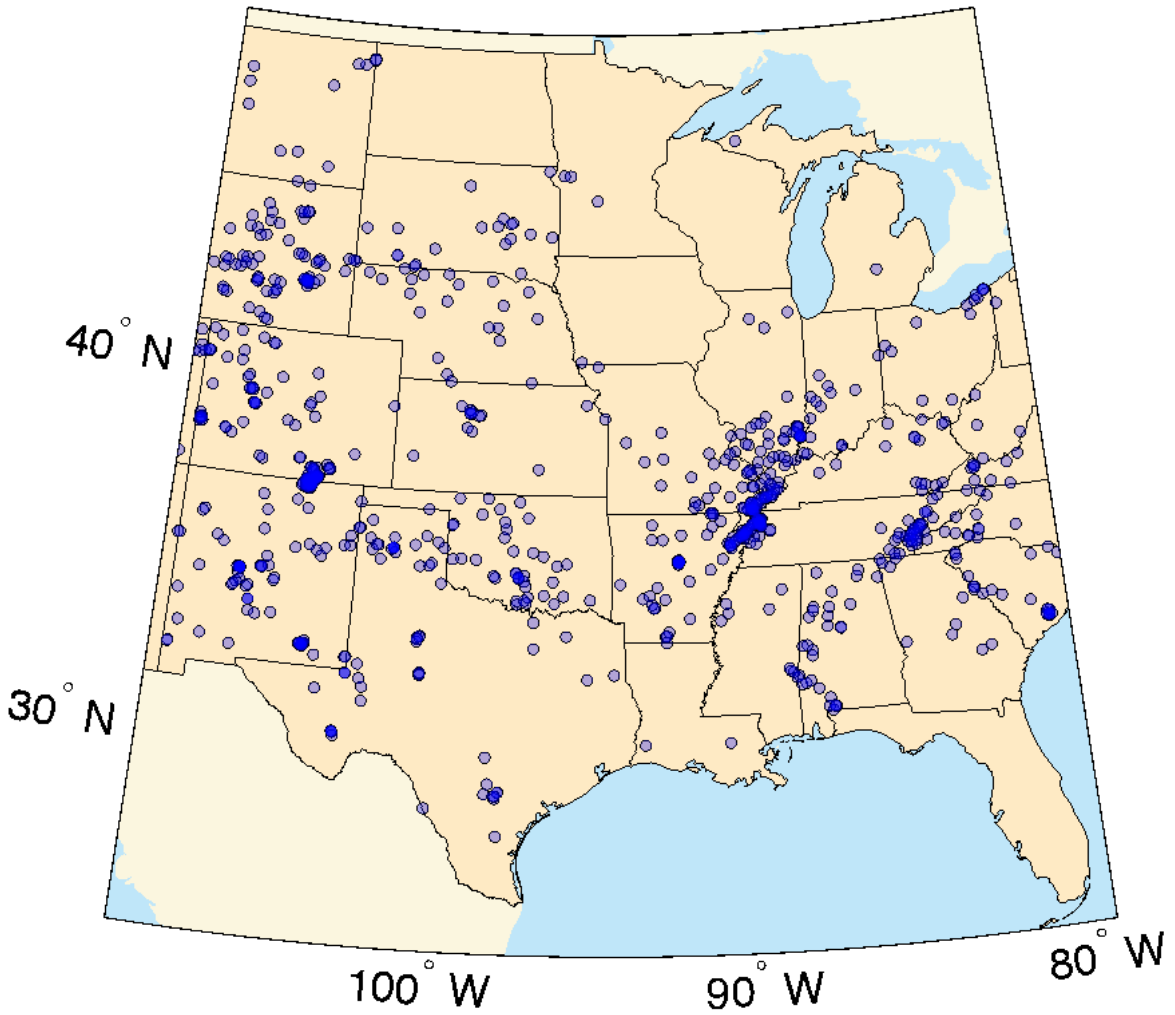


Earthquakes in the Central and Eastern United States

1974 – 2008

855 M>=3 Earthquakes

~24 EQ/yr

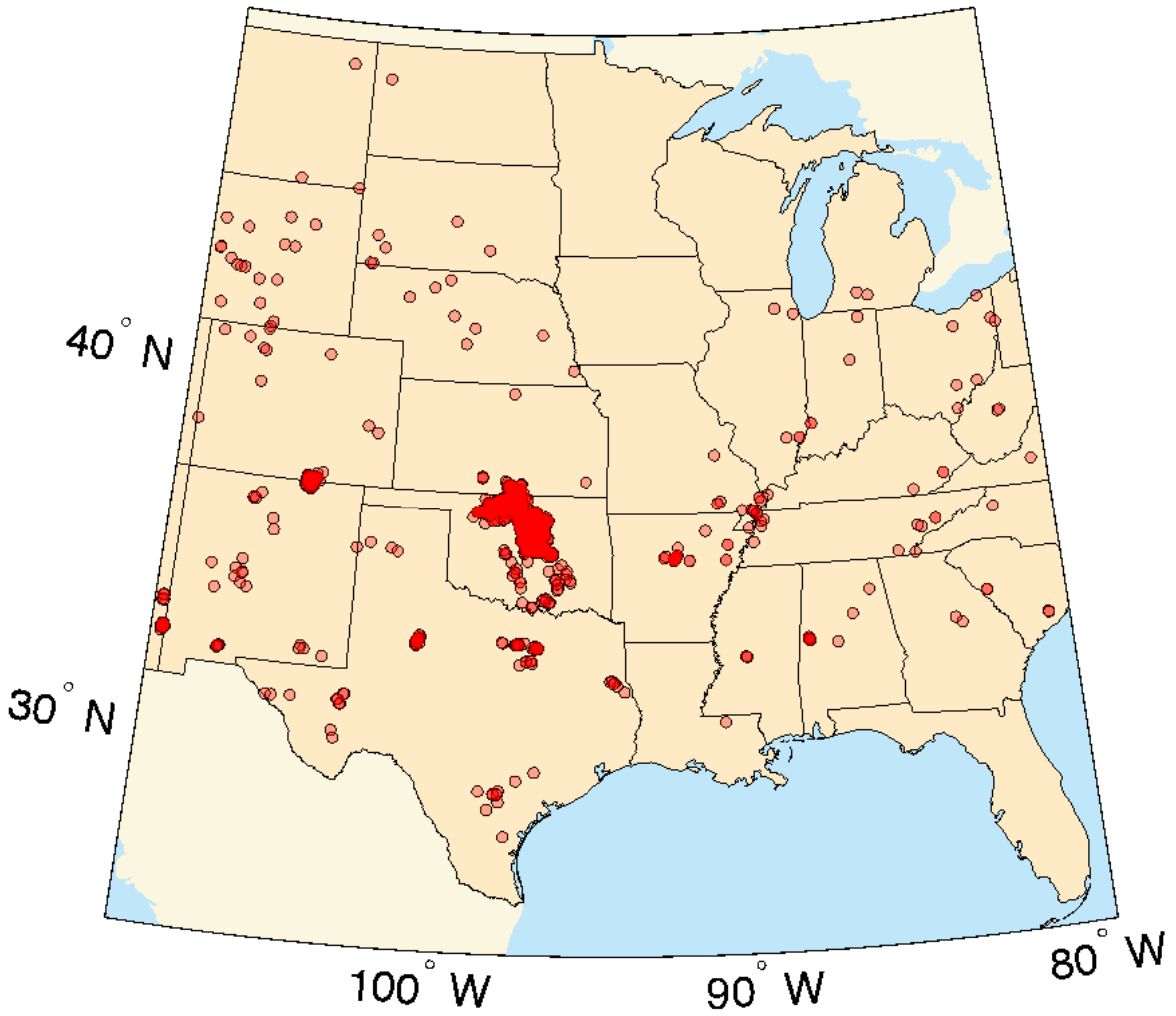


Earthquakes in the Central and Eastern United States

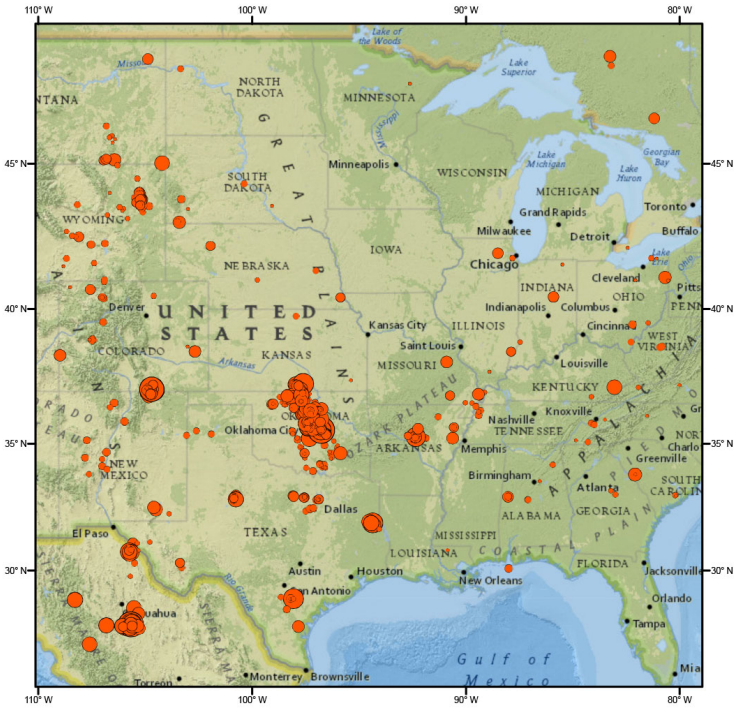
2009 – 1/31/16

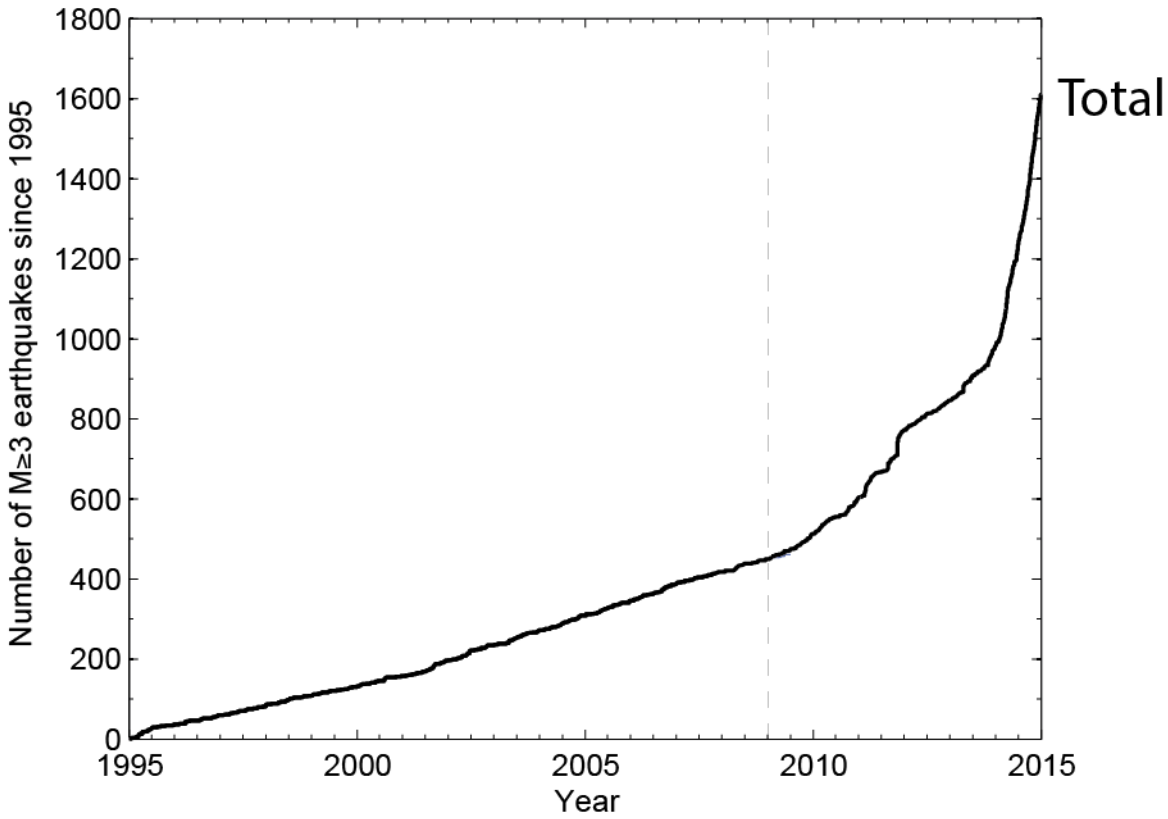
2310 M>=3 Earthquakes

~326 EQ/yr



Rate increase is limited to a few areas





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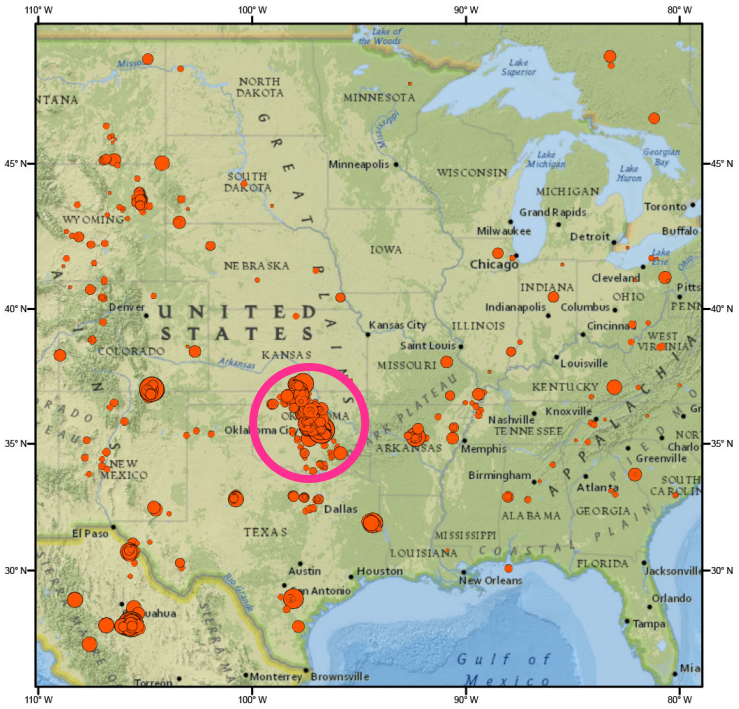

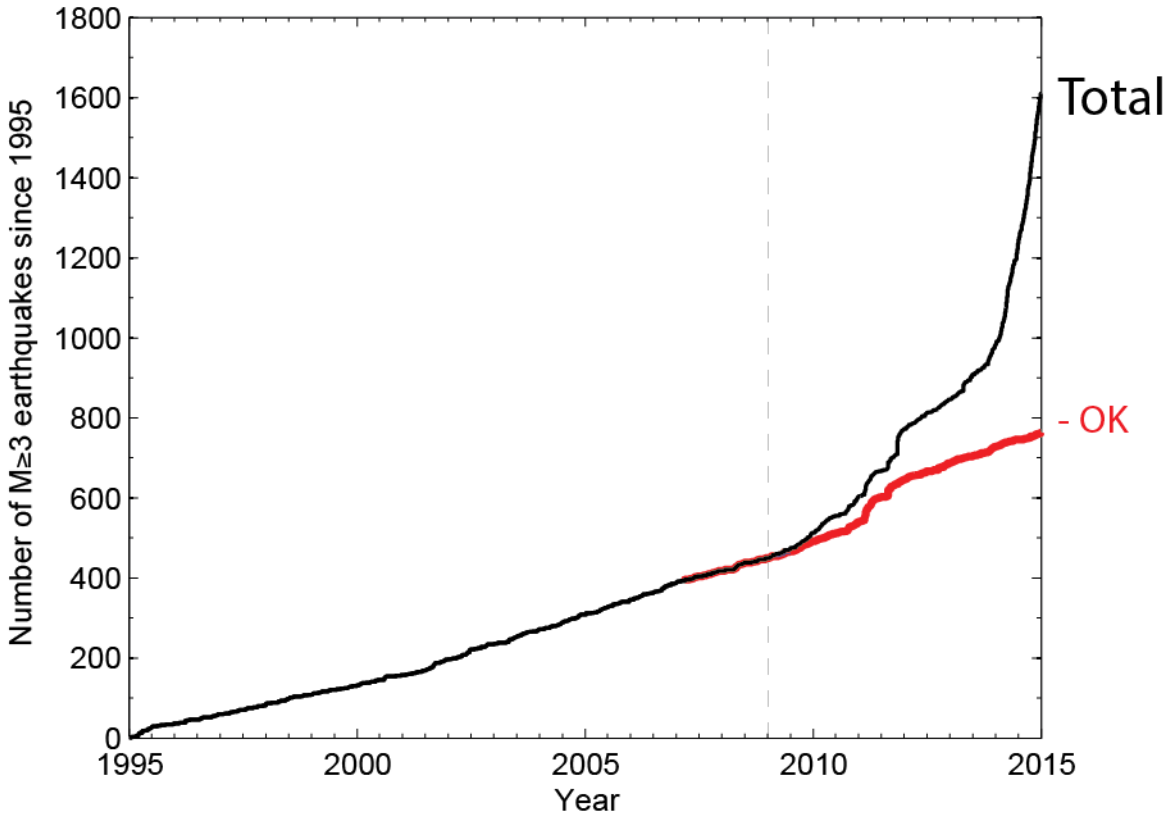

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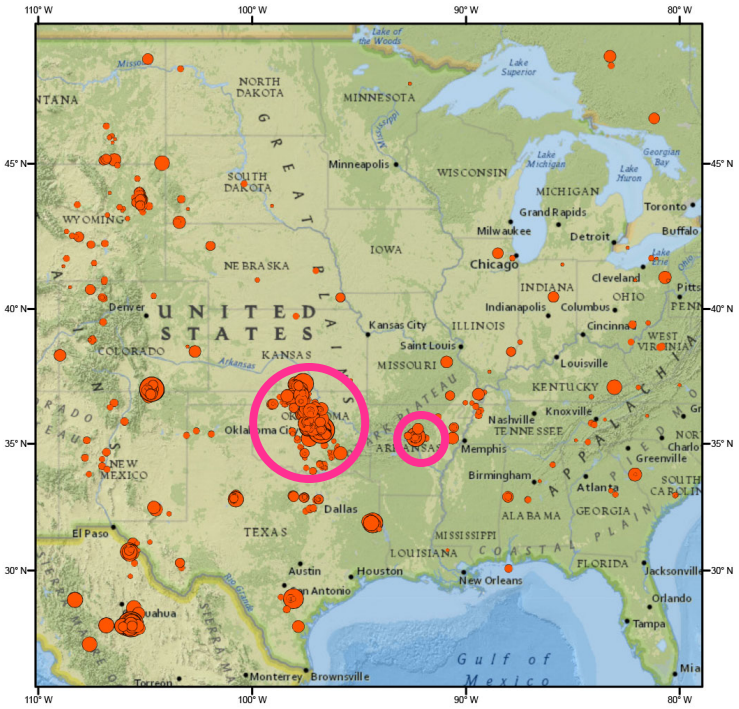

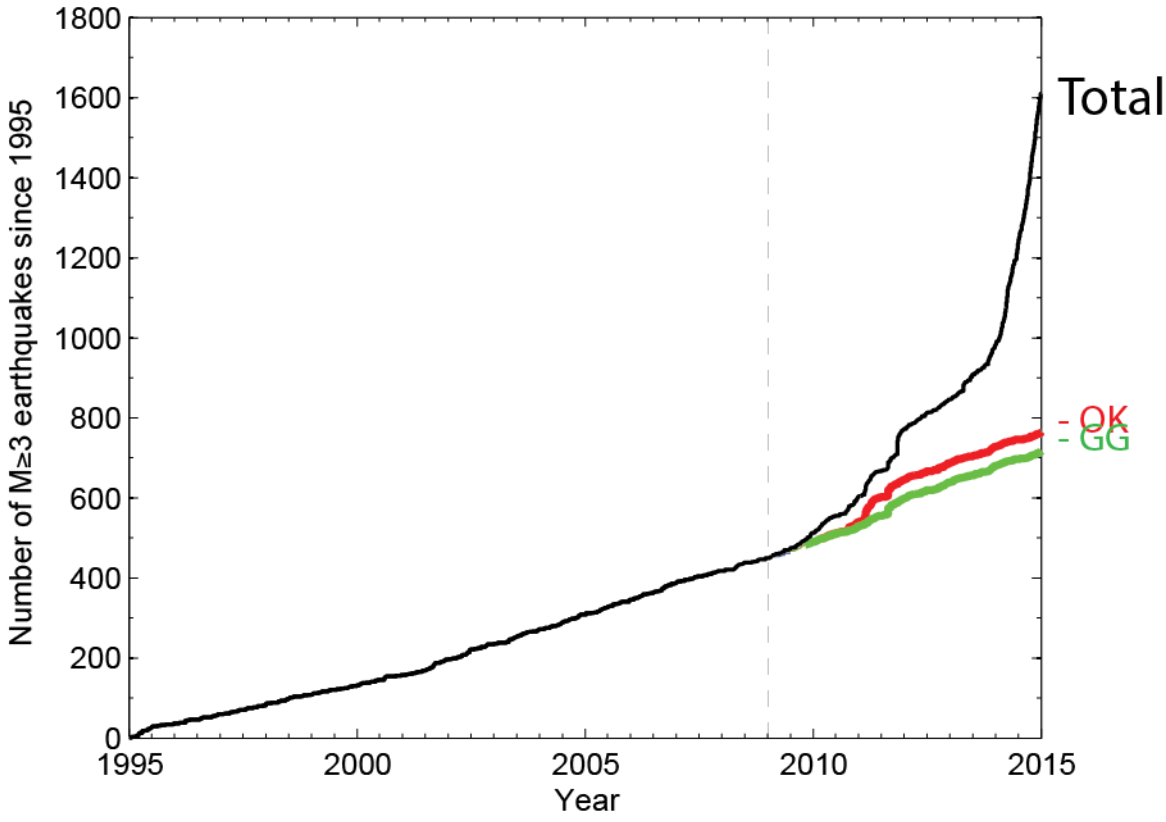

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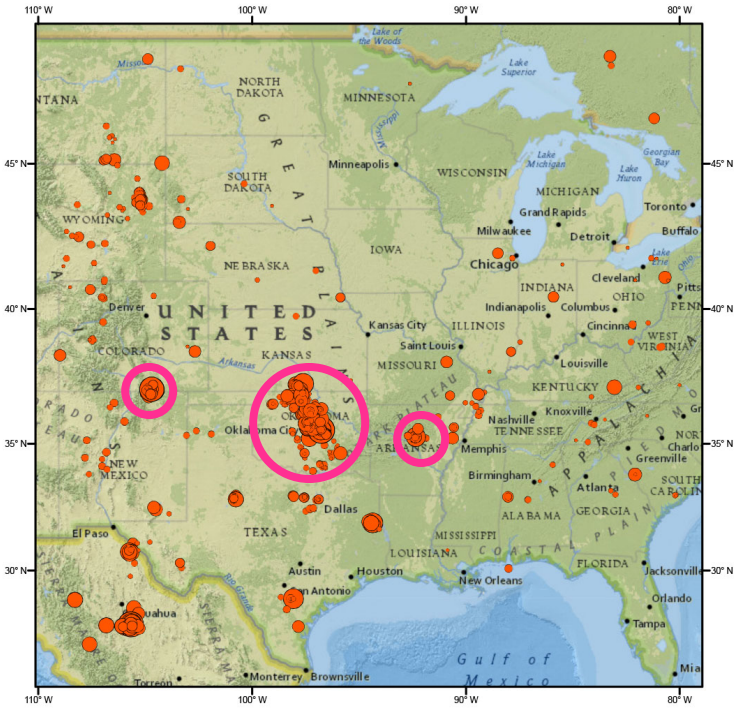

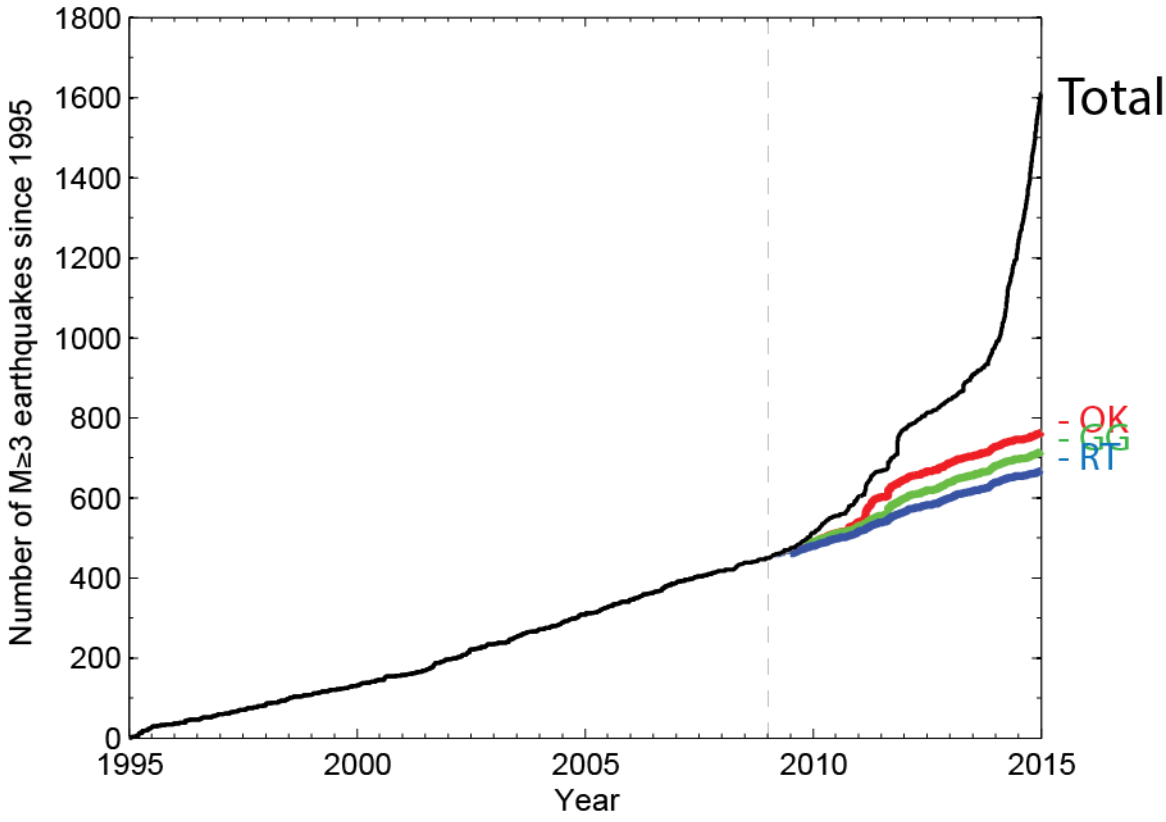

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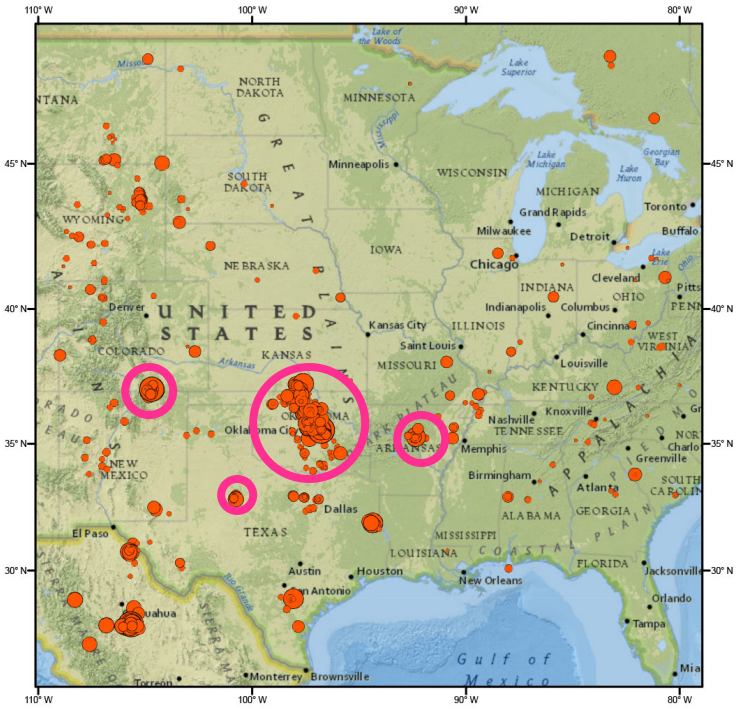

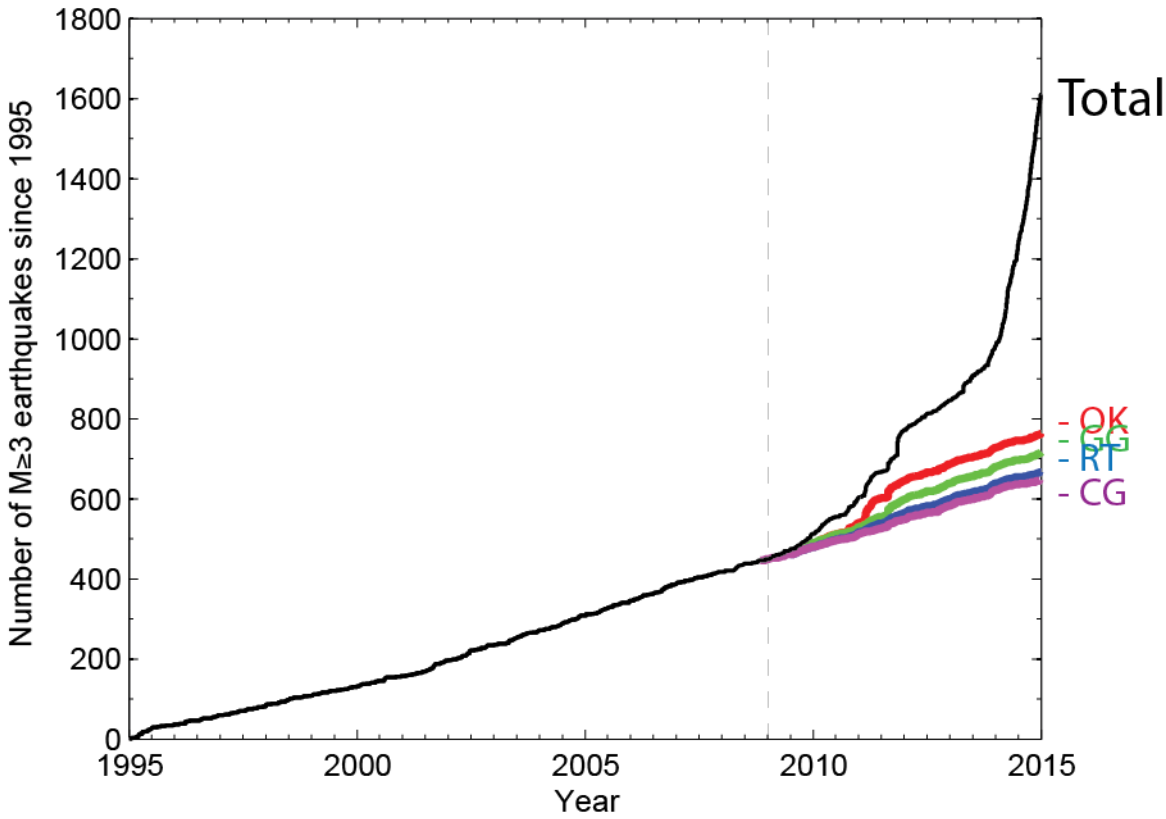

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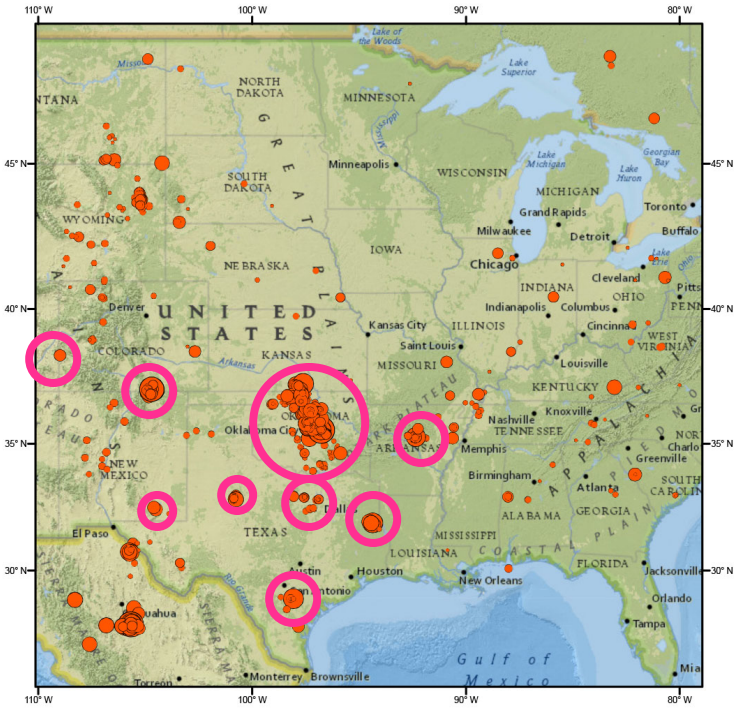
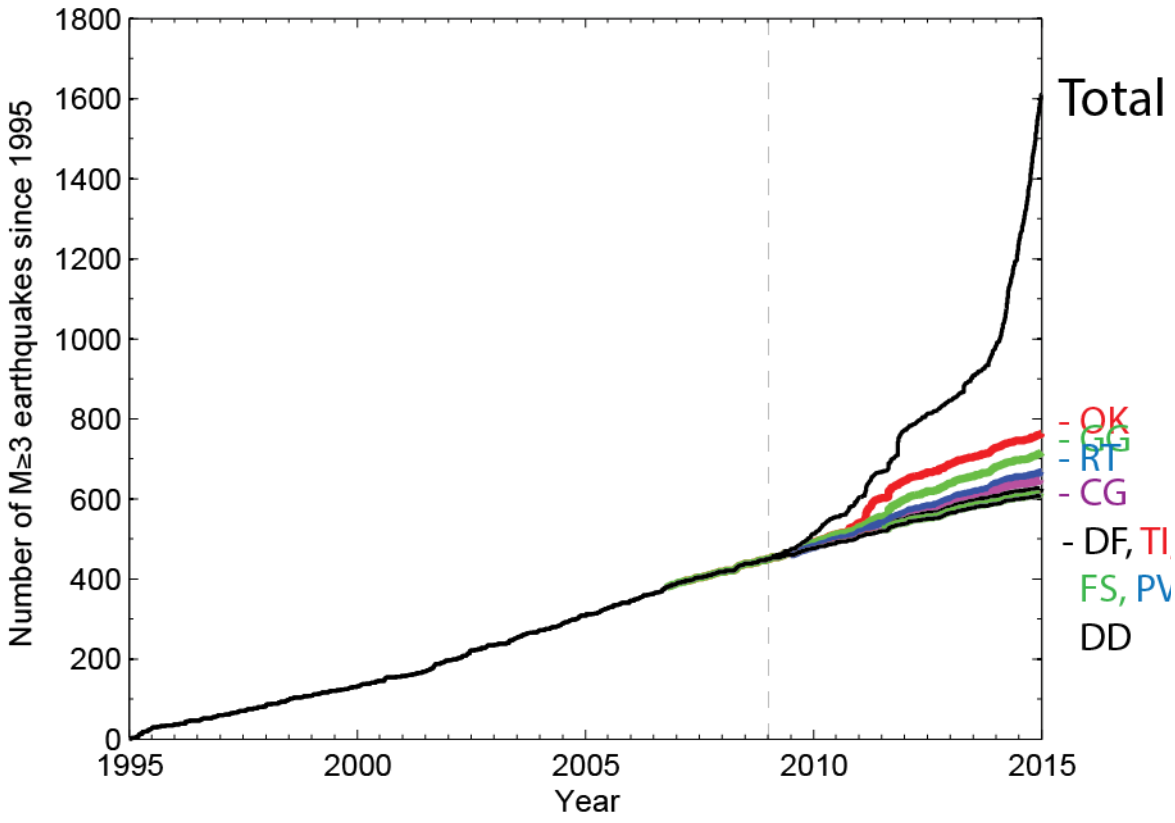
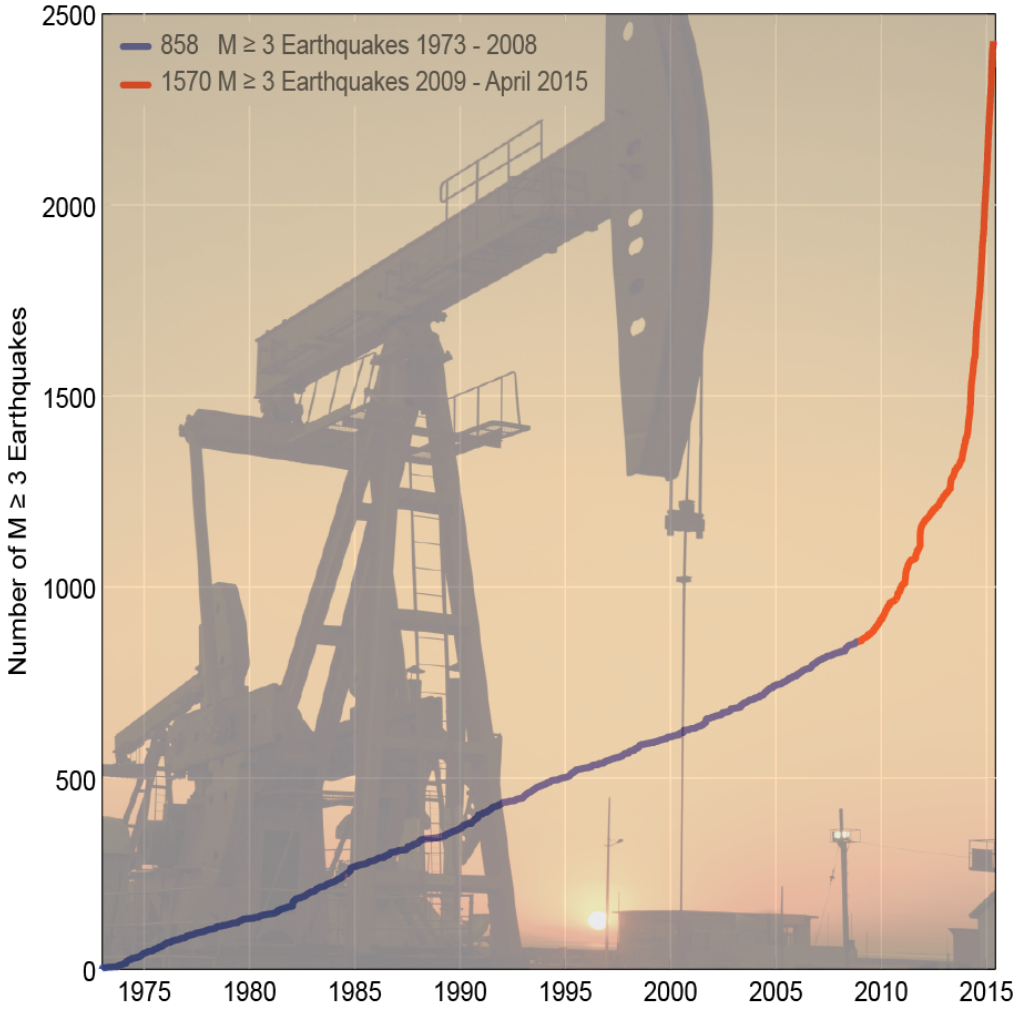




Earthquakes are Being Caused by Oil and Gas Operations



Different O&G Operations

Hydraulic Fracturing

M_{max} ~4.6

Oil Production (extraction)

M_{max} 7.0

Different O&G Operations

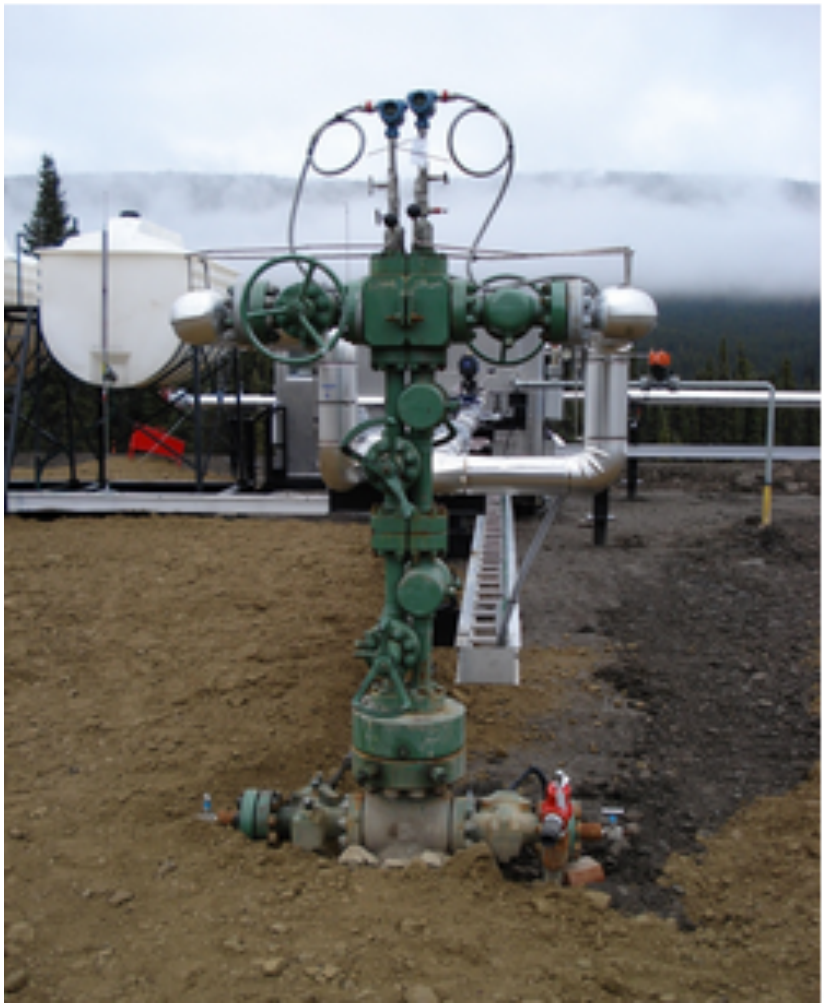
Wastewater Disposal

M_{max} 5.6

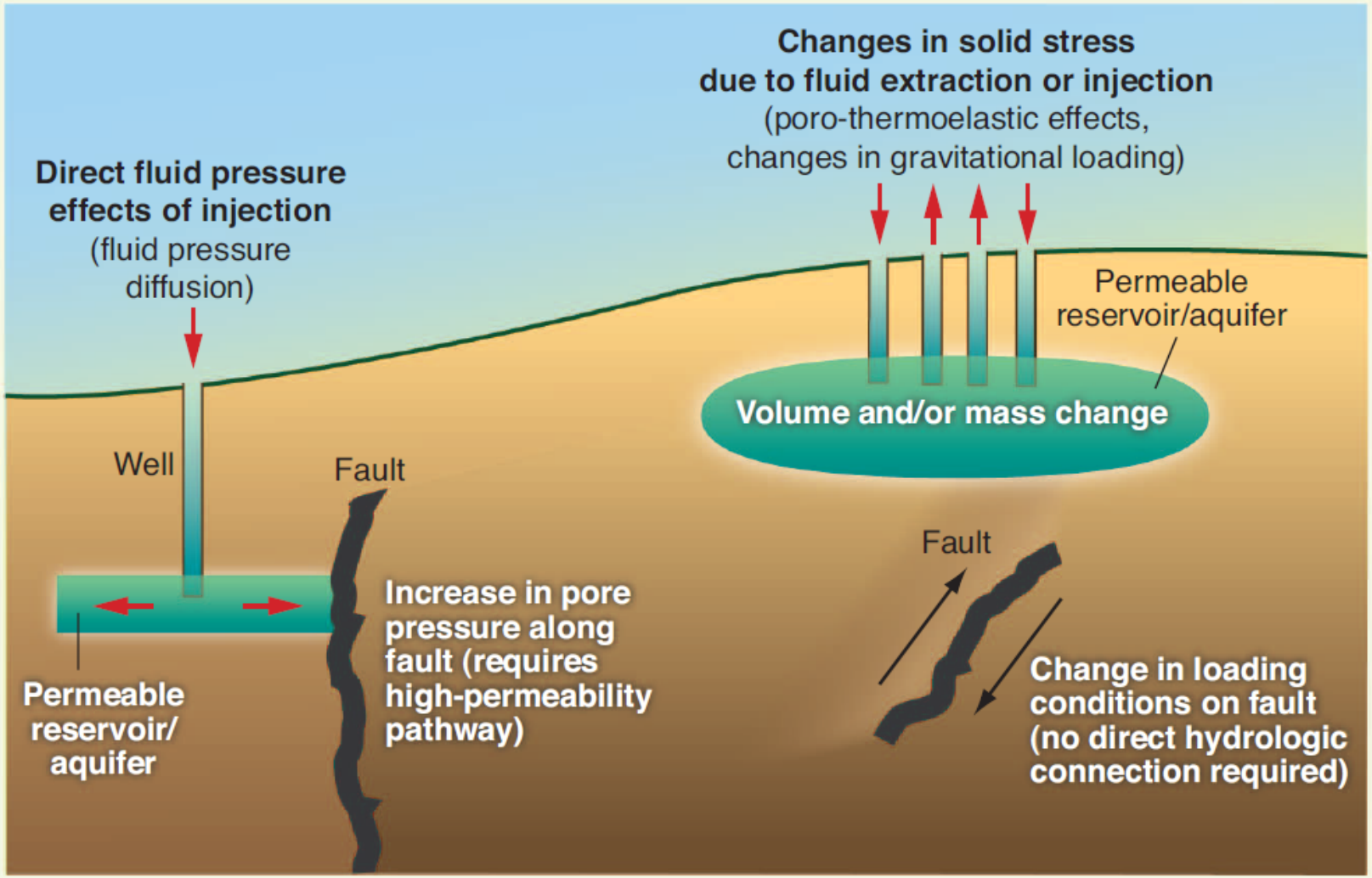
Different O&G Operations

Wastewater Disposal
M_{max} 5.6

Enhanced Oil Recovery
M_{max} 4.5

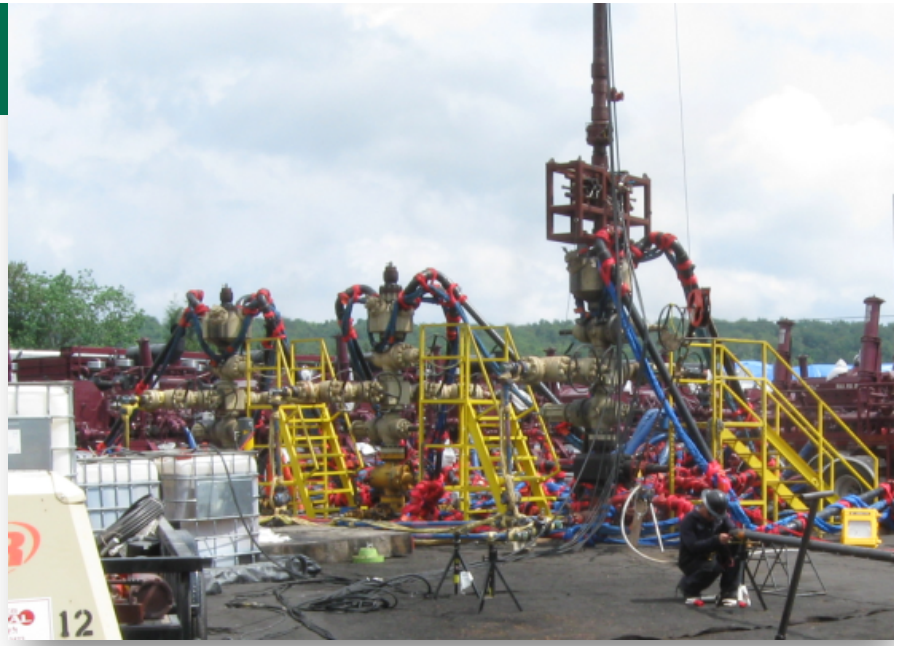


How Do These Operations Cause Earthquakes?



What is Hydraulic Fracturing?

- Invented in 1947
- Making Earthquakes!
  - Very small: -2≤M≤1
- High pressure injection to increase permeability
- Short duration (hours)
- ~60,000 bbls/well
- Well goes into production



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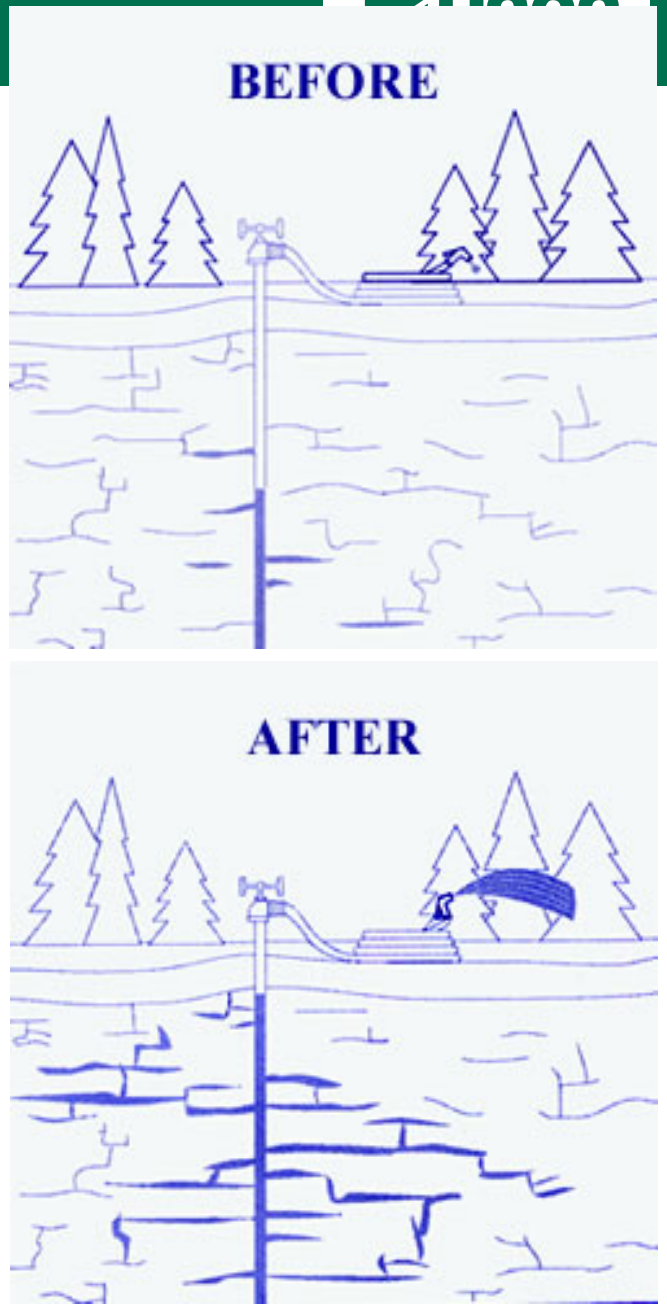

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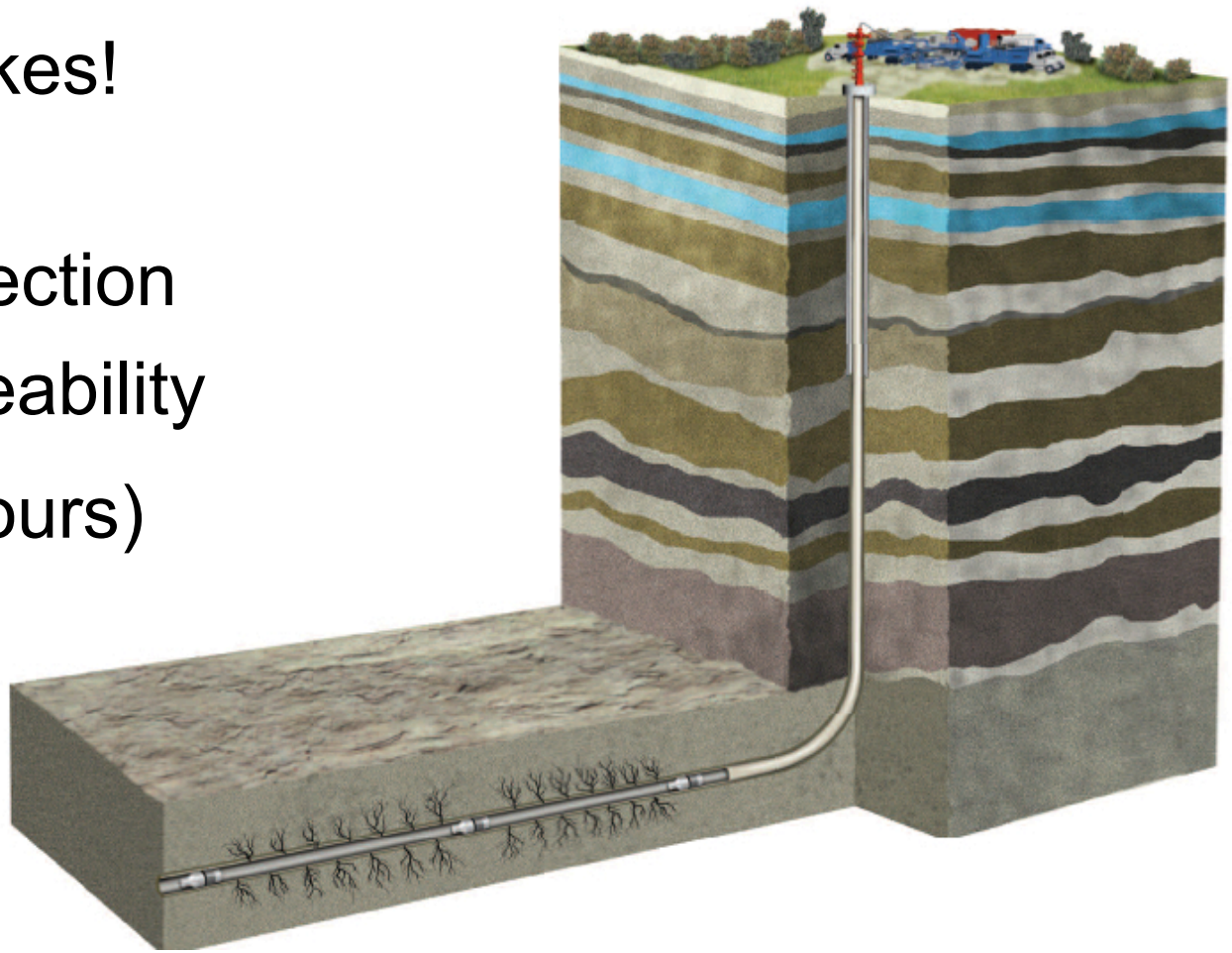
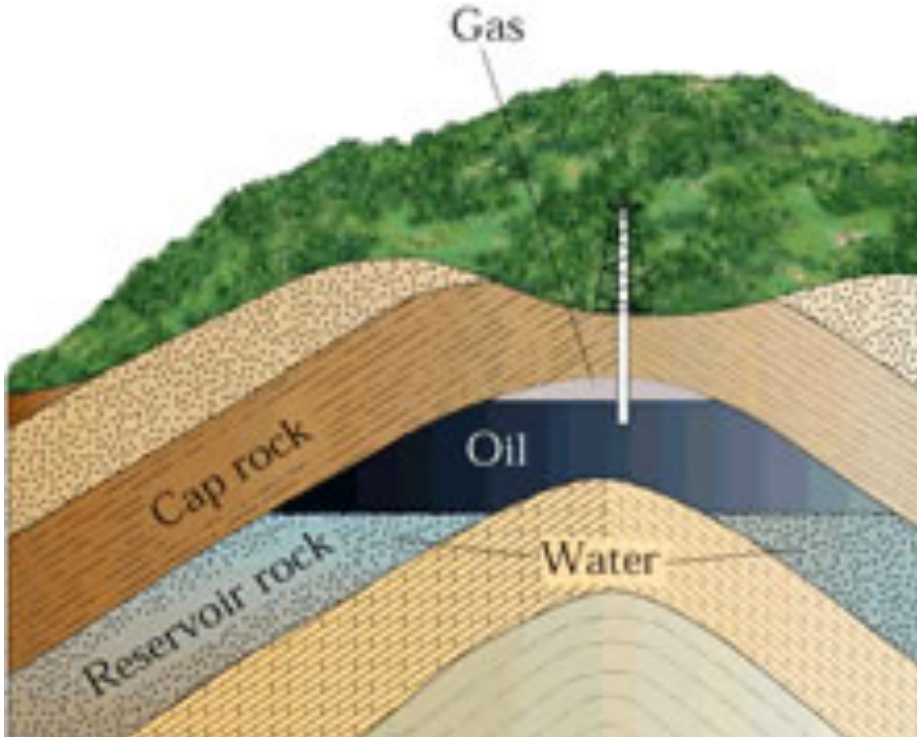


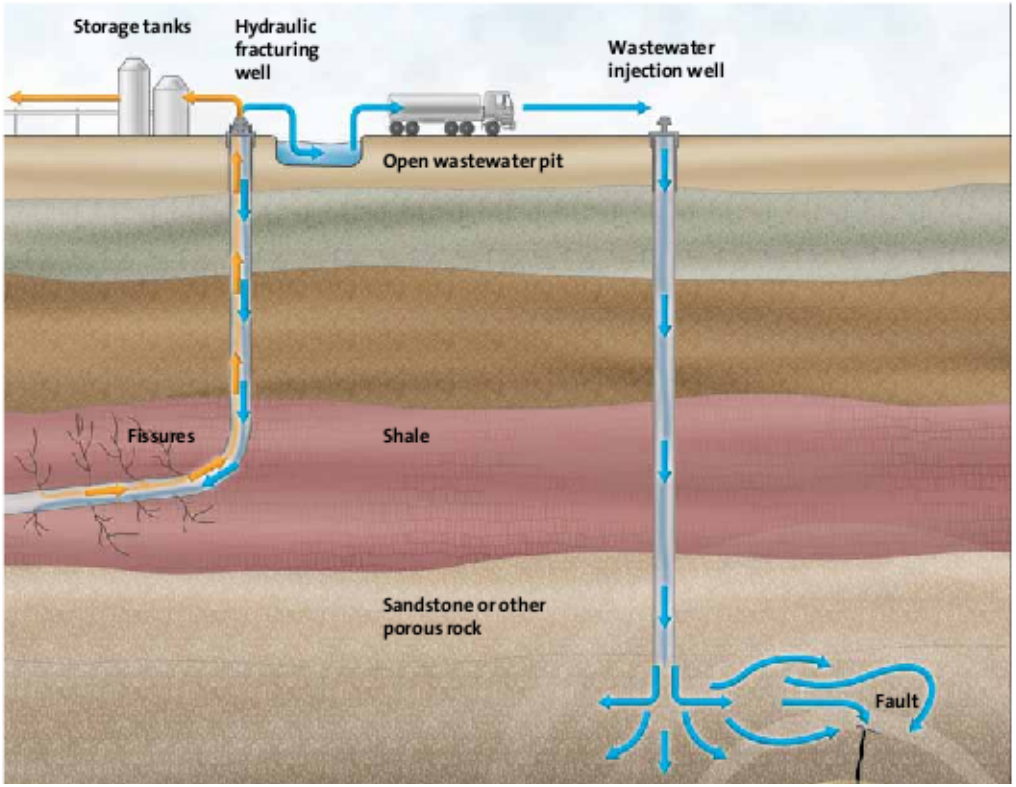
What is Wastewater?

- **Co-Produced water (all wells)**
- Frac fluids
- Options:
  - Reuse frac fluid
  - Surface discharge
  - Disposal at depth



What is Wastewater Disposal?

- Deep Wells injecting into porous formations
- Inject for years
- Up to 1M bbl/mo
- ~35K in the US
- Few connected to felt earthquakes



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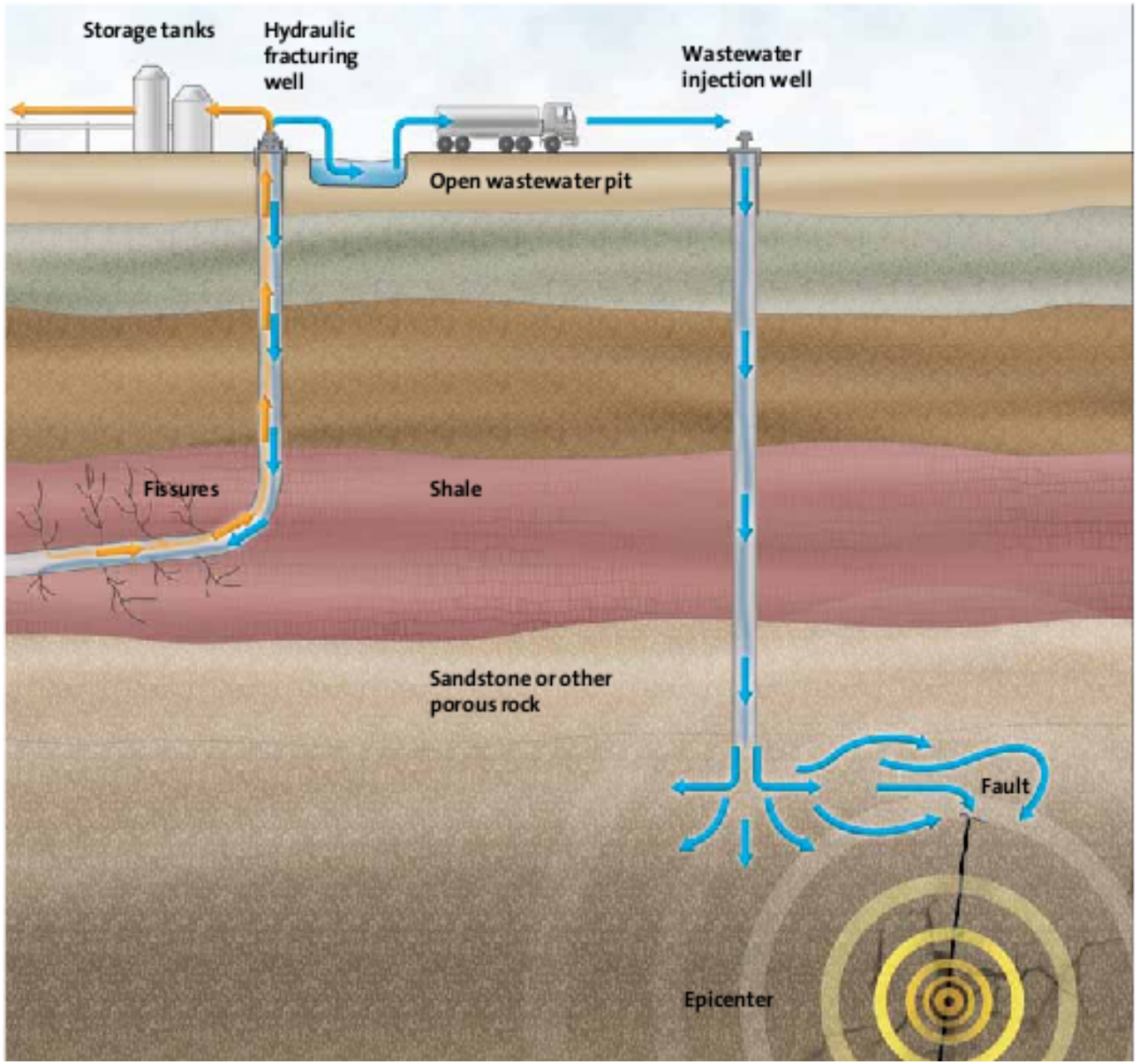

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Wastewater Injection vs. Fracking

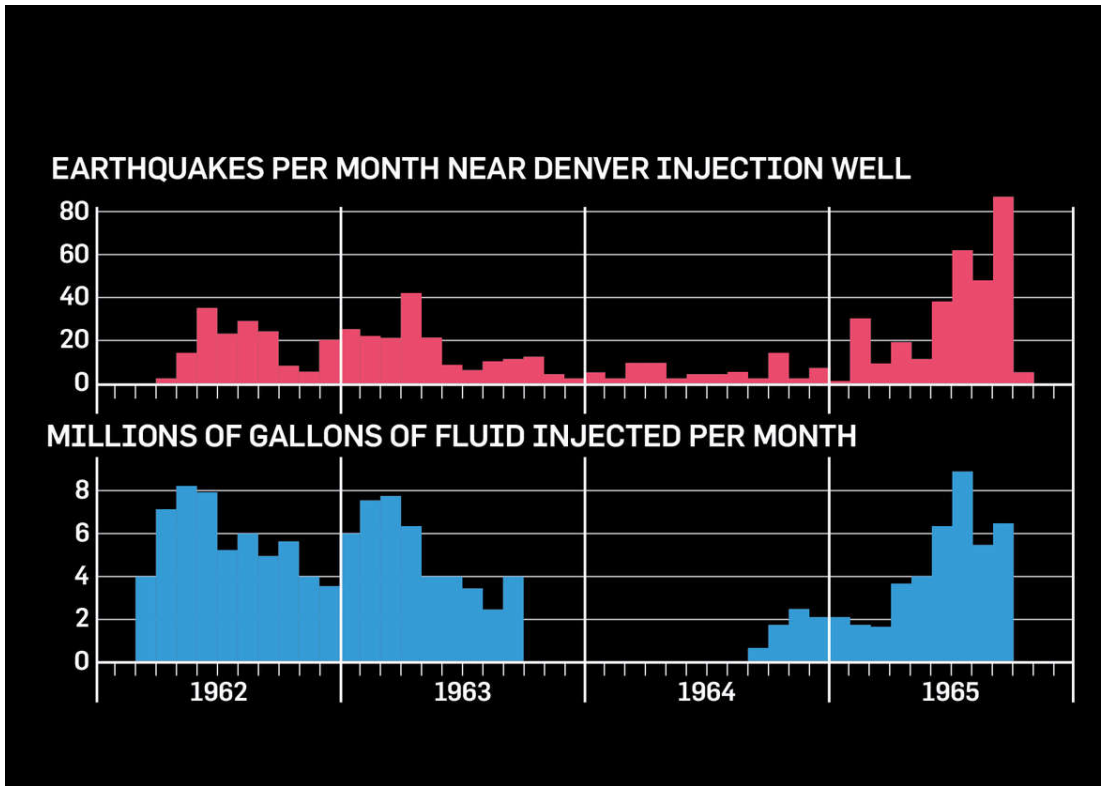
- Long Term (years-decades)
- High volume (1M-1B Bbls)
- ~35,000 wells
- Many felt earthquakes
- 20+ damaging earthquakes

- Short Term (hours-days)
- Low volume (5K-50K Bbls)
- 1M+ wells
- Very few felt EQs
- 0 damaging EQs

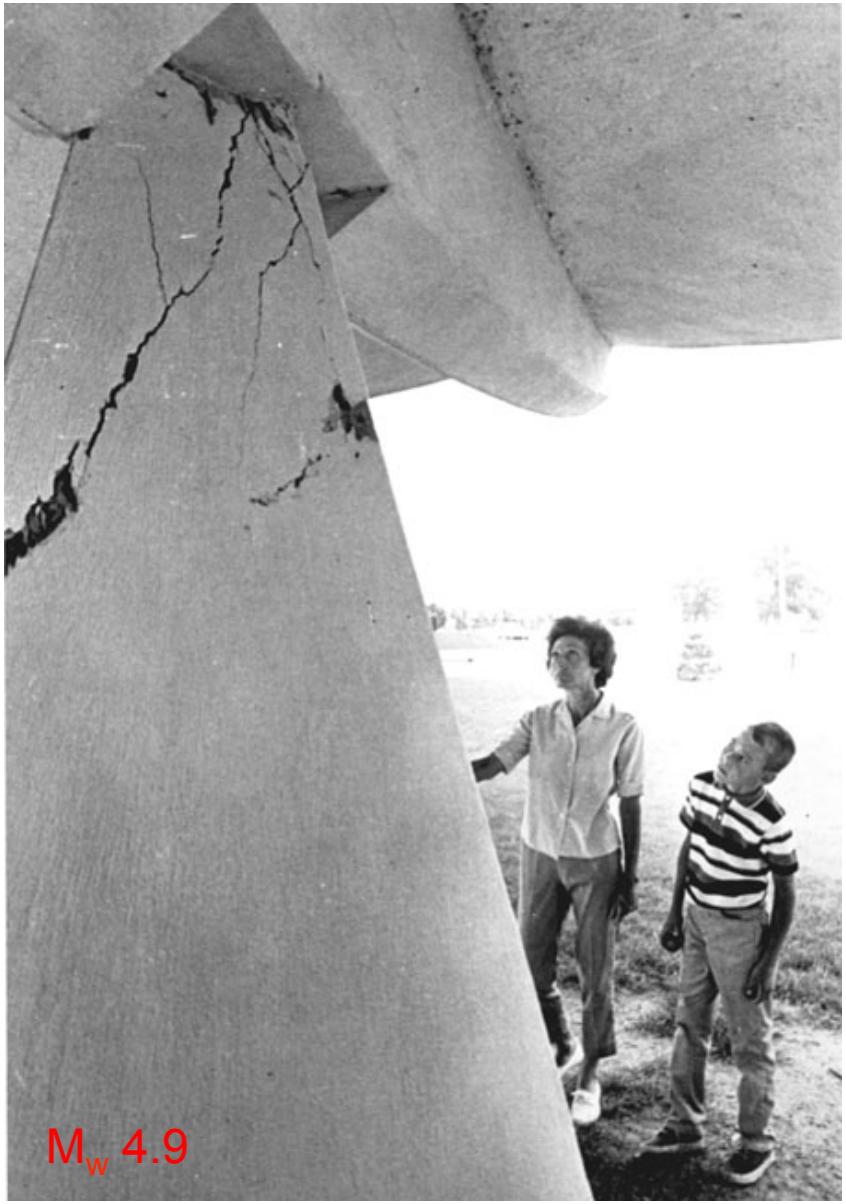
Wastewater disposal is more likely to induce earthquakes!

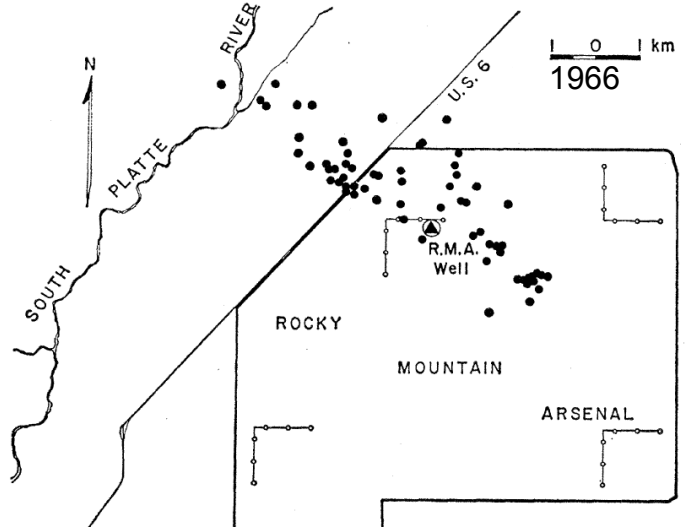
Rocky Mountain Arsenal: The First Observation of Injection-Induced EQs

- Fluid injection begins 1962
  - 130,000 bbls/month
- Earthquakes began shortly after injection

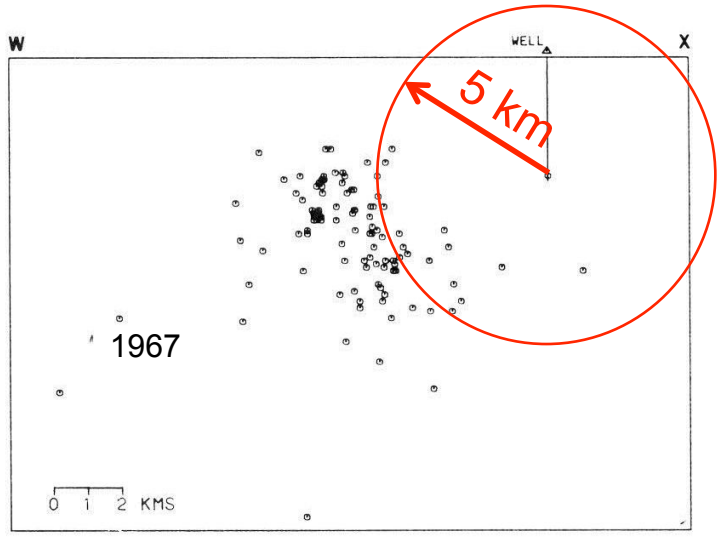


Rocky Mountain Arsenal, Colorado

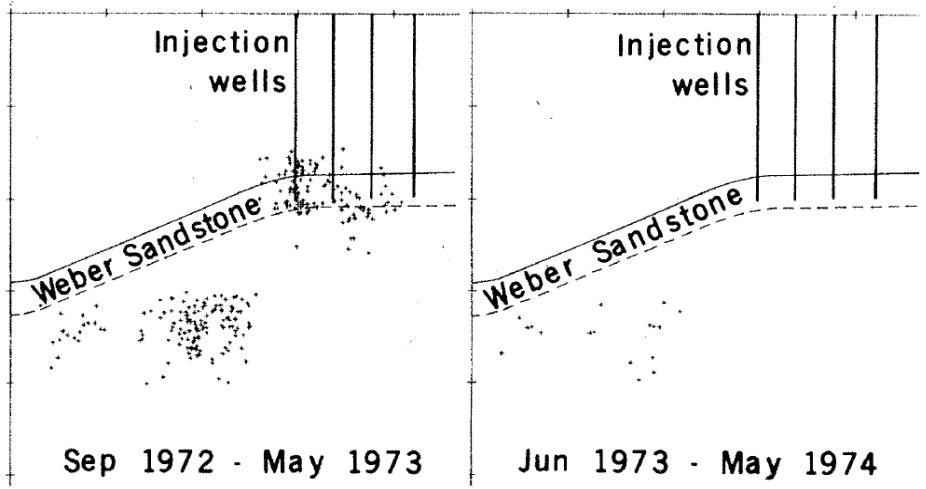


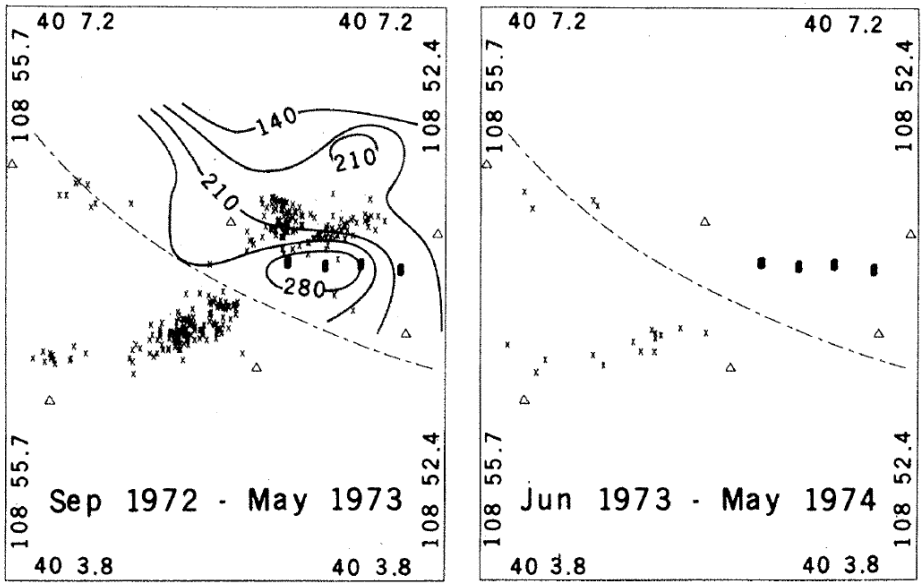


Post-Injection Earthquakes

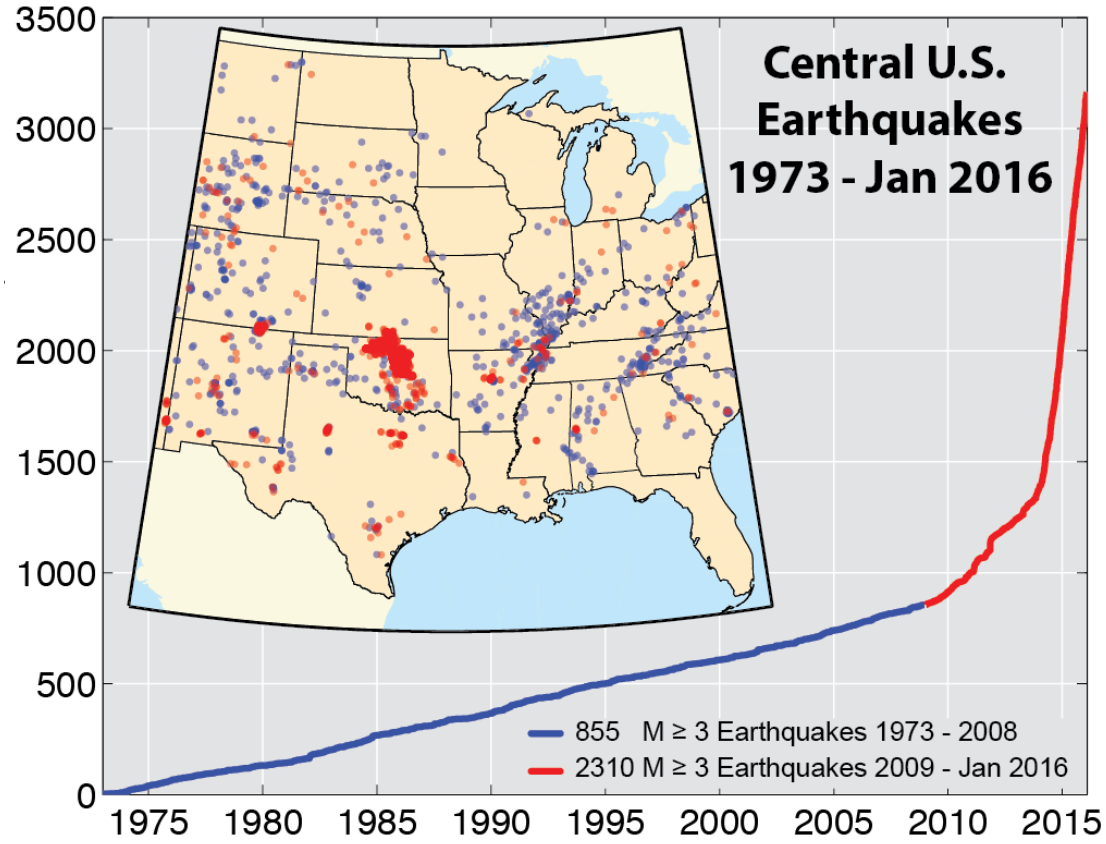


Controlling Earthquakes: The Rangely Experiment





What's Happening Now?

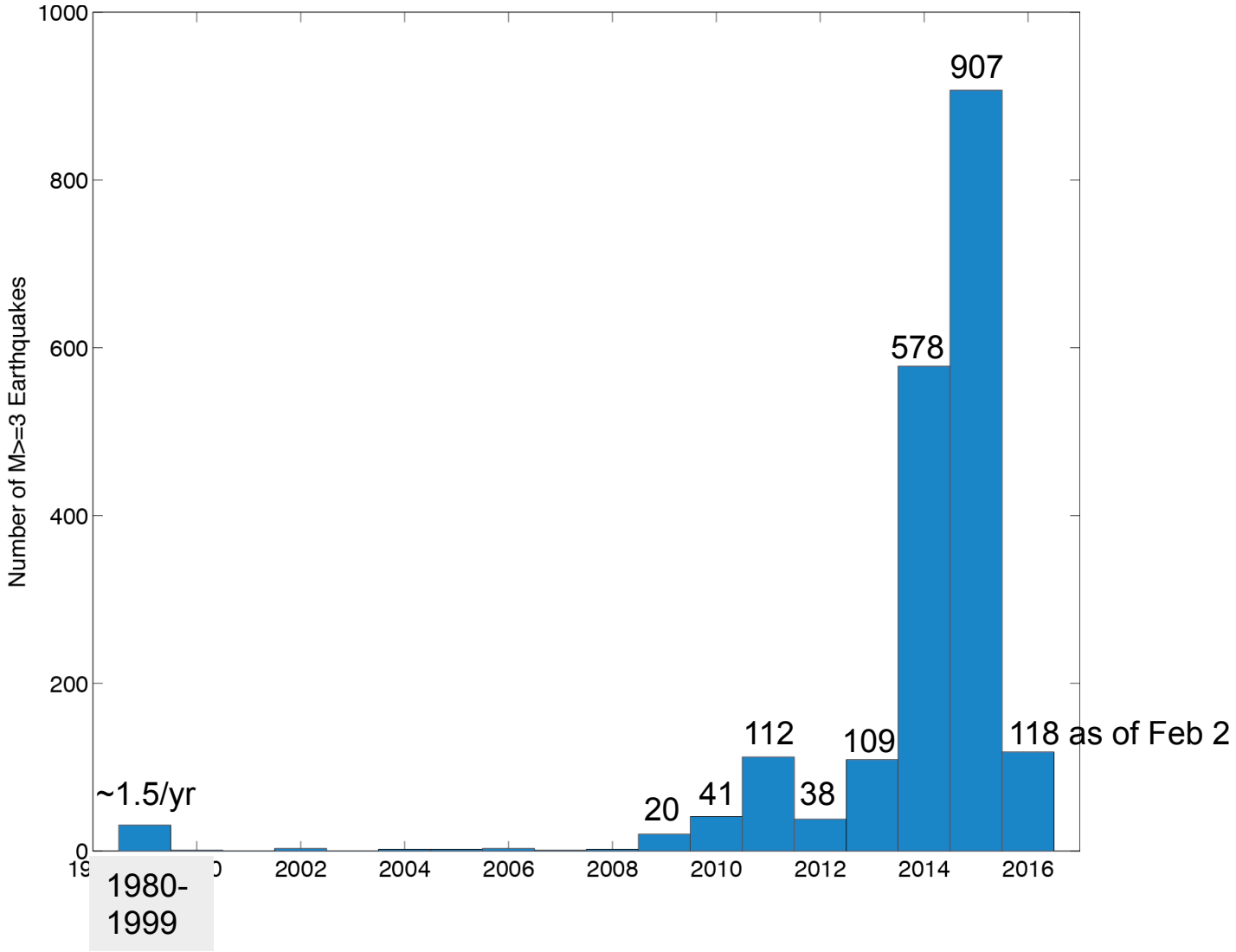


Oklahoma has more EQs than California!

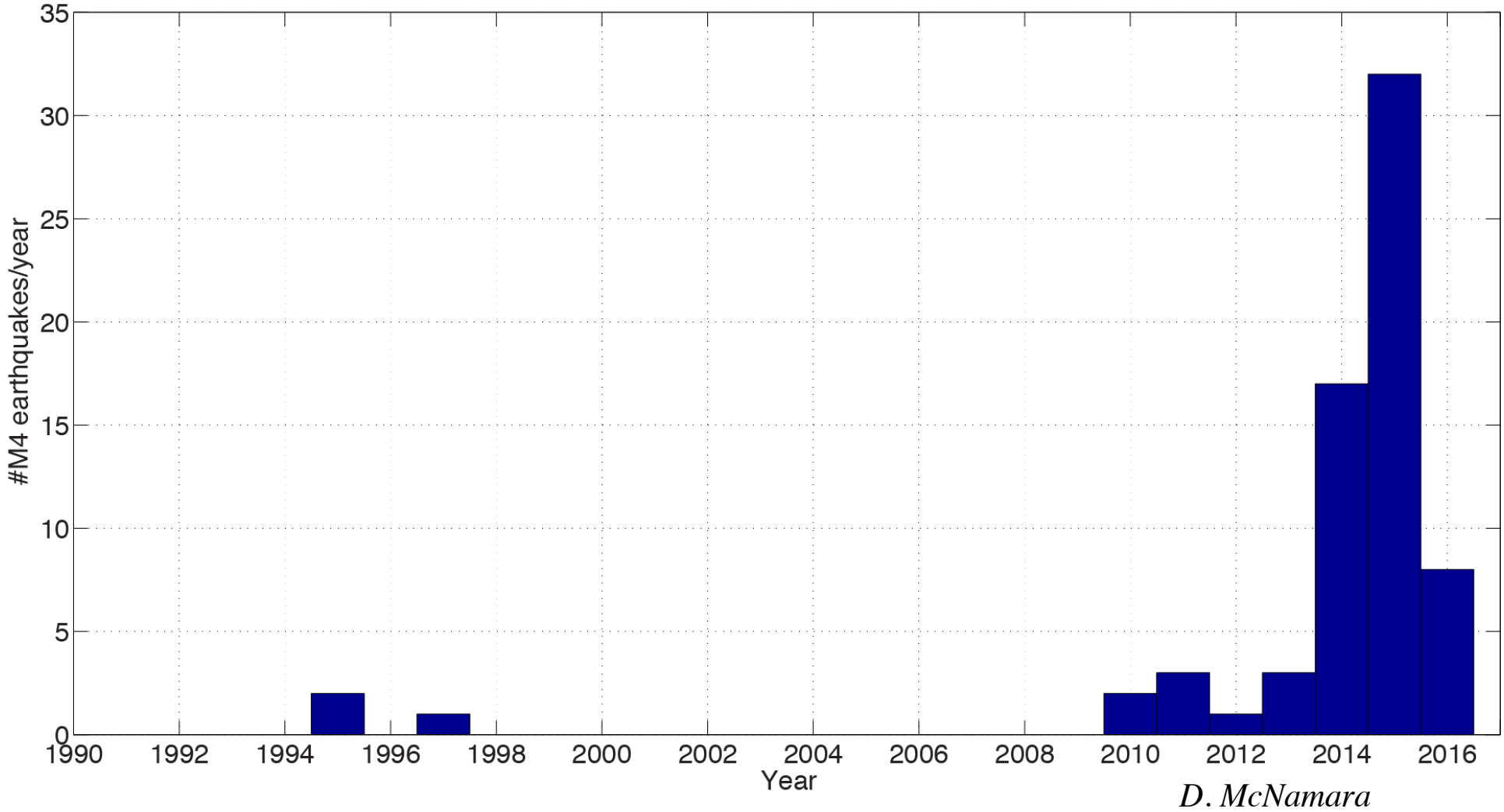
Before:
Scattered seismicity with a few more active fault zones

Now:
Few areas with many EQs

M3 Earthquakes in Oklahoma

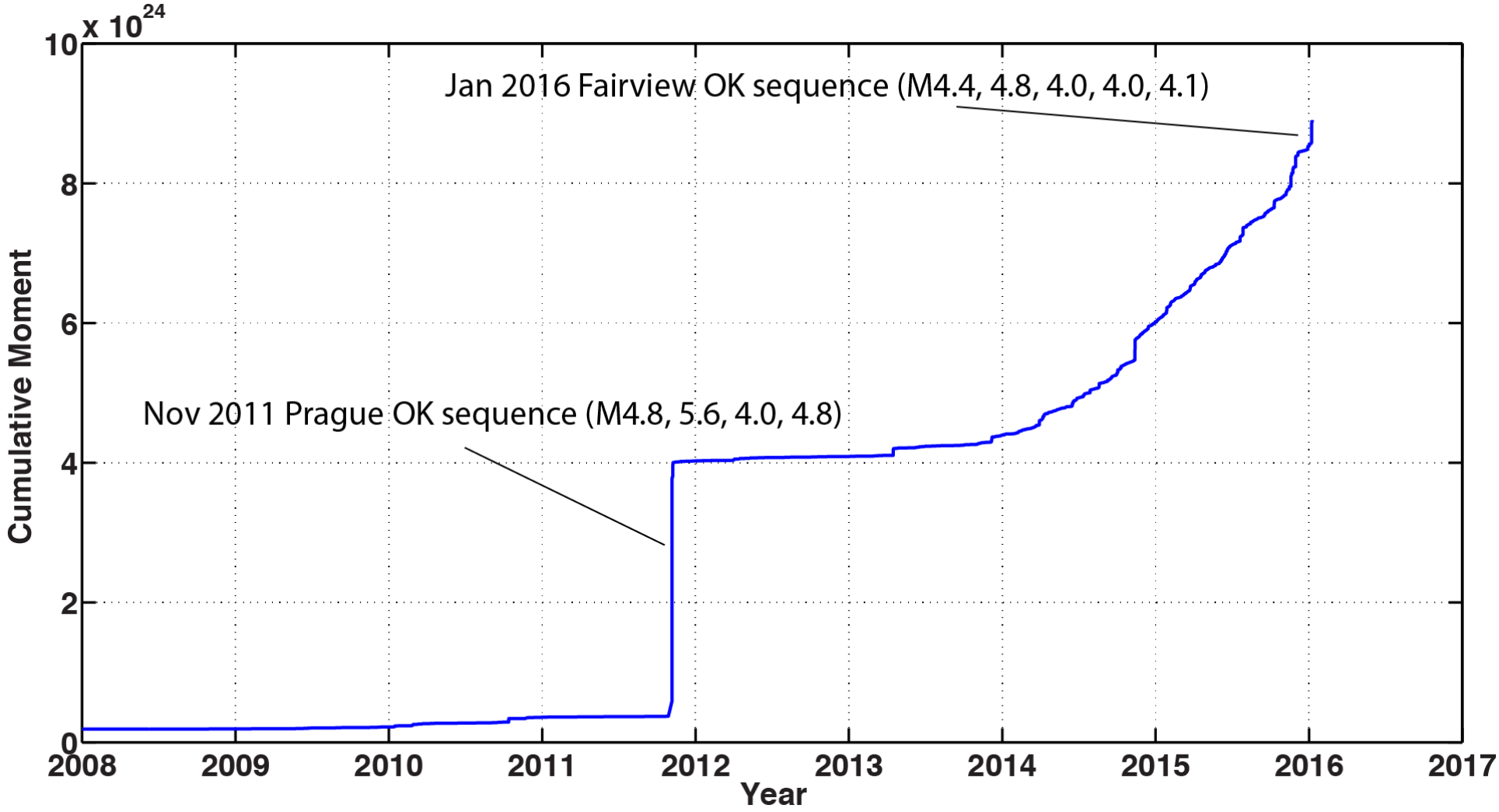


M4 Earthquakes in Oklahoma



D. McNamara

Oklahoma Moment Rate

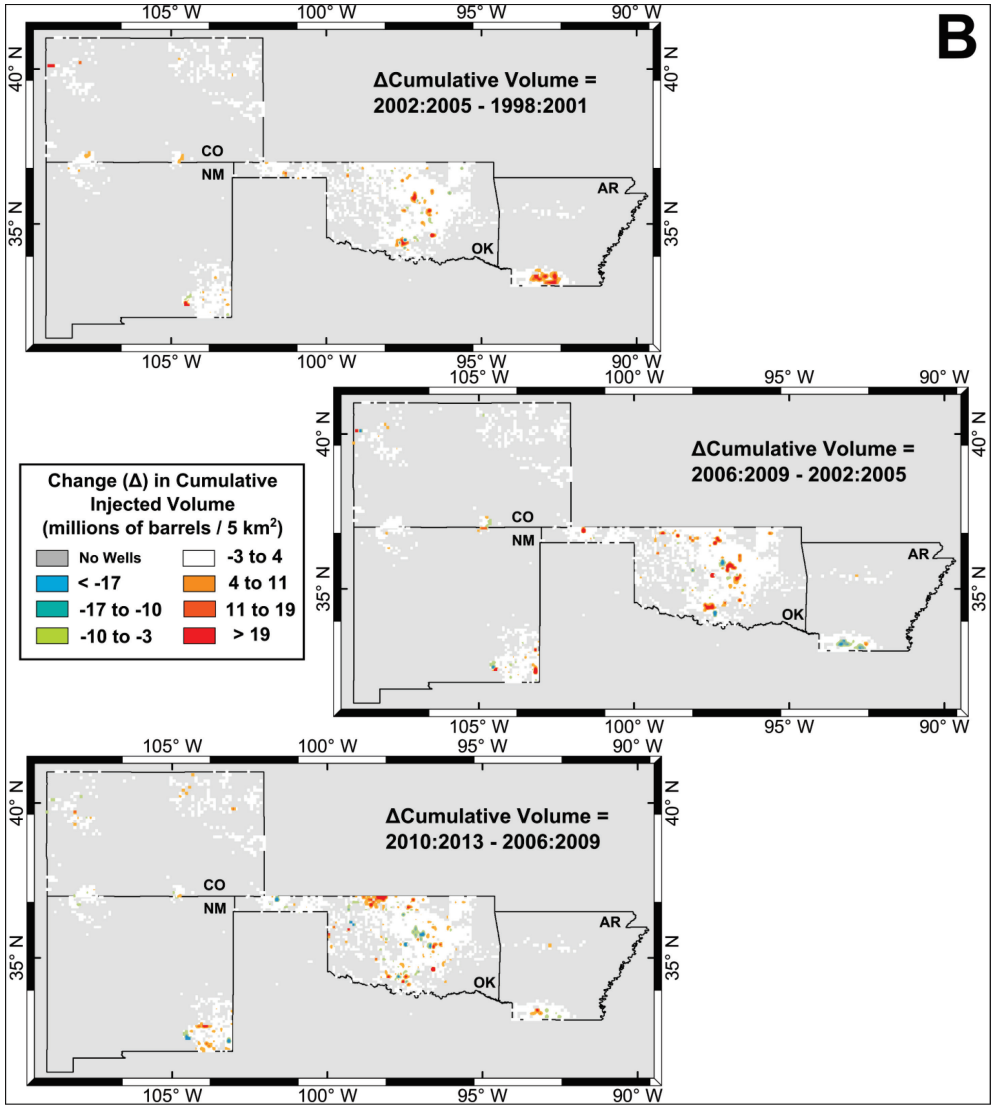


D. McNamara

Oklahoma Seismicity Animation

O. Boyd

Increased Earthquake Rate Corresponds w/ Areas of Increased Injection

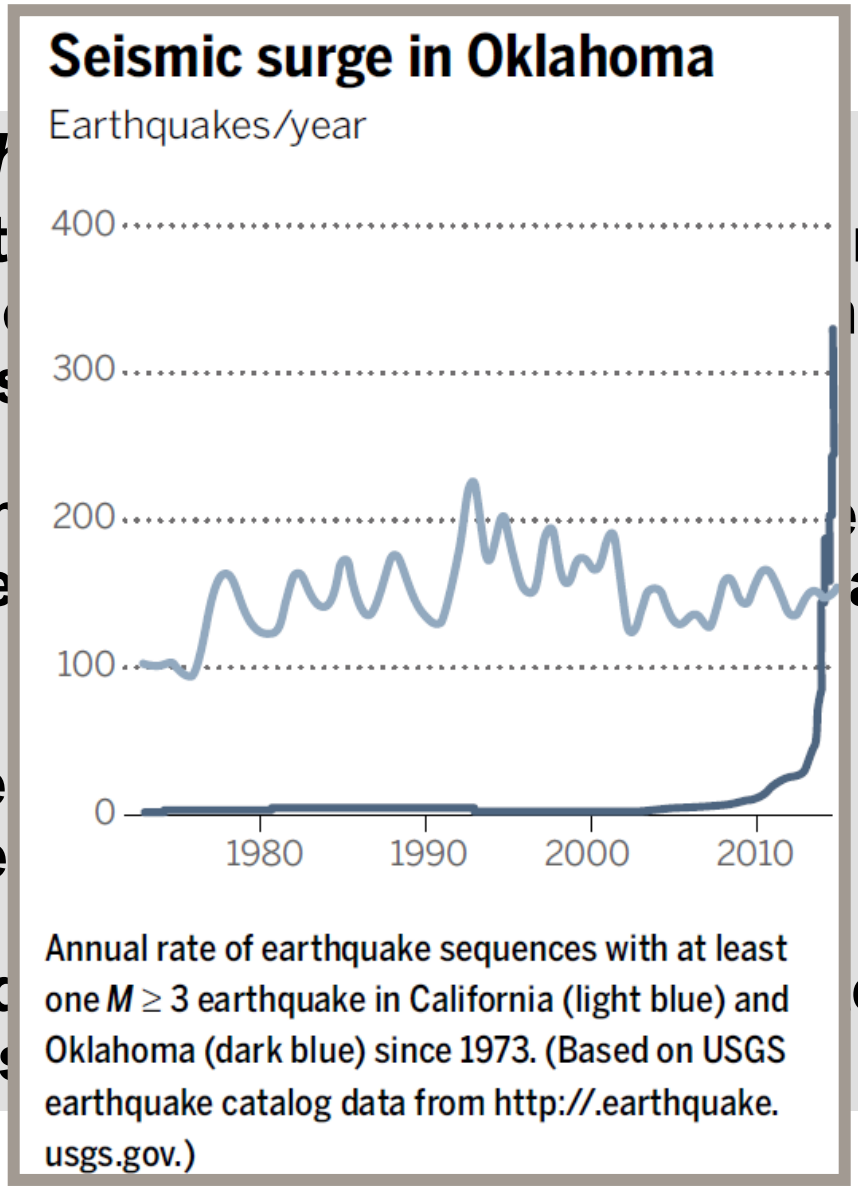


Weingarten *et al.*, 2015

M4 Earthquakes in Oklahoma

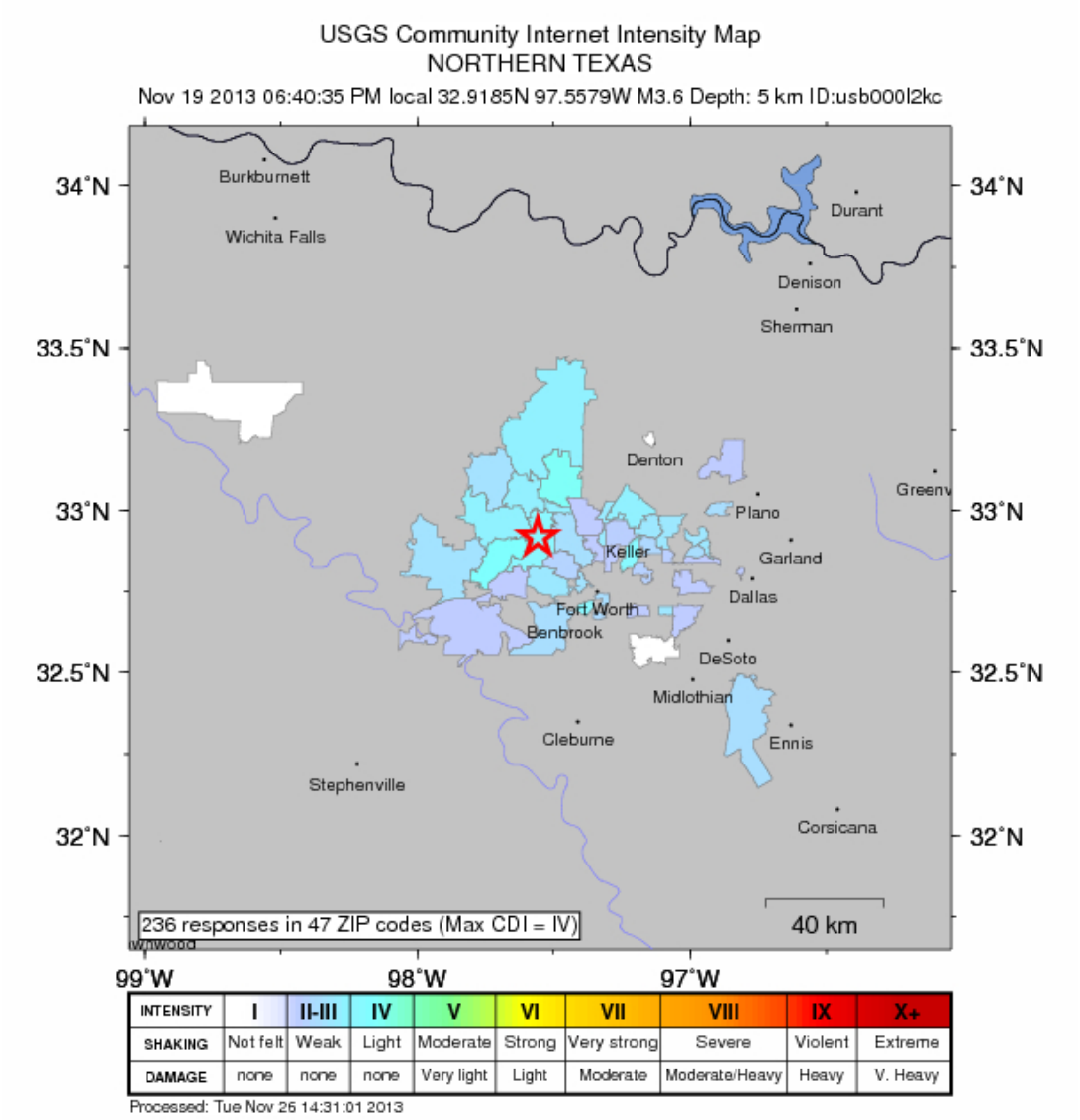
For Oklah

- **Over t** **rate in Oklah** **ıer than the his**
- **Comm** **3.0 and greate** **an in entire**
- **We've** **M4 quake**
- **Eartho** **er surpas**

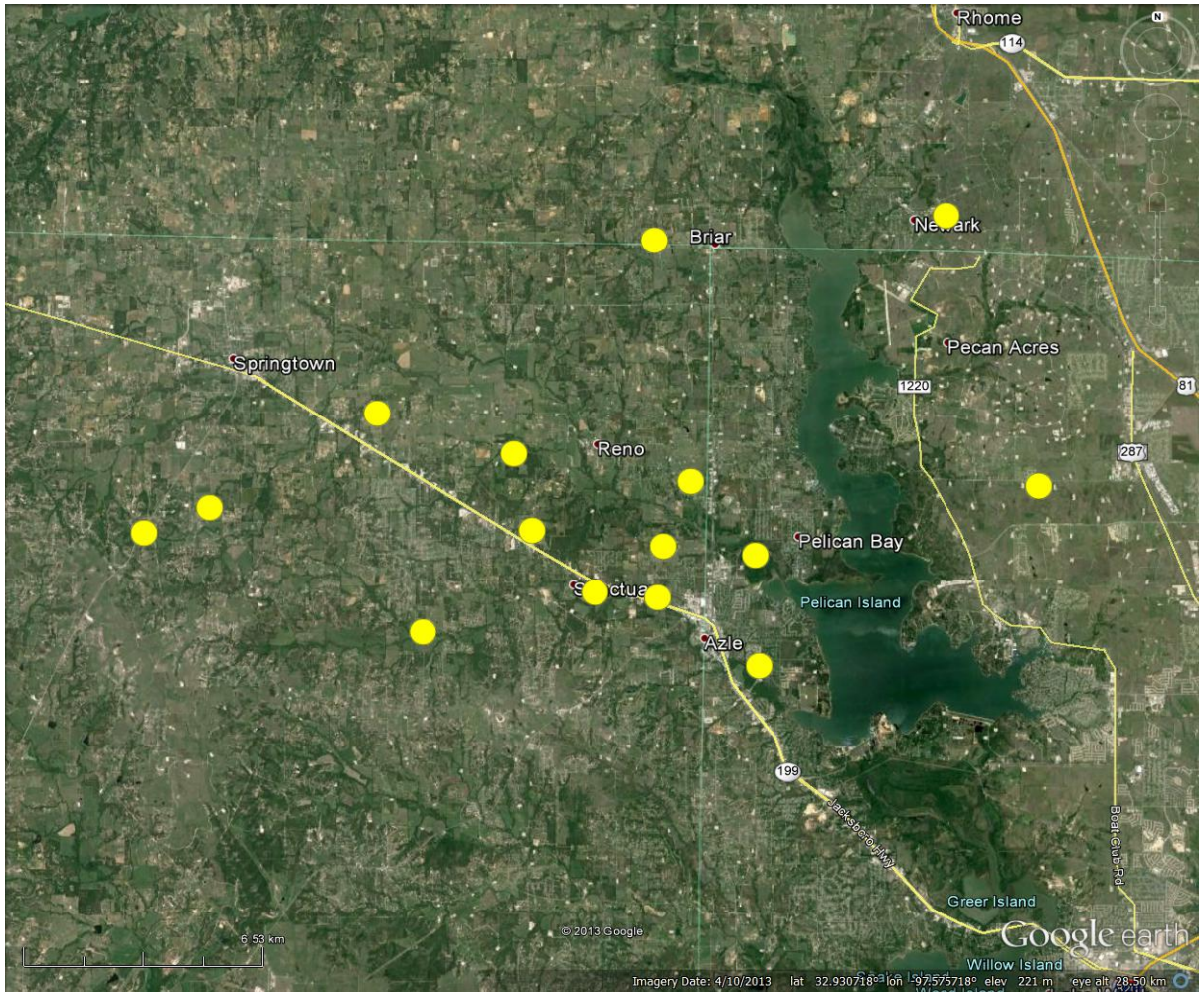


Annual rate of earthquake sequences with at least one $M \geq 3$ earthquake in California (light blue) and Oklahoma (dark blue) since 1973. (Based on USGS earthquake catalog data from http://.earthquake.usgs.gov.)

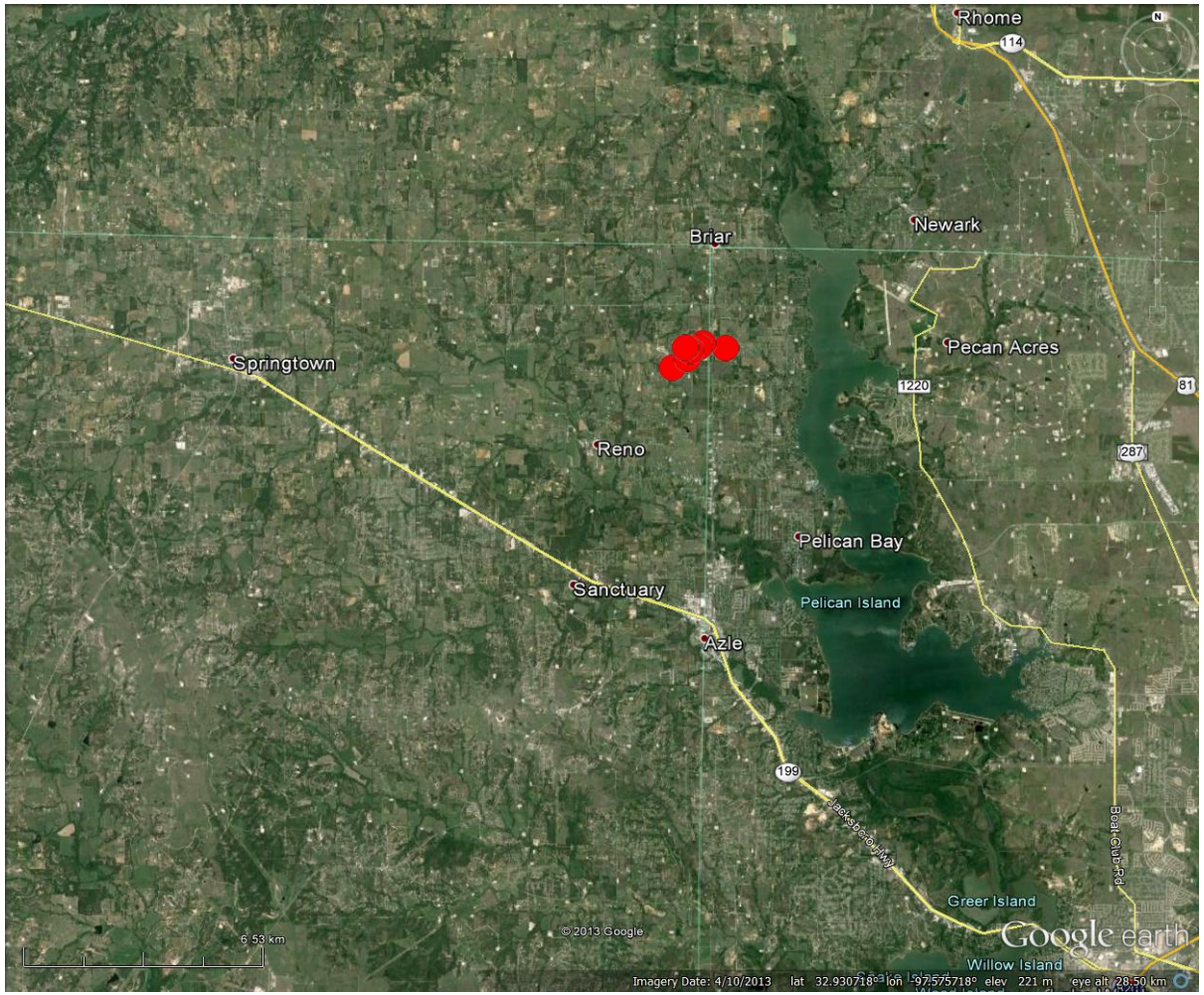
Azle, Texas earthquakes Nov 2013 – Jan 2014



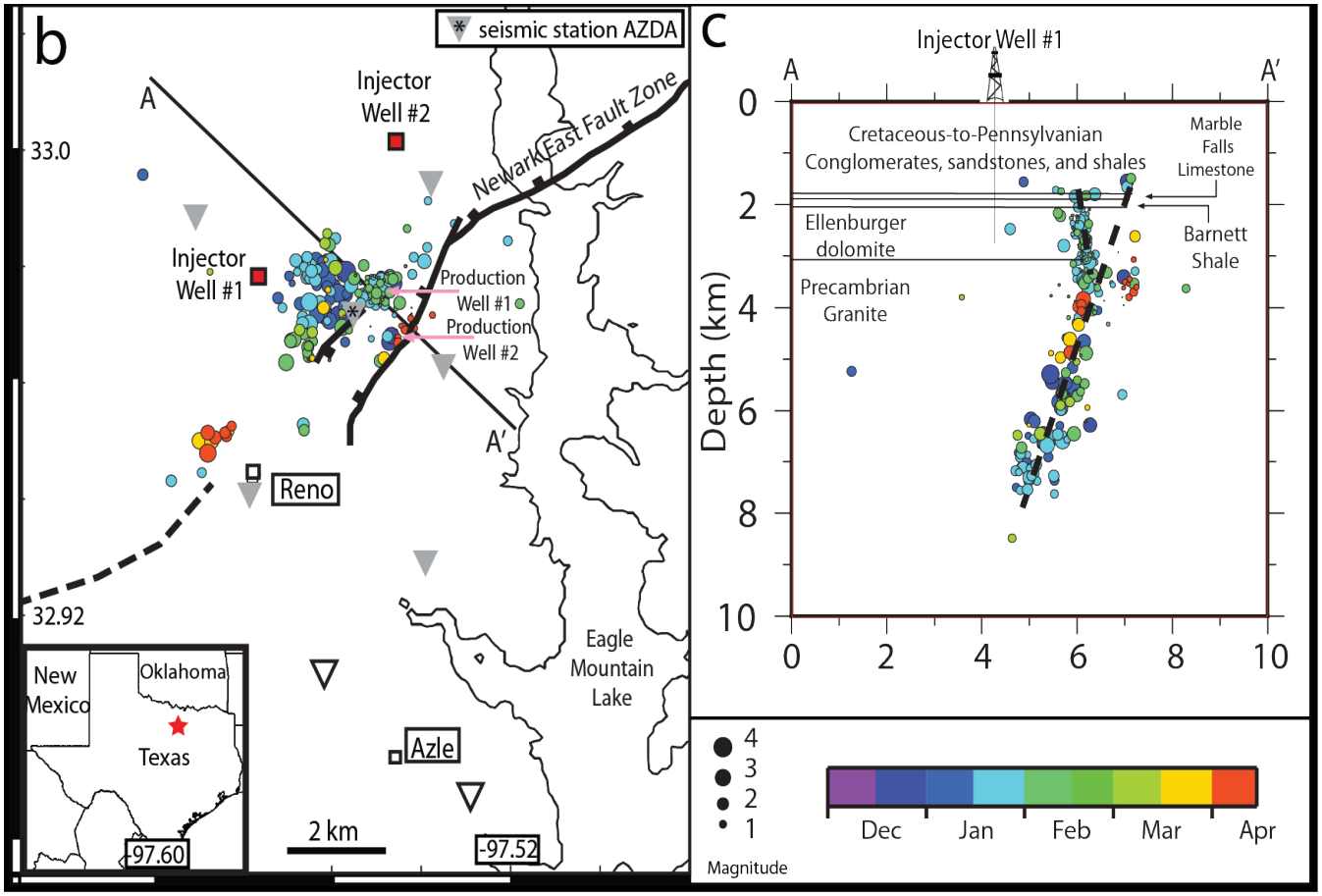
Routine USGS Locations



Locations using temporary array

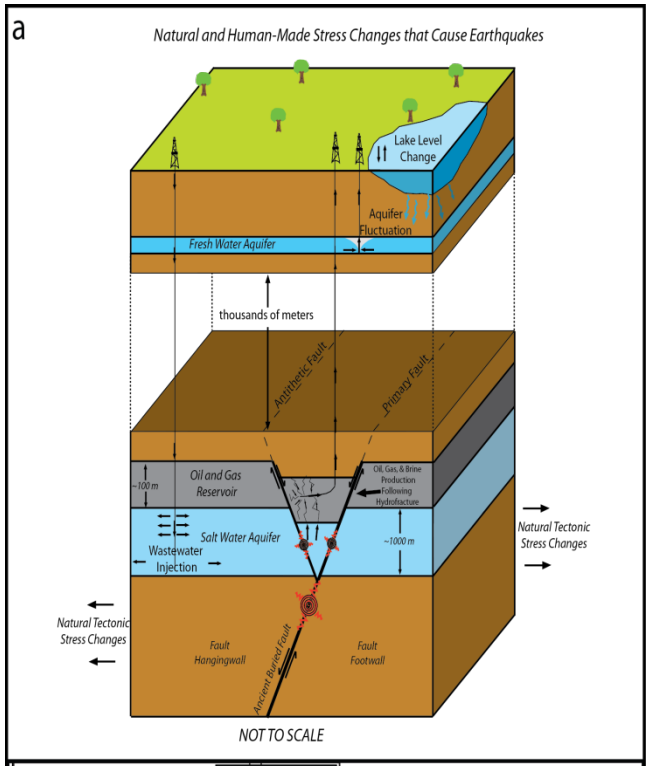


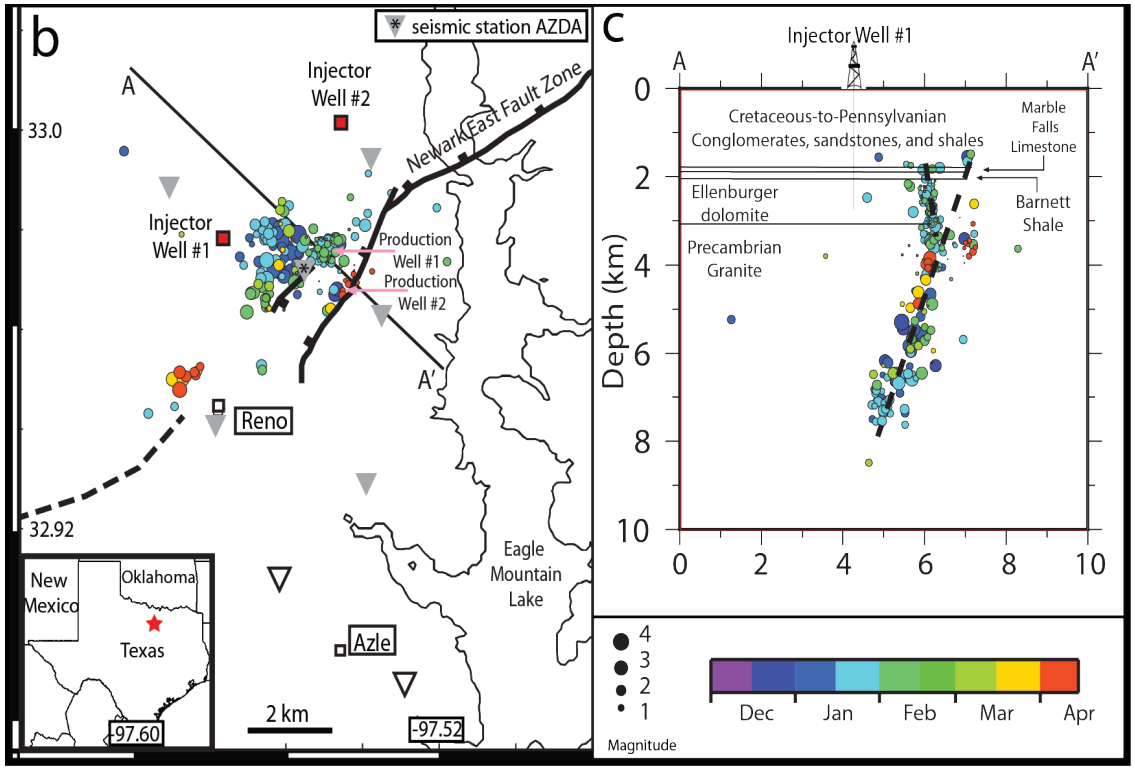
Faults, Seismicity, and Wells



Hornbach *et al.*, 2015

Why earthquakes near Azle?



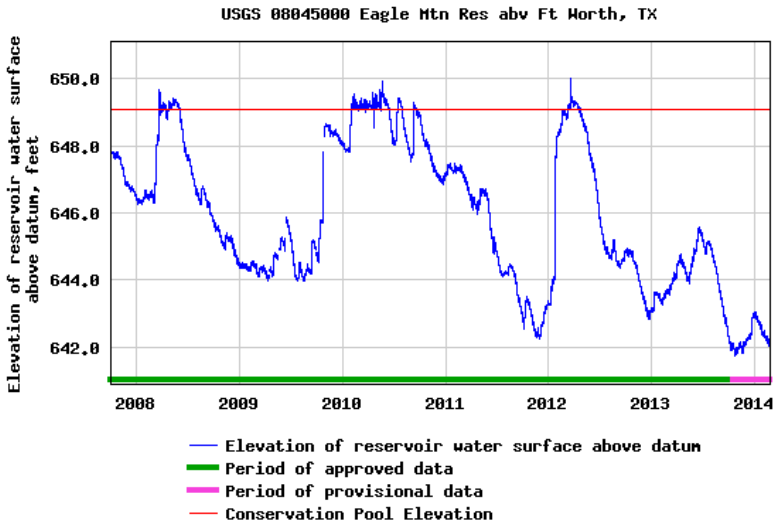


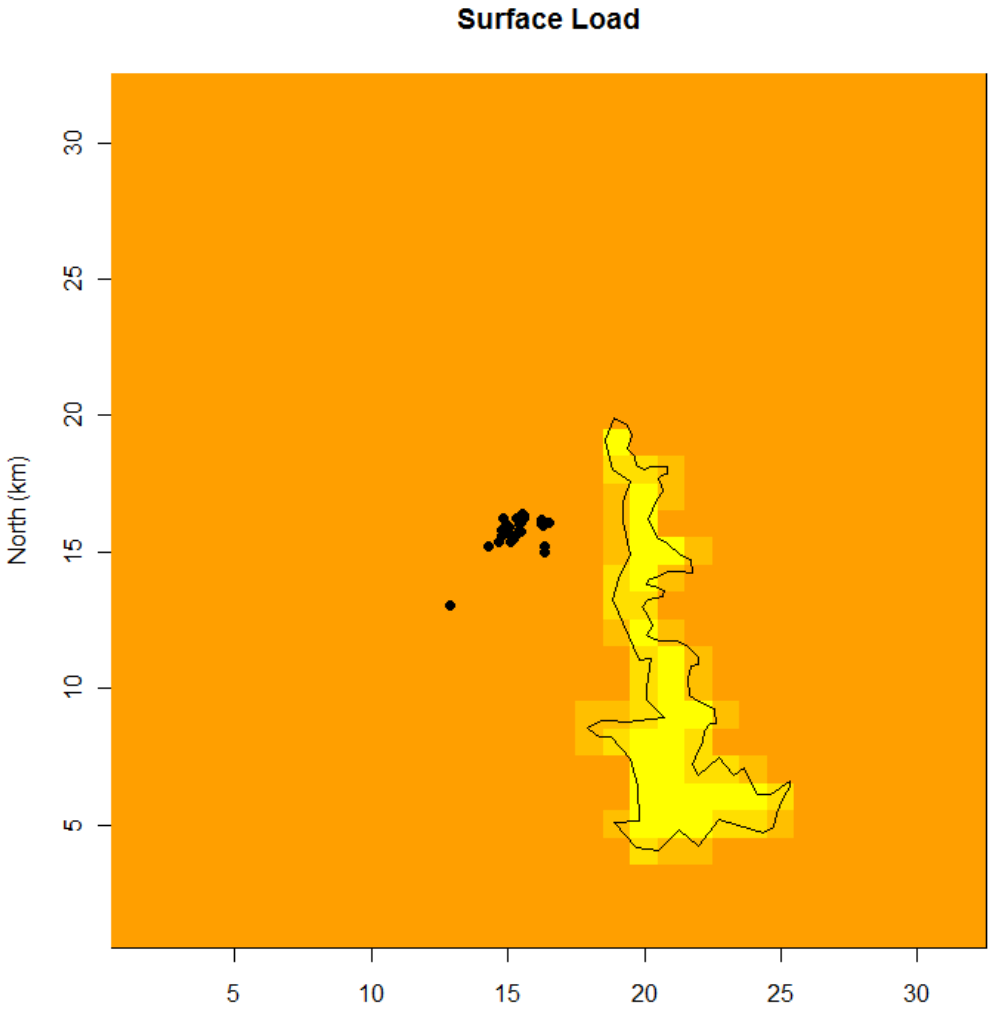
- Natural earthquake activity?
- Water level changes in Eagle Mountain Lake?
- Water table decline due to prolonged drought?
- Production from the Barnett Shale?
- Waste water disposal?

Hornbach *et al.*, 2015

Lake Level Changes?

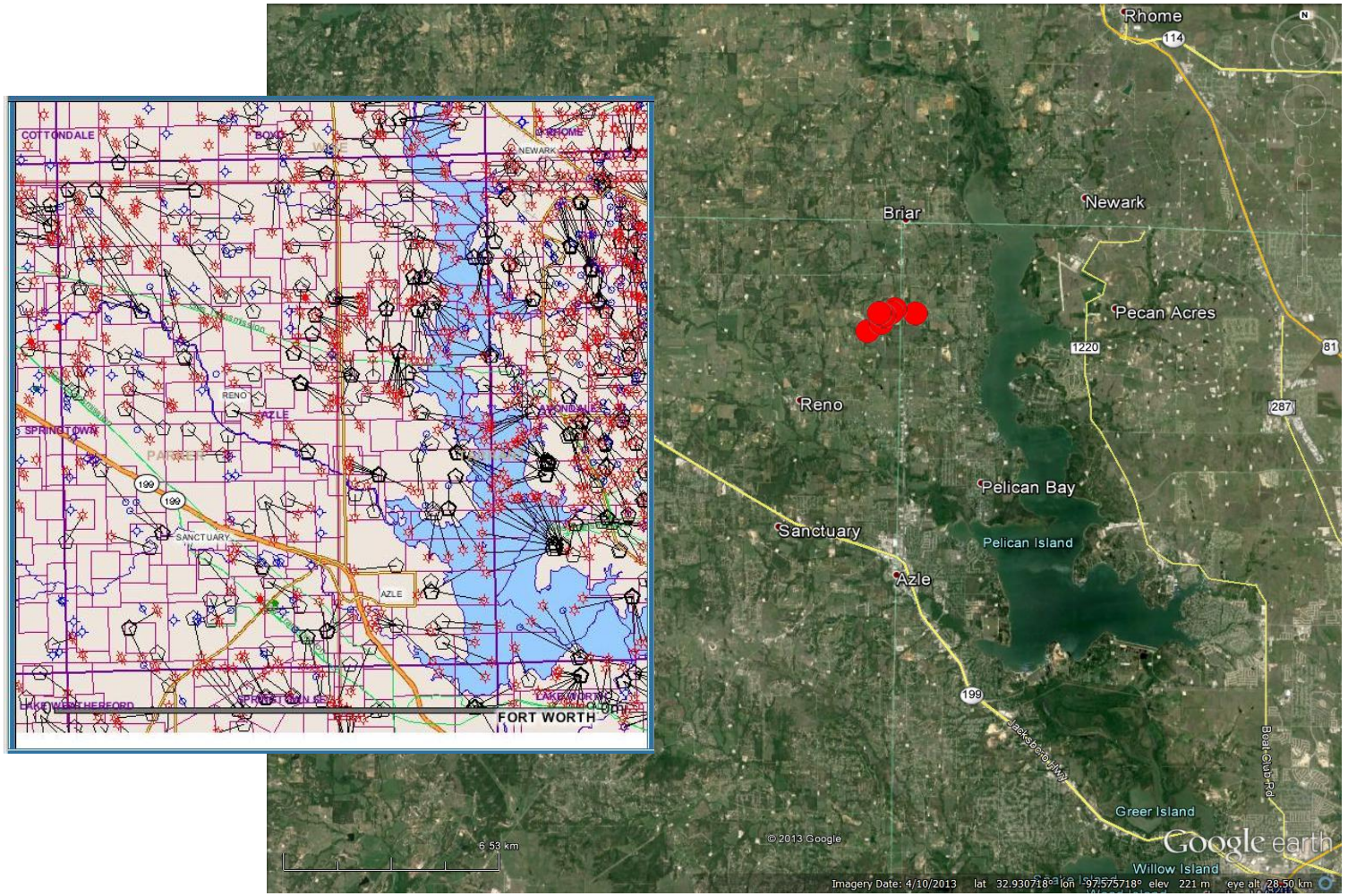
Maximum stress change
< 1 KPa.



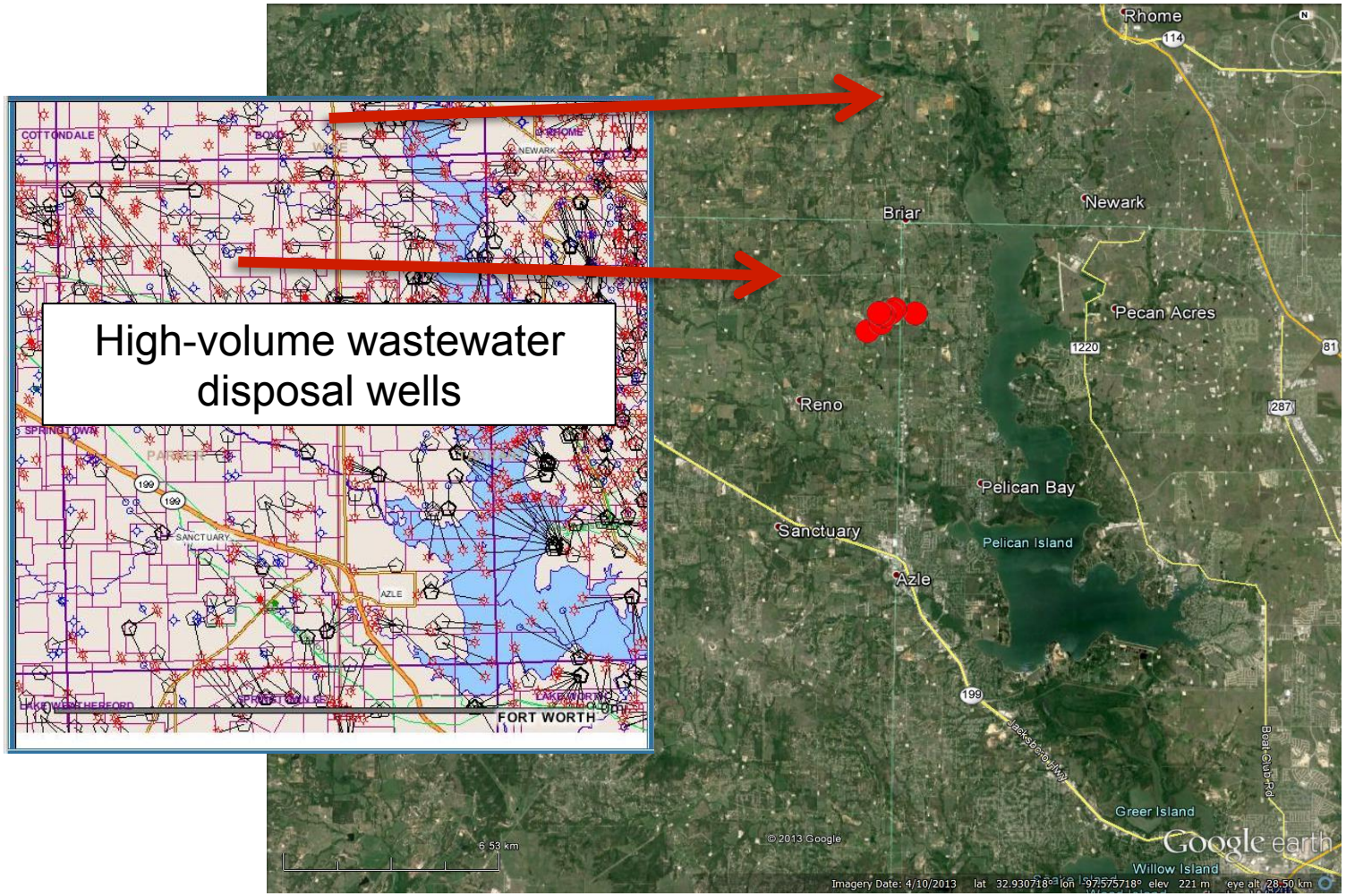


Hornbach *et al.*, 2015

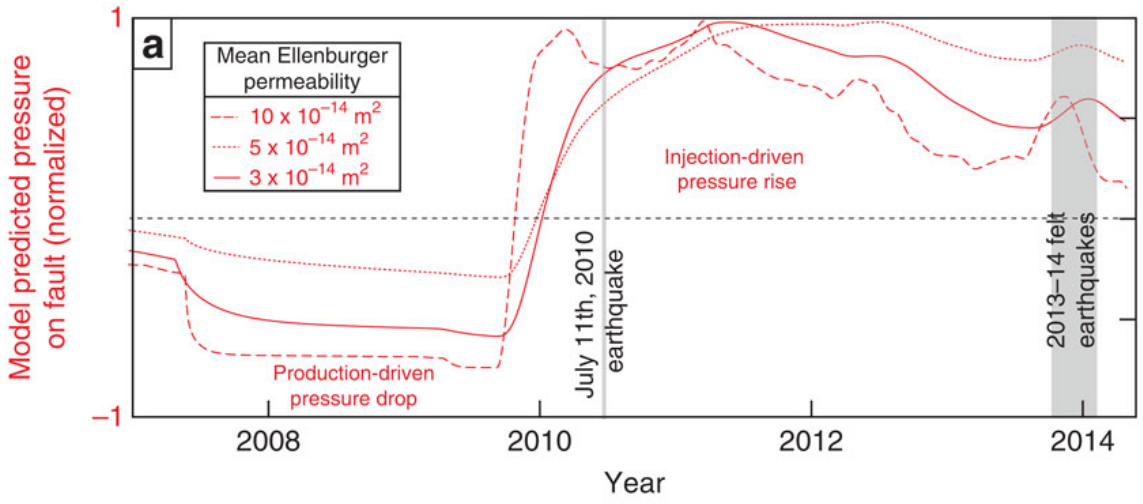
Oil Production?

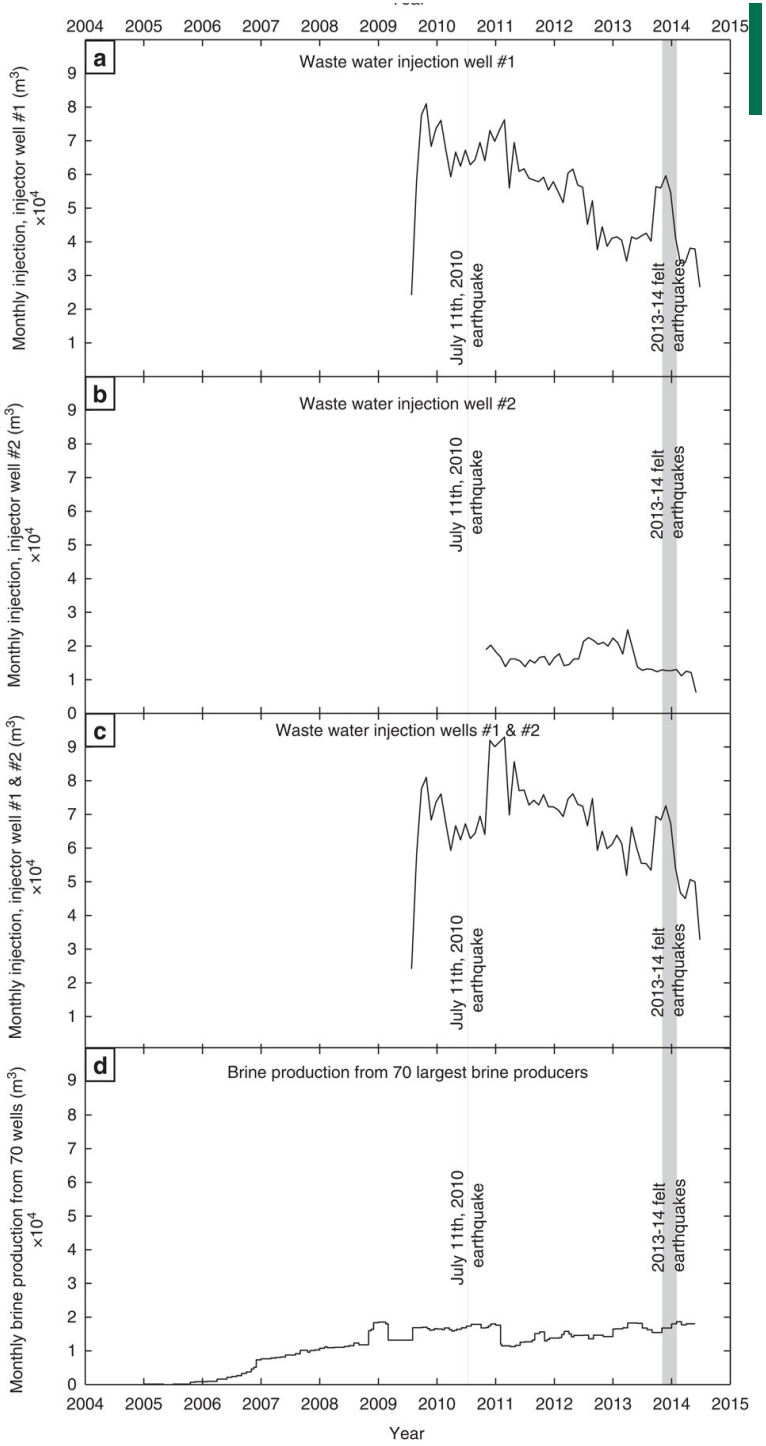


Wastewater Disposal?



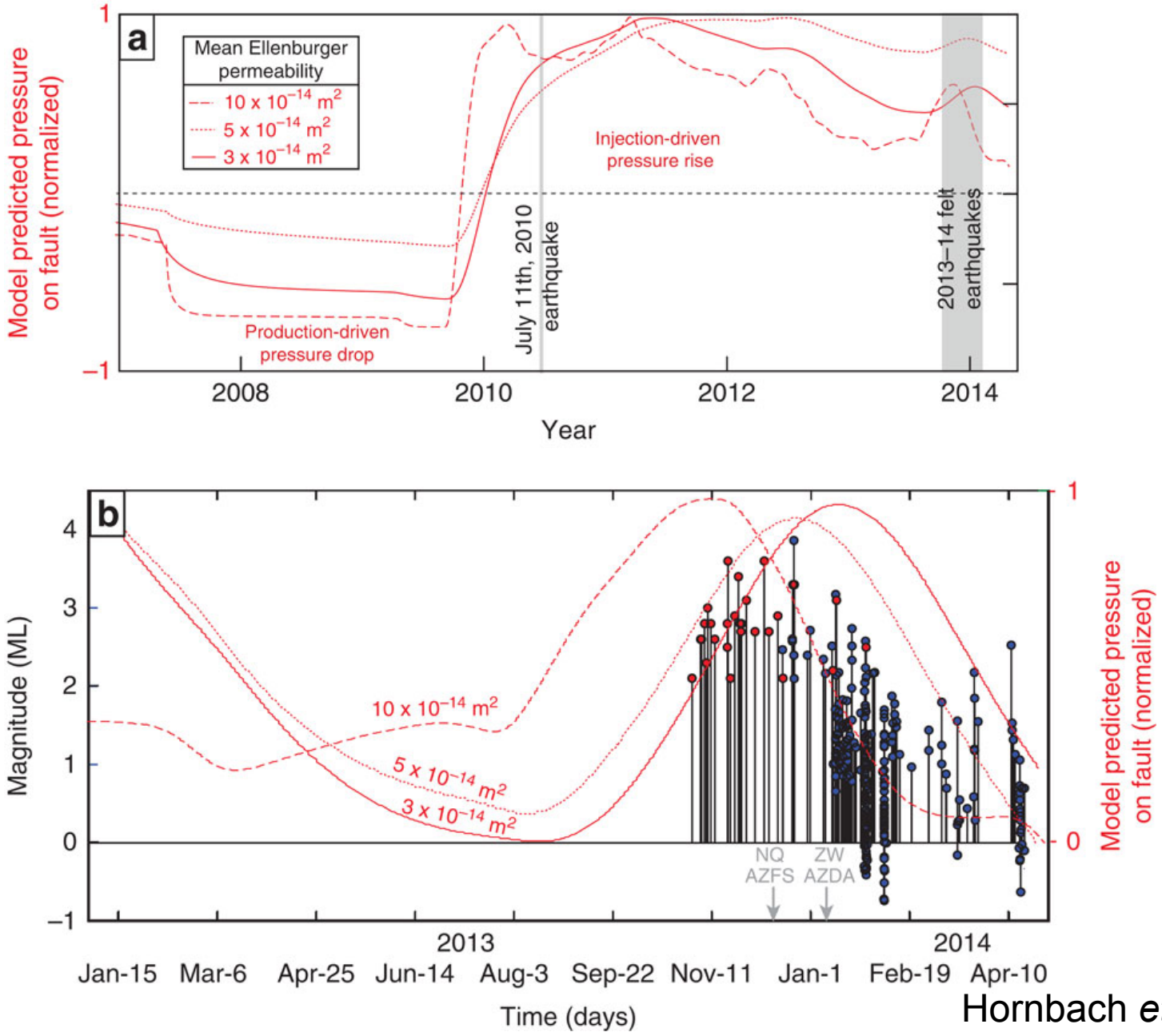
Injection Rate Timing Doesn't Correlate to EQ Timing





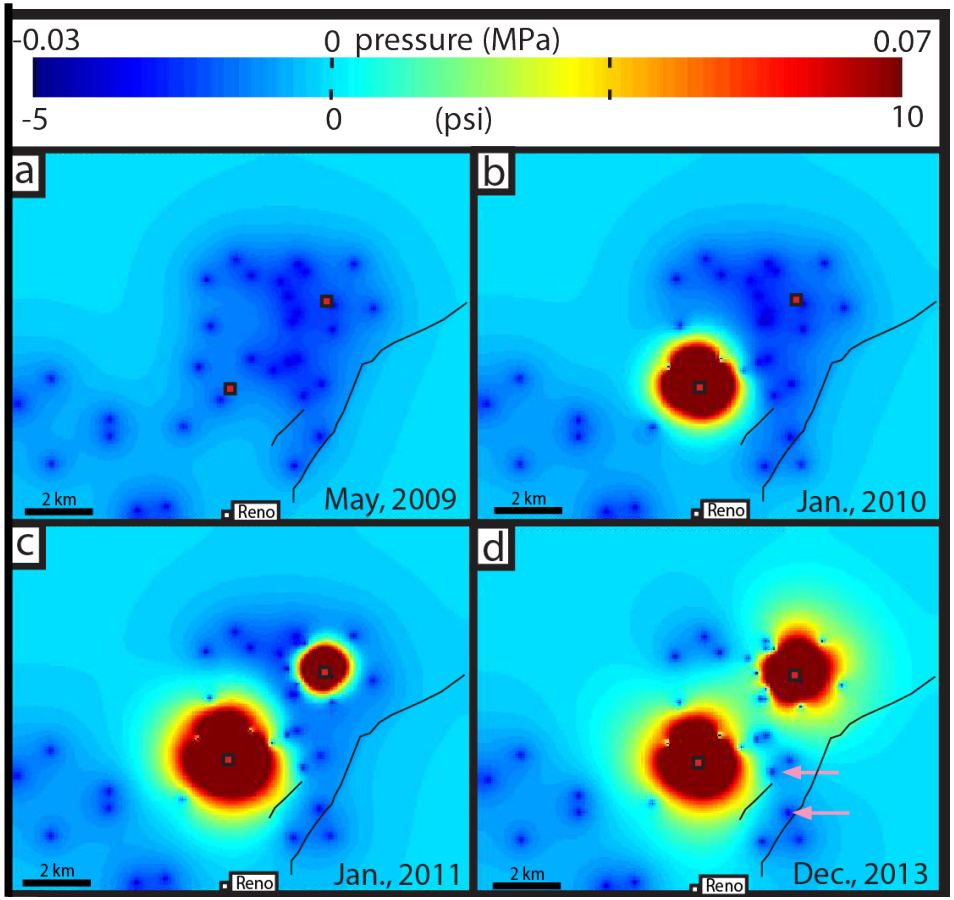
Hornbach *et al.*, 2015

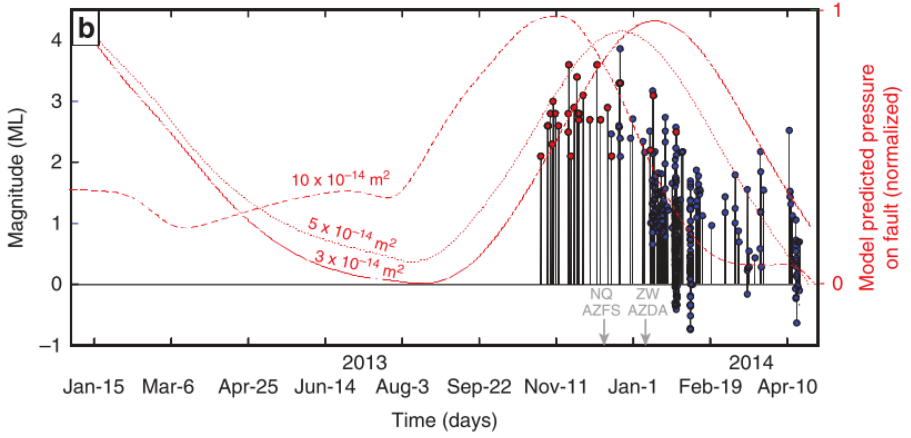
Modeling Shows There Should be a Delay

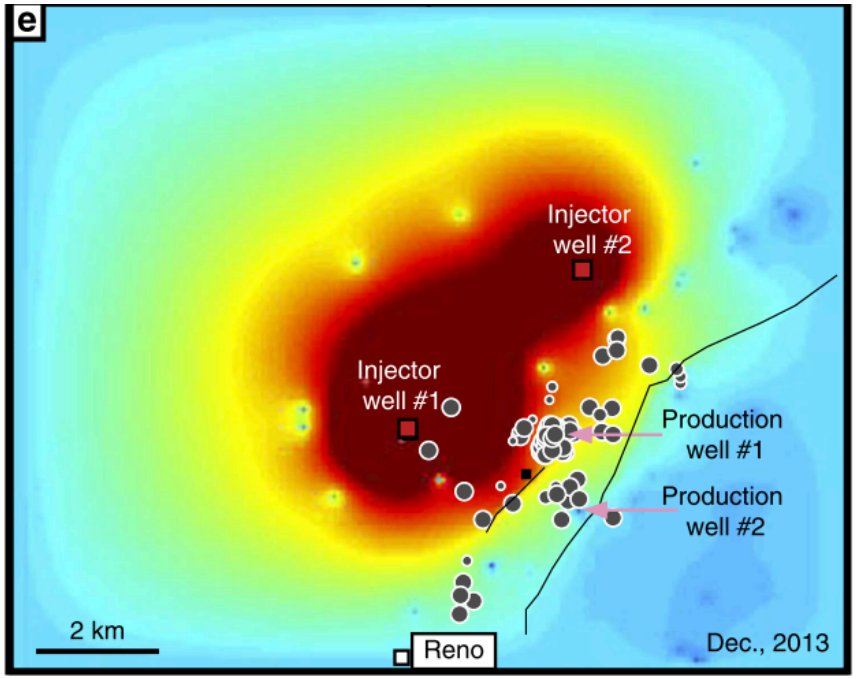


Hornbach *et al.*, 2015

Combination of Production and Injection

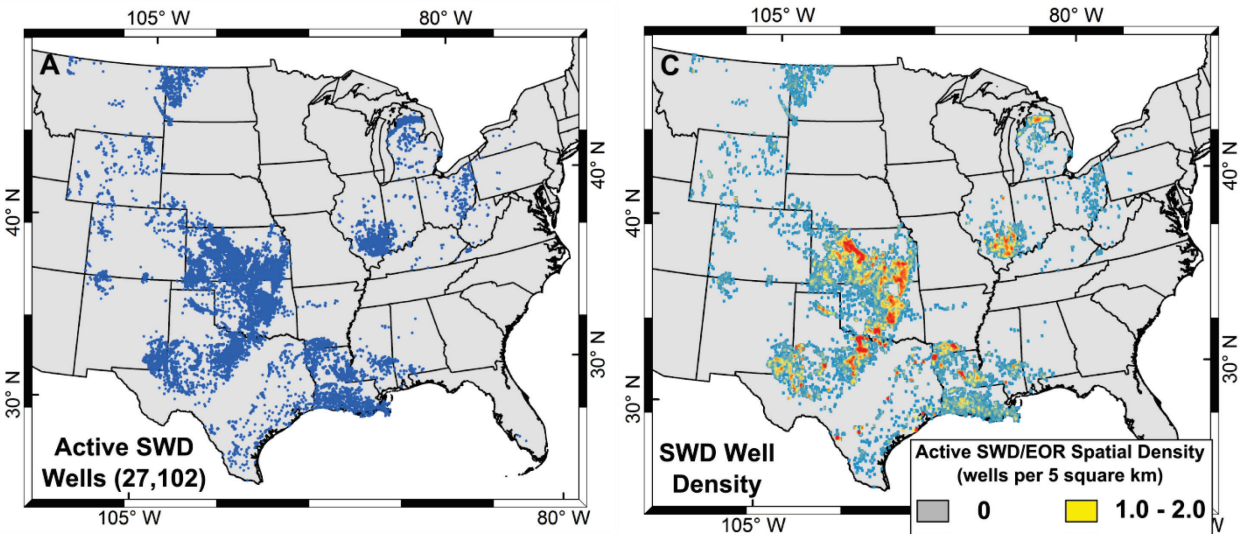






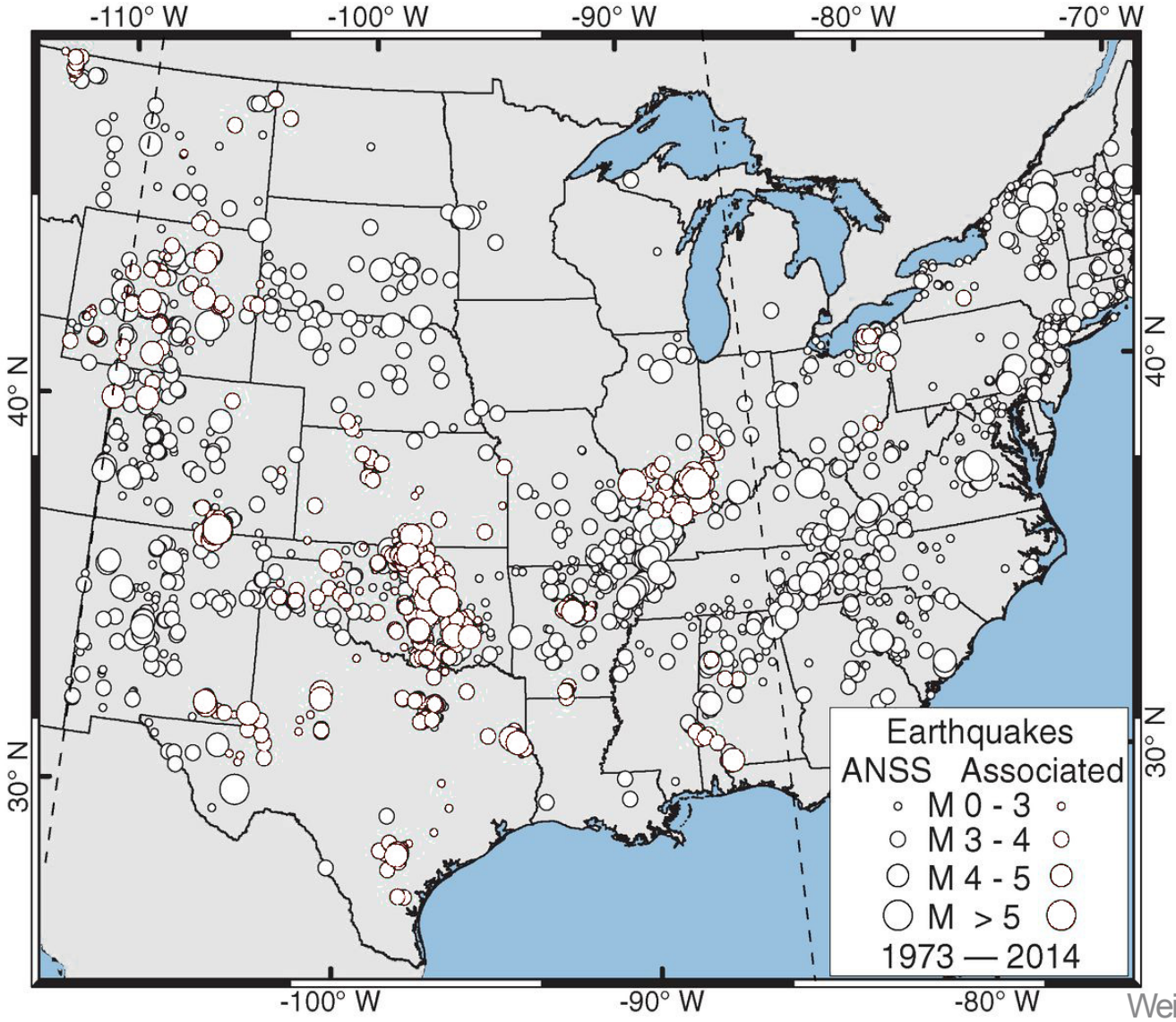
Hornbach *et al.*, 2015

Survey of Injection and EQs Across the CUS



Weingarten *et al.*, 2015

Survey of Injection and EQs Across the CUS



Weingarten *et al.*, 2015

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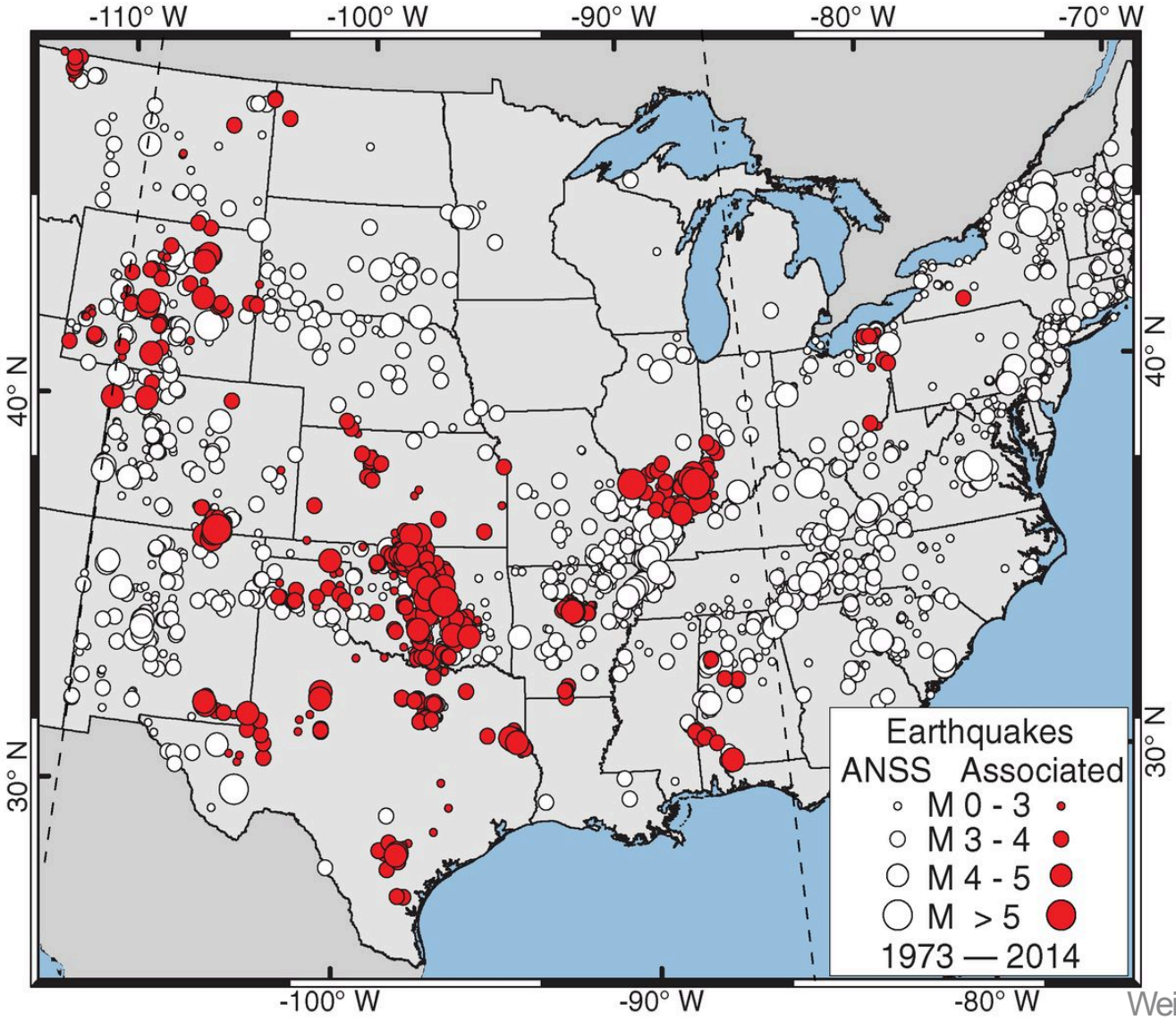
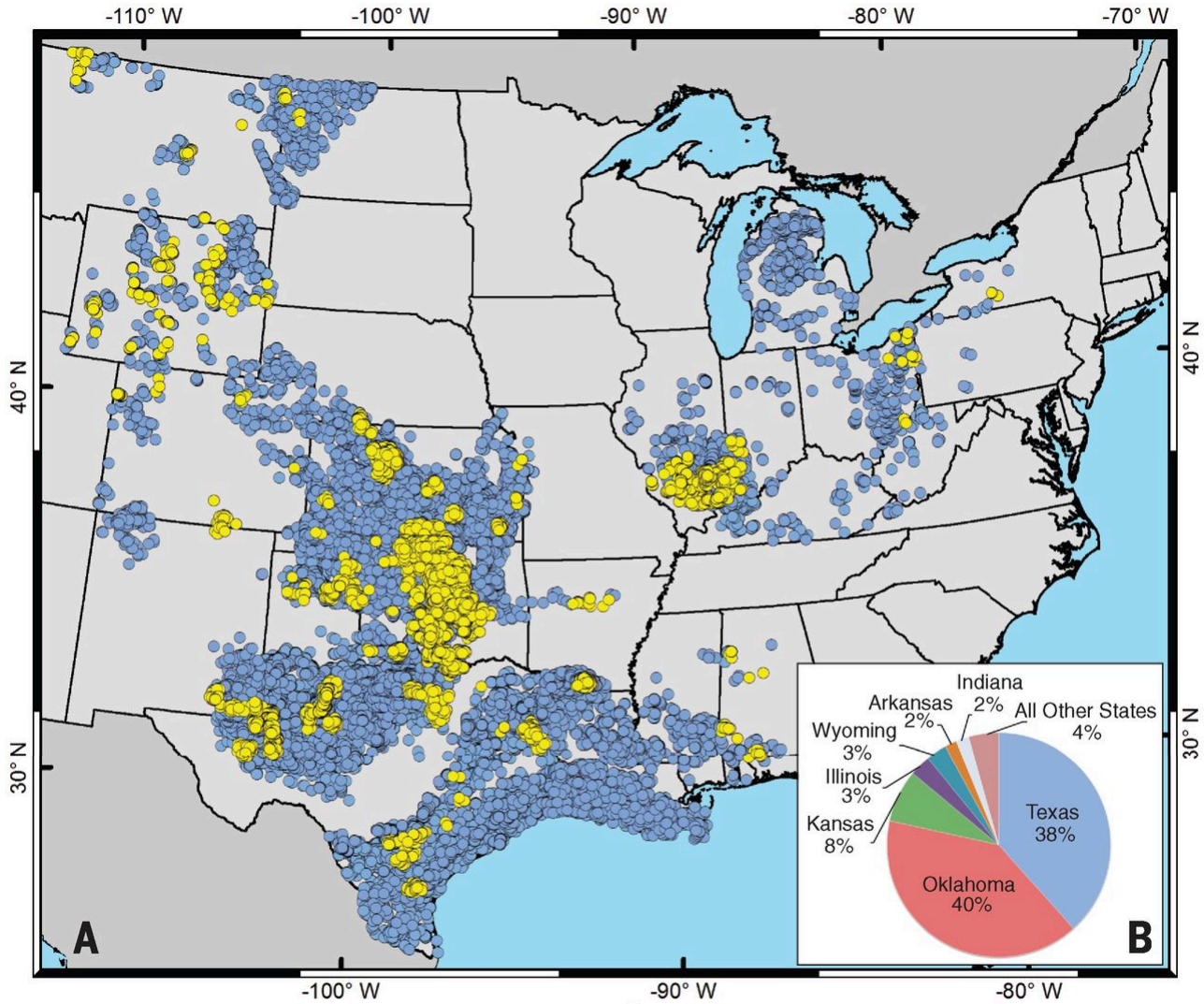


Weingarten *et al.*, 2015

Survey of Injection and EQs Across the CUS

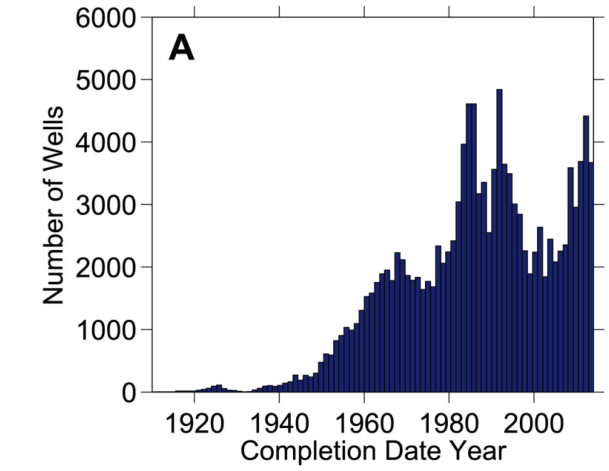


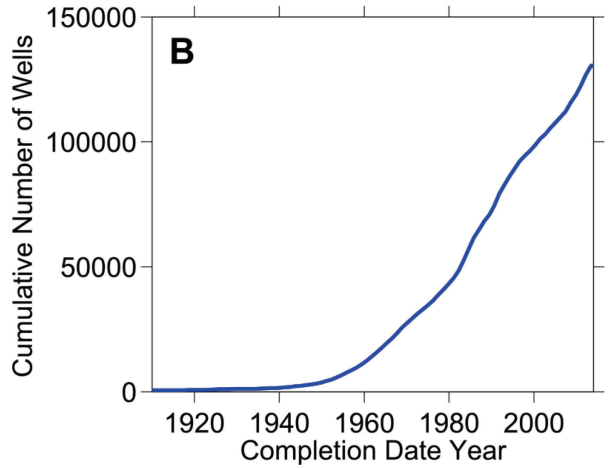
Active Injection Wells
27,102 - Salt Water Disposal
78,968 - Enhanced Oil Recovery

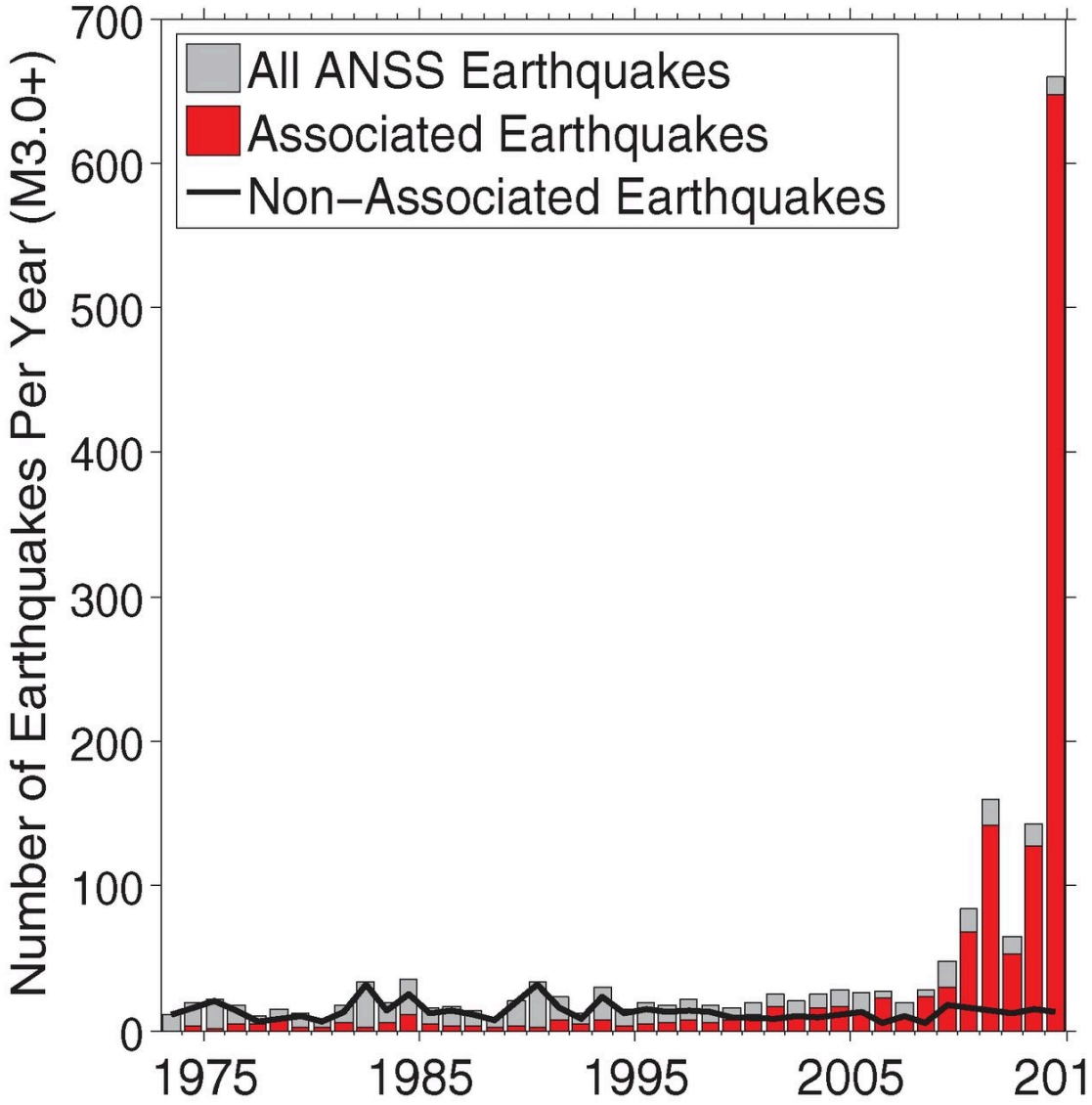
Associated Injection Wells
6,961 - Salt Water Disposal
11,796 - Enhanced Oil Recovery

Weingarten *et al.*, 2015

Number of EQs “Associated” with Wells



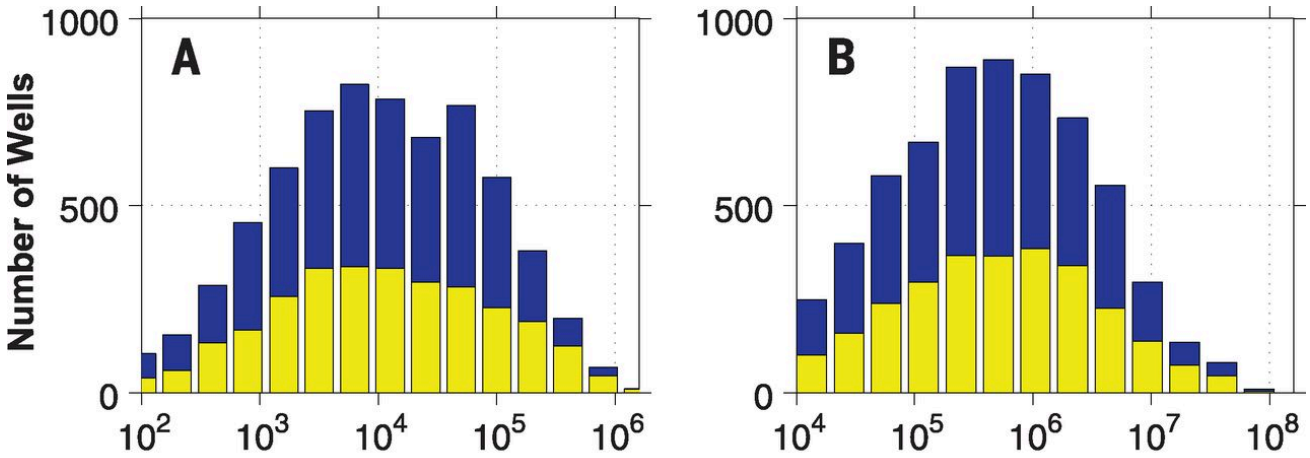




Weingarten *et al.*, 2015

What Controls Whether a Well Induces Earthquakes?

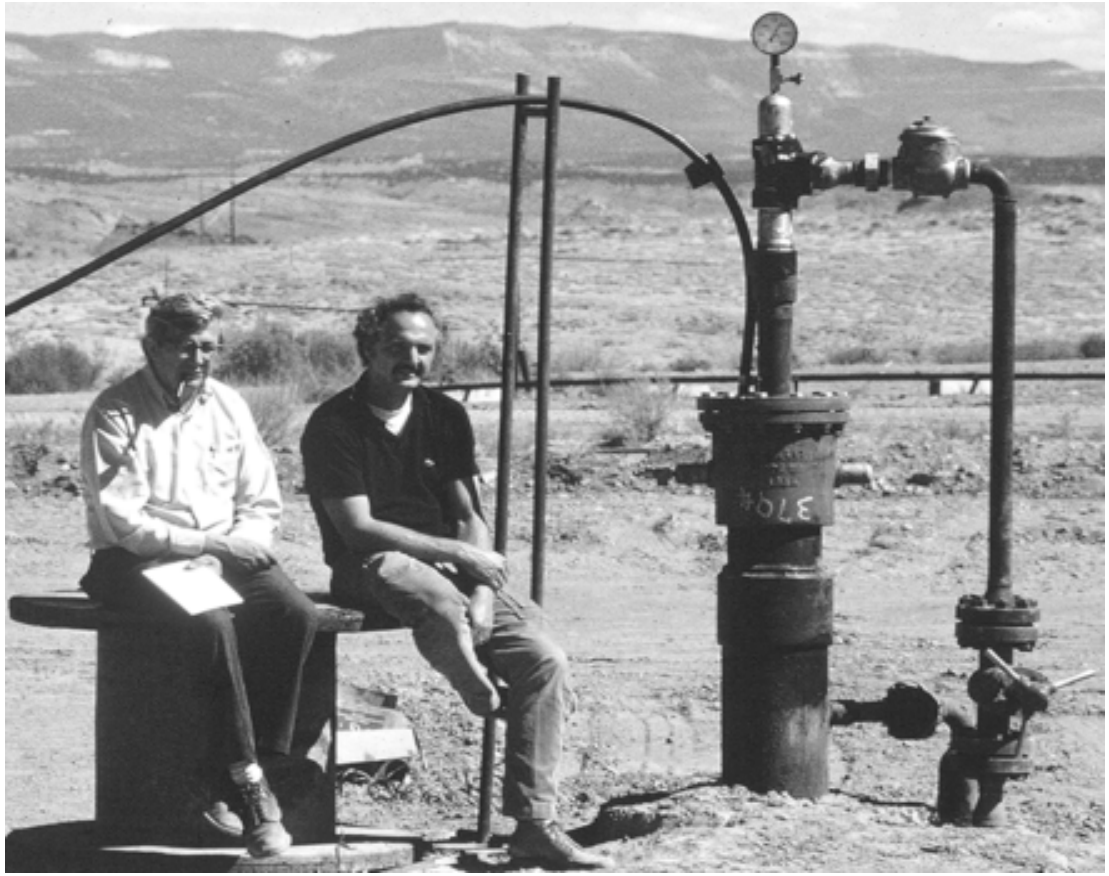
- Injection Rate
- Total Injected Volume
- Proximity to Basement
- Injection Pressure
- Geologic Factors



Weingarten *et al.*, 2015

Outlook

- We can control induced earthquakes to some degree
  - Rangely, Paradox Valley, Montney Trend



Outlook

- Forced shut-downs have reduced earthquake rates
  - Youngstown, Anthony, Greeley, Love County

Outlook

- Many states considering/have enacted regulations
  - Oklahoma, Kansas, Ohio, Texas, California, Arkansas, Oklahoma

Outlook

- EPA has released guidance on minimizing induced EQs

MINIMIZING AND MANAGING POTENTIAL IMPACTS OF INJECTION-INDUCED SEISMICITY FROM CLASS II DISPOSAL WELLS: PRACTICAL APPROACHES

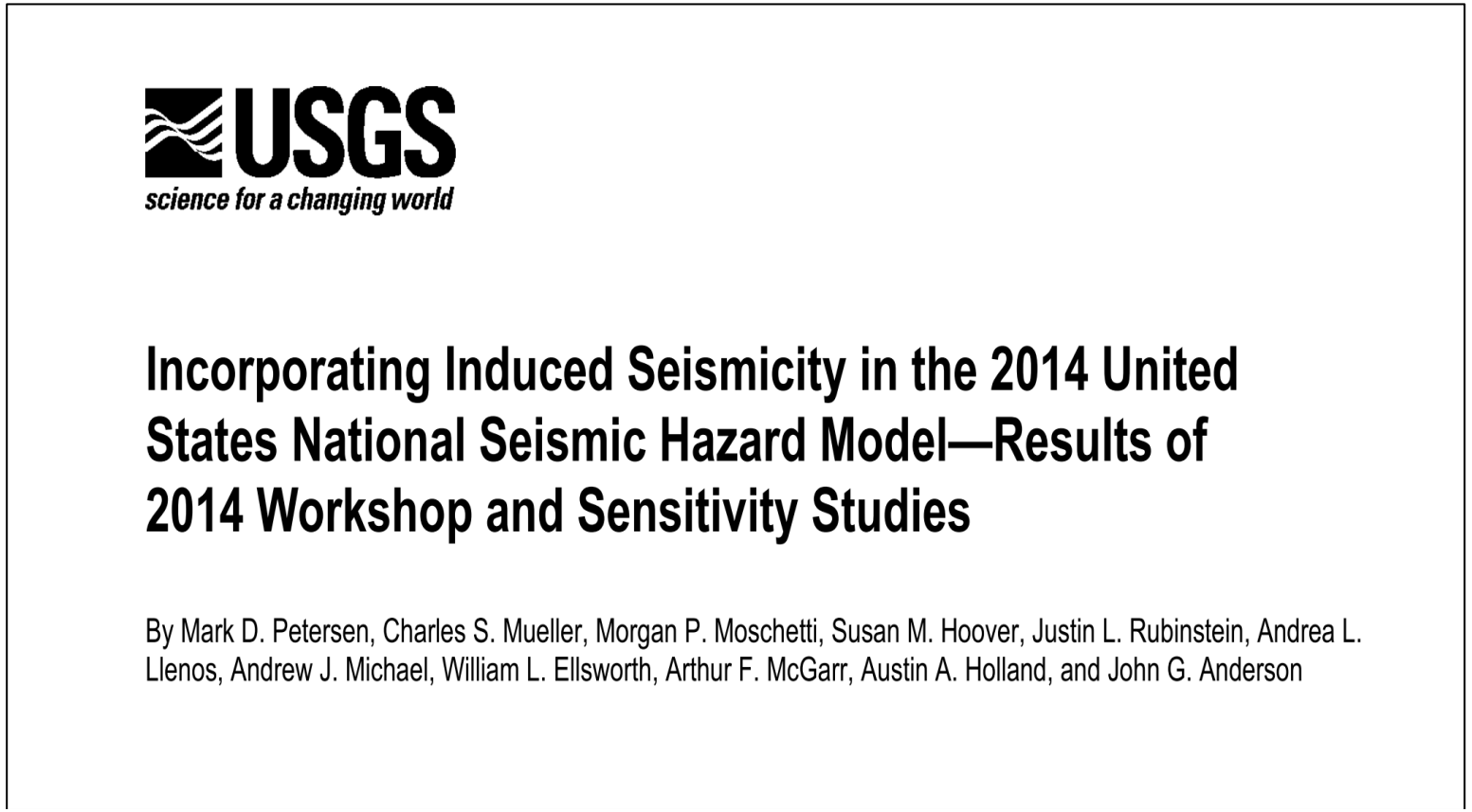
Underground Injection Control National Technical Workgroup
U.S. Environmental Protection Agency
Washington, DC

Draft: December 24, 2013
Revised: November 12, 2014

Outlook

- USGS has released a preliminary model for estimating induced earthquake hazard

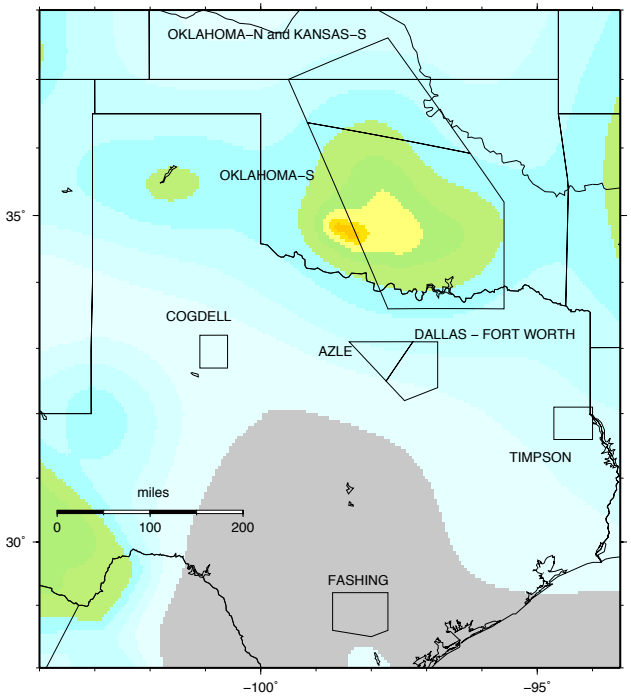
"Final" Model coming soon



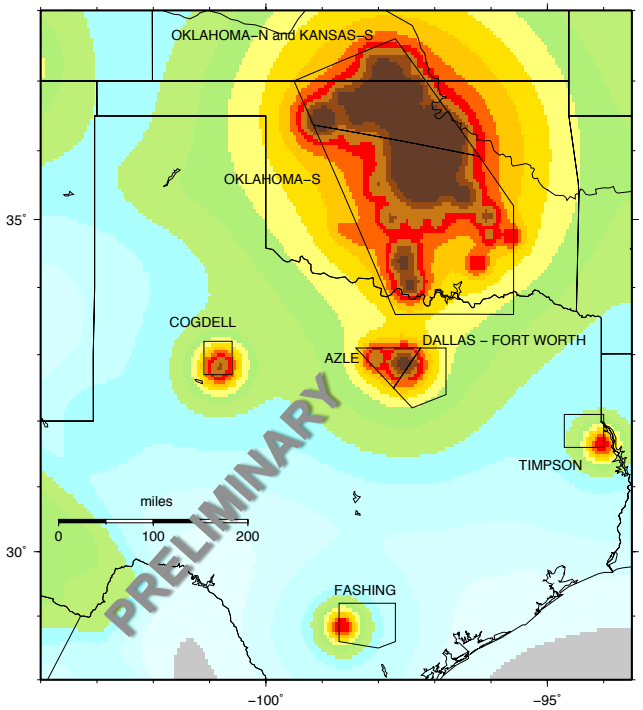
Outlook

- USGS has released a preliminary model for estimating induced earthquake hazard

Hazard Without Induced EQs



Preliminary Hazard With Induced EQs



Moving Forward

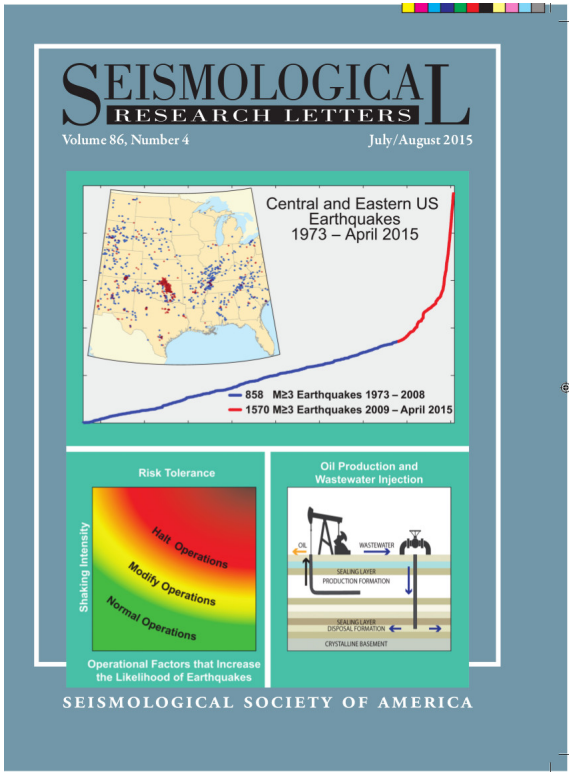
- High earthquake rates continue (manageable?)
- No large earthquakes **yet**
- Earthquakes in the central US are potentially more dangerous than those in the western US

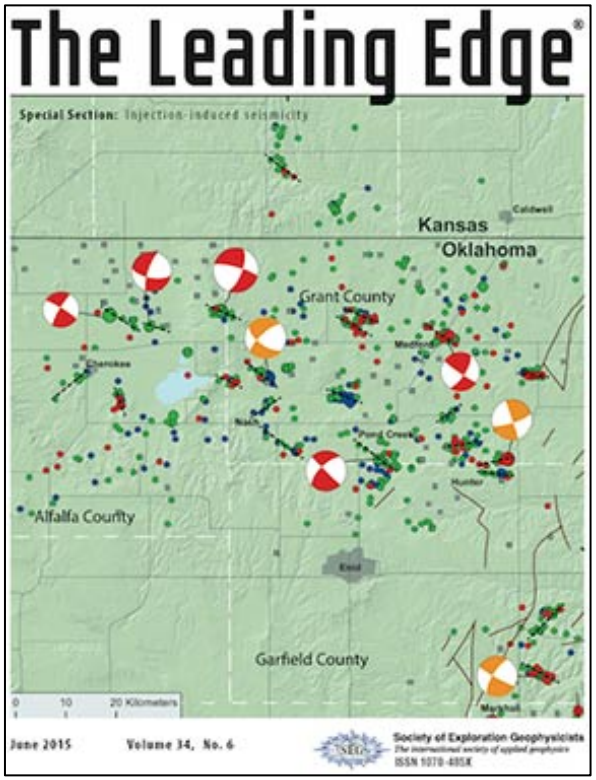
- Continued collaboration and cooperation between scientists, industry, and regulators is key
- Data sharing is key
- More research is needed

Areas of Ongoing Research

- Are the physical processes underlying induced earthquakes somehow different than natural earthquakes?
  - Stress Drop
- Are there ways to differentiate induced earthquakes from natural earthquakes?
  - Waveforms
  - Statistics
- How do we compute the hazard for induced earthquakes?
  - Ground motion
  - M_{max}
  - Rapidly evolving sequences
- How should these hazard computations be used?

More information





Myths and Facts on Wastewater Injection, Hydraulic Fracturing, Enhanced Oil Recovery, and Induced Seismicity

by Justin L. Rubinstein and Alireza Babaie Mahani

INTRODUCTION

The central United States has undergone a dramatic increase in seismicity over the past 6 years (Fig. 1), rising from an average

and the evidence is mounting that the seismicity in many of these locations is induced by the deep injection of fluids from nearby oil and gas operations. Earthquakes that are caused by human activities are known as induced earthquakes. Most injec-

earthquake.usgs.gov/research/induced