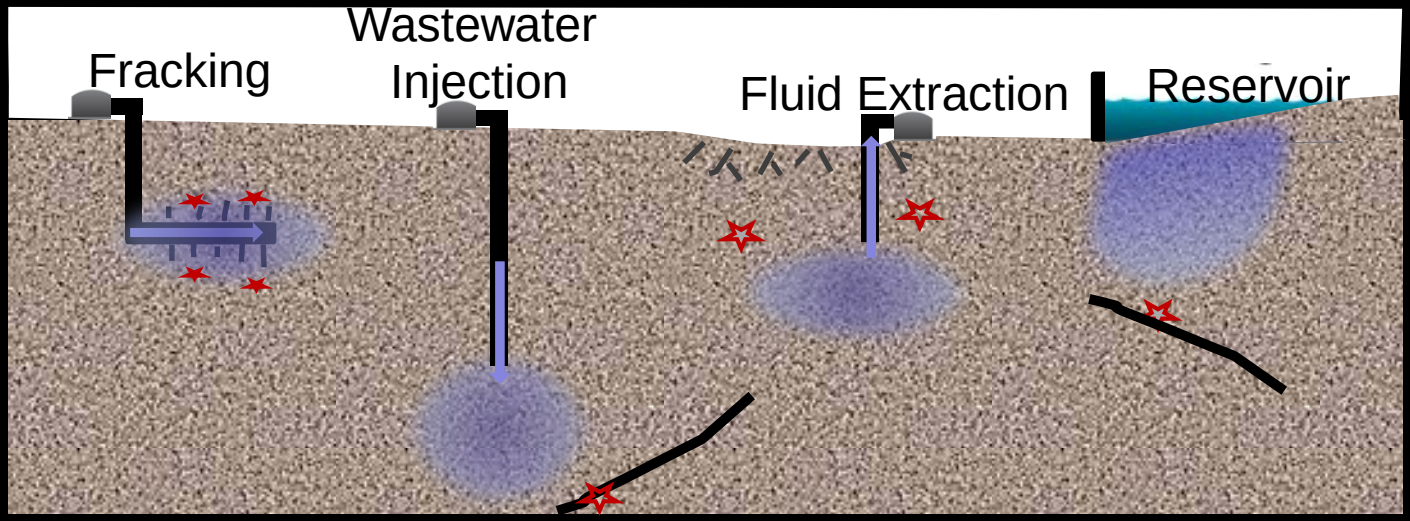
Fluid Induced Seismicity



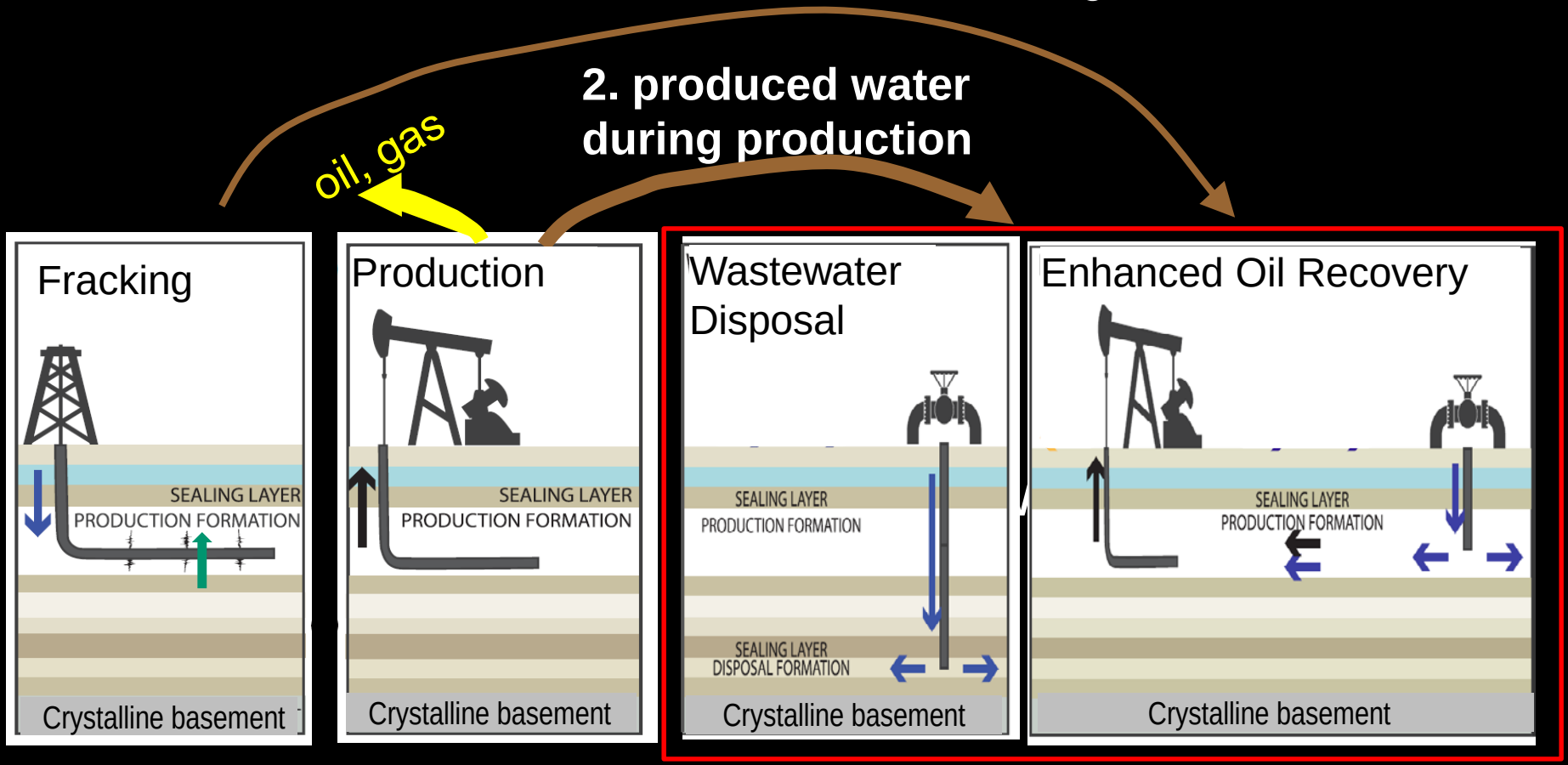
Shemin Ge
Department of Geological Sciences, University of Colorado

References:

Matthew Weingarten, Shemin Ge, Jonathan Godt, Barbara Bekins, Justine Rubinstein 2015, High-rate injection is associated with the increase in U.S.mid-continent seismicity, *Science*, 19 June 348(6241), 1336-1340.

Keranen, Kathleen, Matthew Weingarten, Geoffrey A. Abers, Barbara Bekins, Shemin Ge. 2014. Sharp increase since 2008 induced by massive wastewater injection. *Science*. 25 July, 345(6195), 448-451

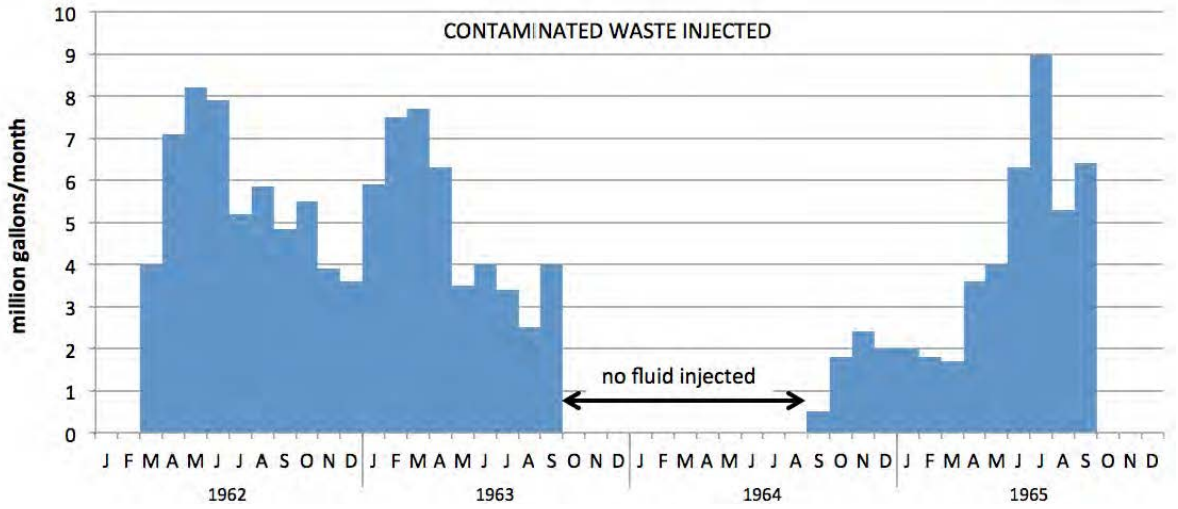
To extract oil/gas from these tight shales, wastewater is produced at various stages

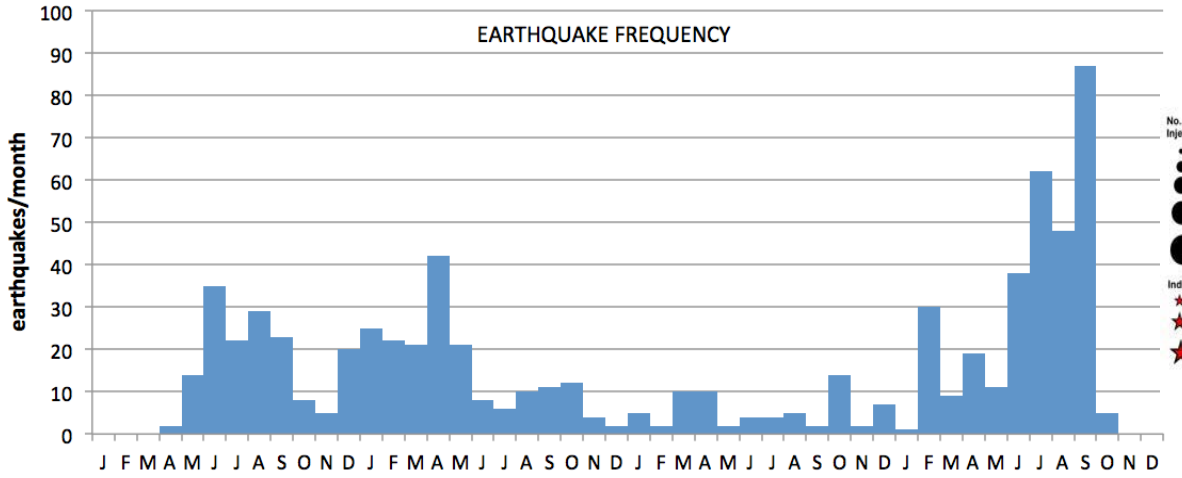


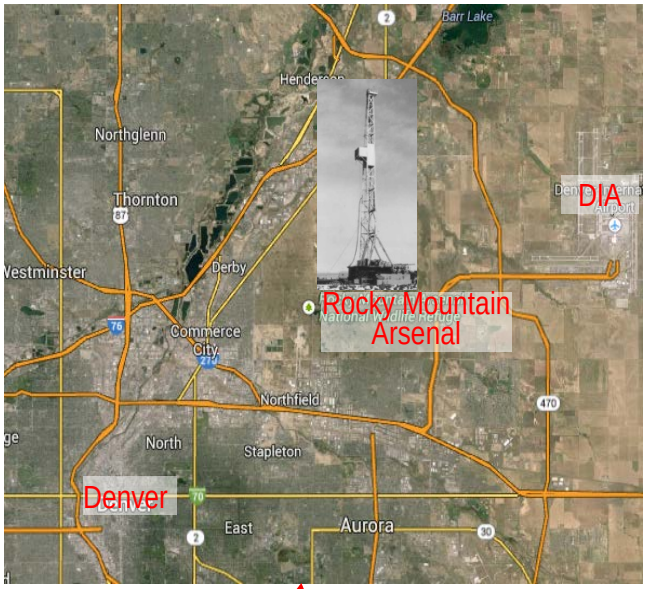
[after Rubinstein and Mahani, 2015]

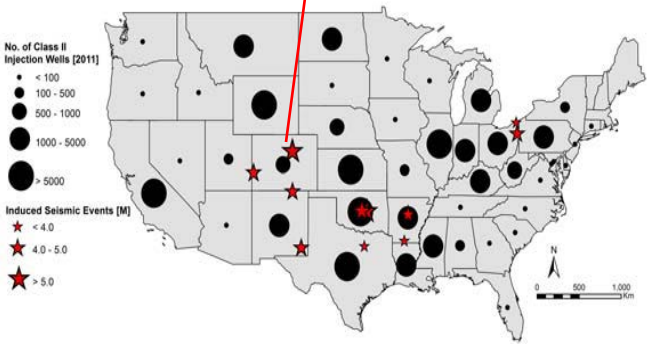
~ 40% of the wastewater is disposed by deep well injection

Rocky Mountain Arsenal, 1960's
Temporal Correlation







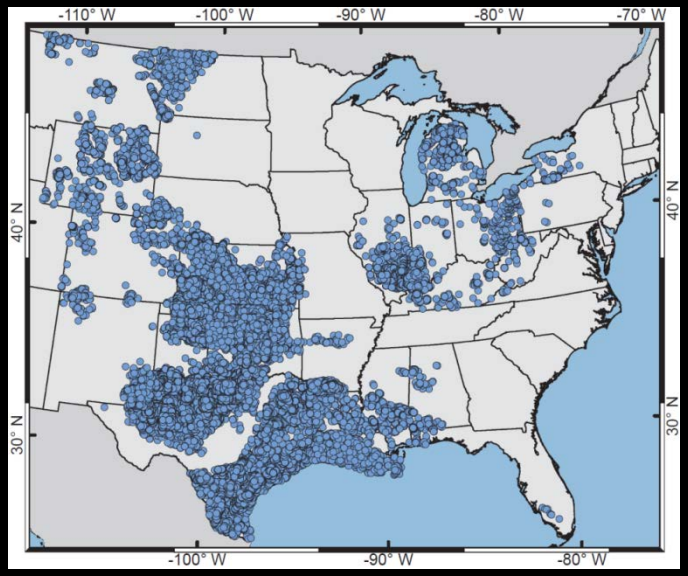


[Healy et al.,1968]

Why are some injection sites more prone to seismicity than others?

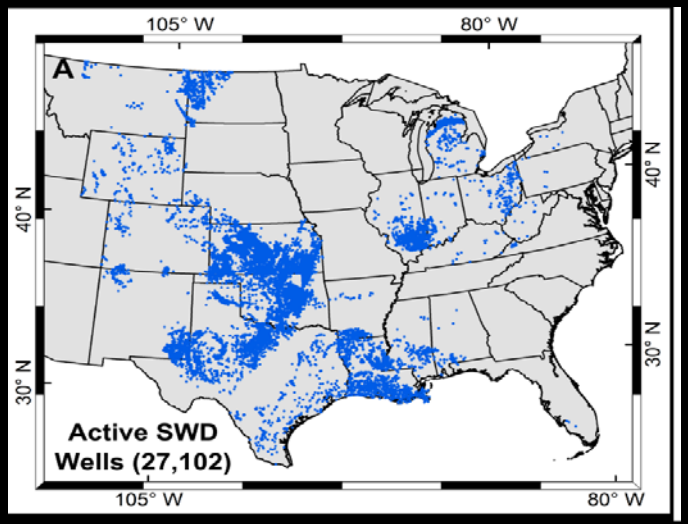
Injection Wells

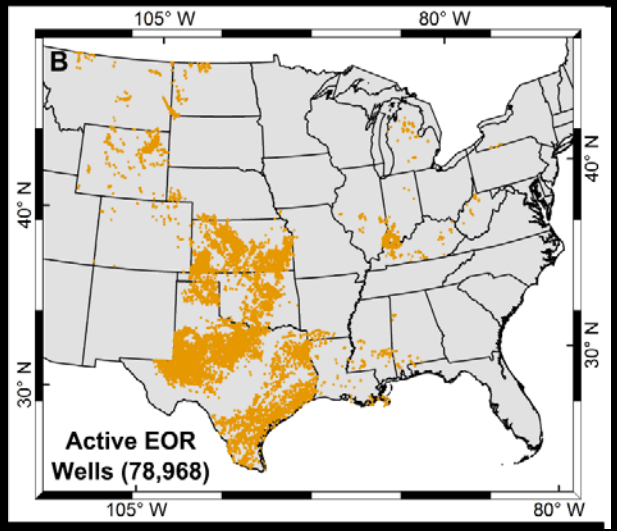
188,570
34 states



106,070 active:
27,102 Salt water disposal

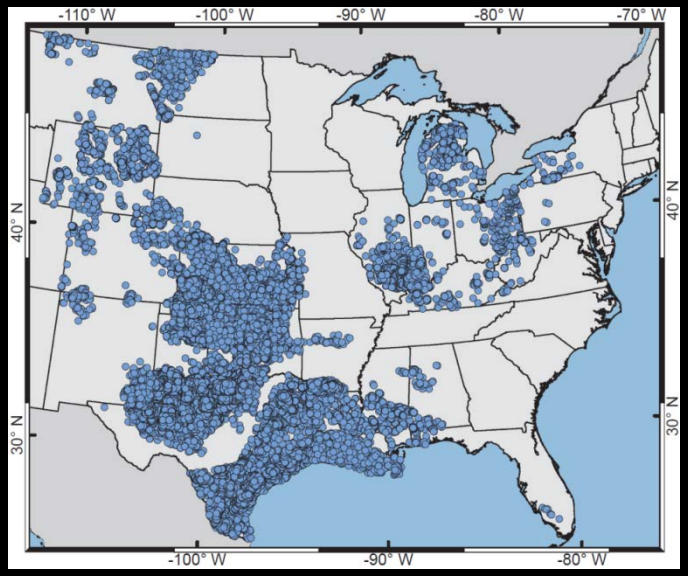
78,968 Enhanced oil recovery



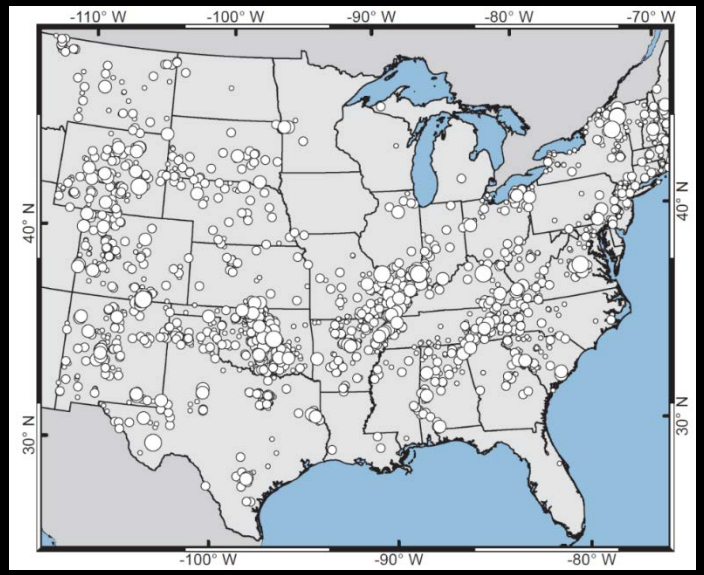


Injection Wells

188,570
34 states



Related?



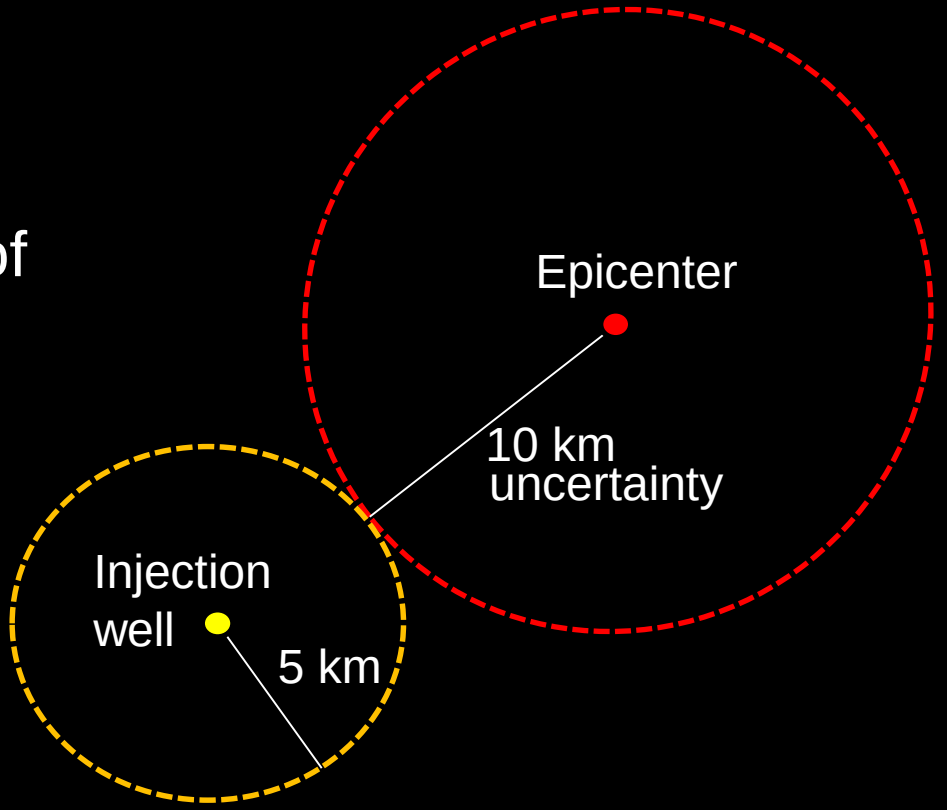
Earthquakes
M > 0.0
1973 - 2015

Advanced National Seismic System earthquake catalog

Spatial and Temporal Association Criteria

- Spatial Criterion

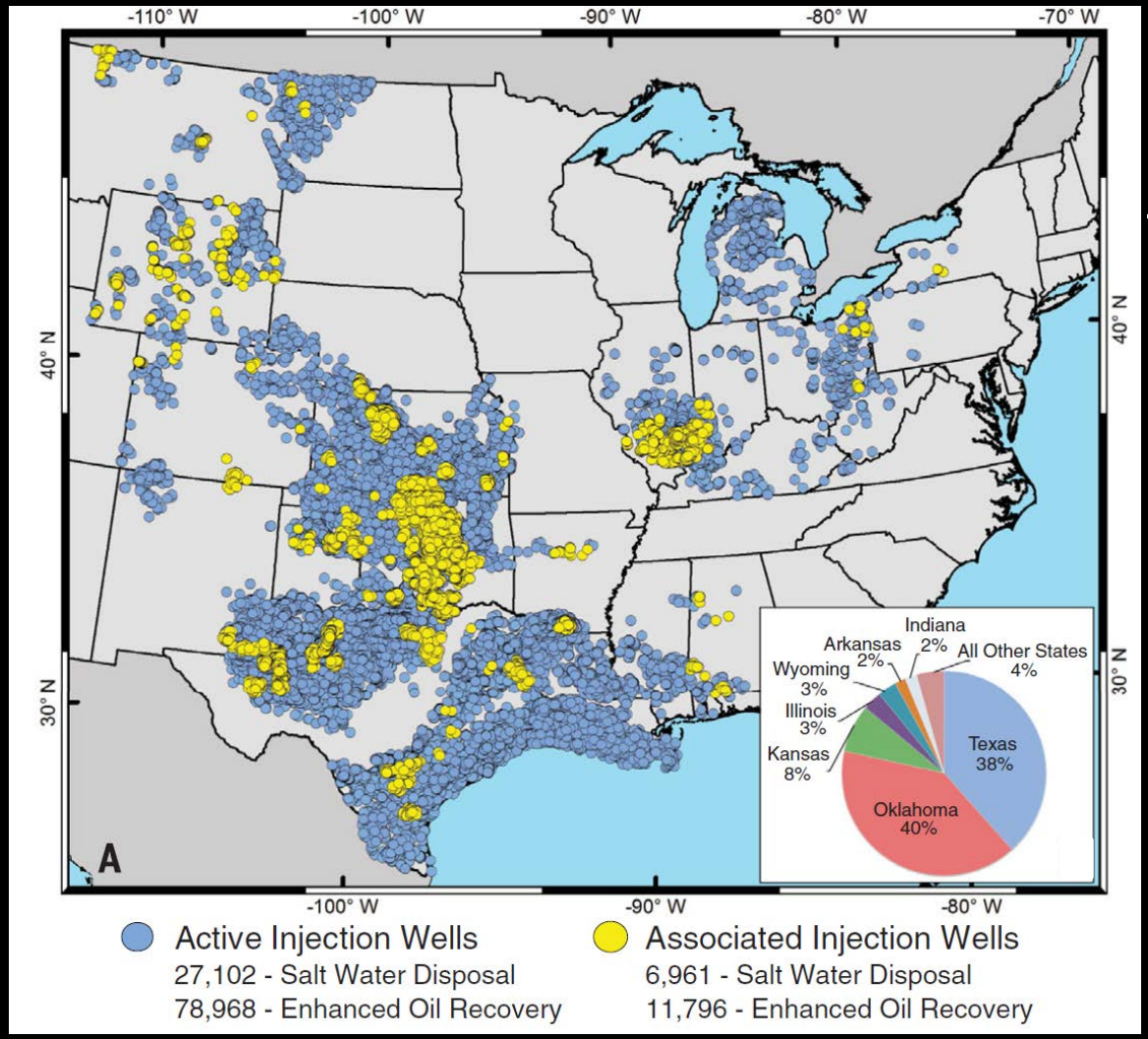
earthquake within 15 km of an injection well is considered to be spatially associated with that well



- Temporal Criterion

well is injecting at the time of the earthquake

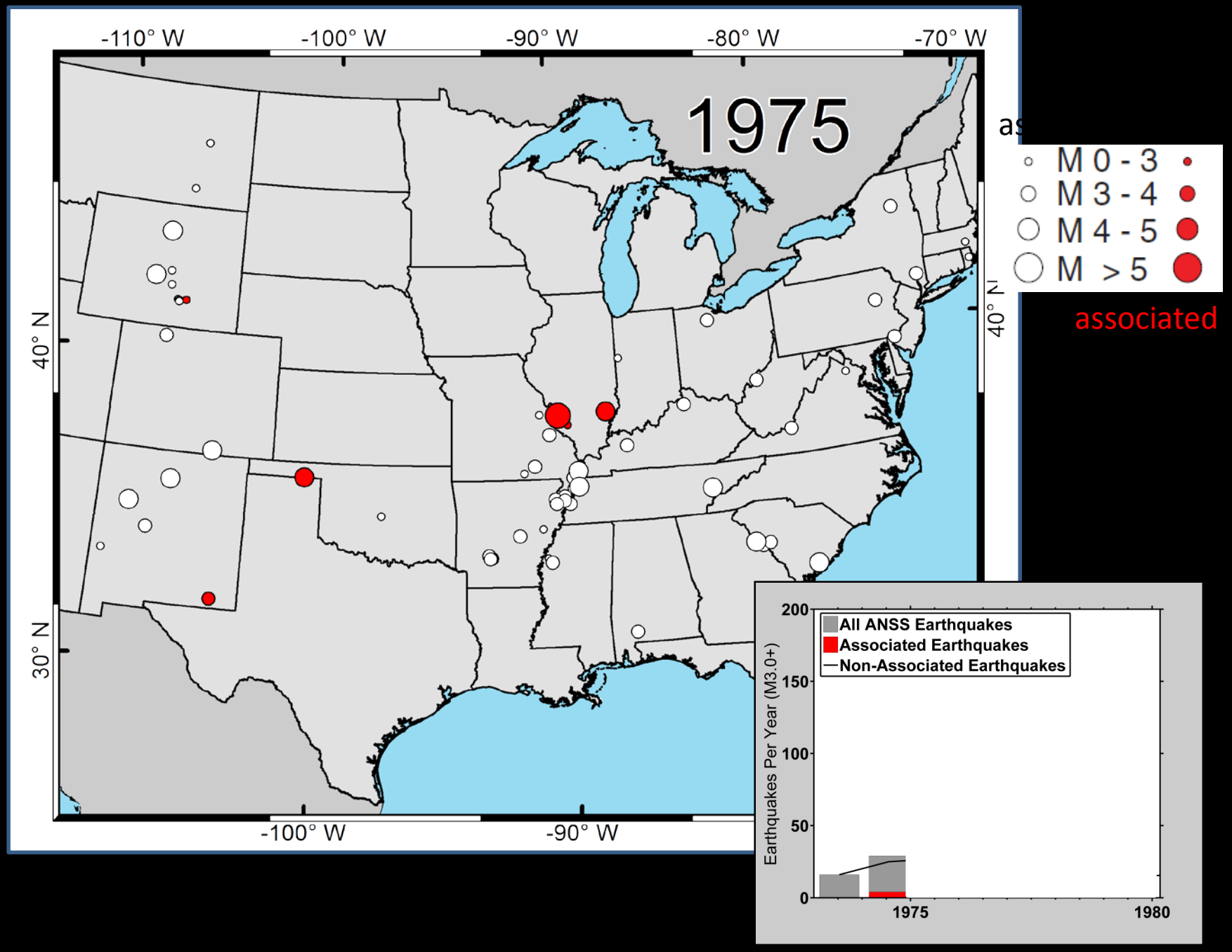
Active and Spatiotemporally Associated Injection wells

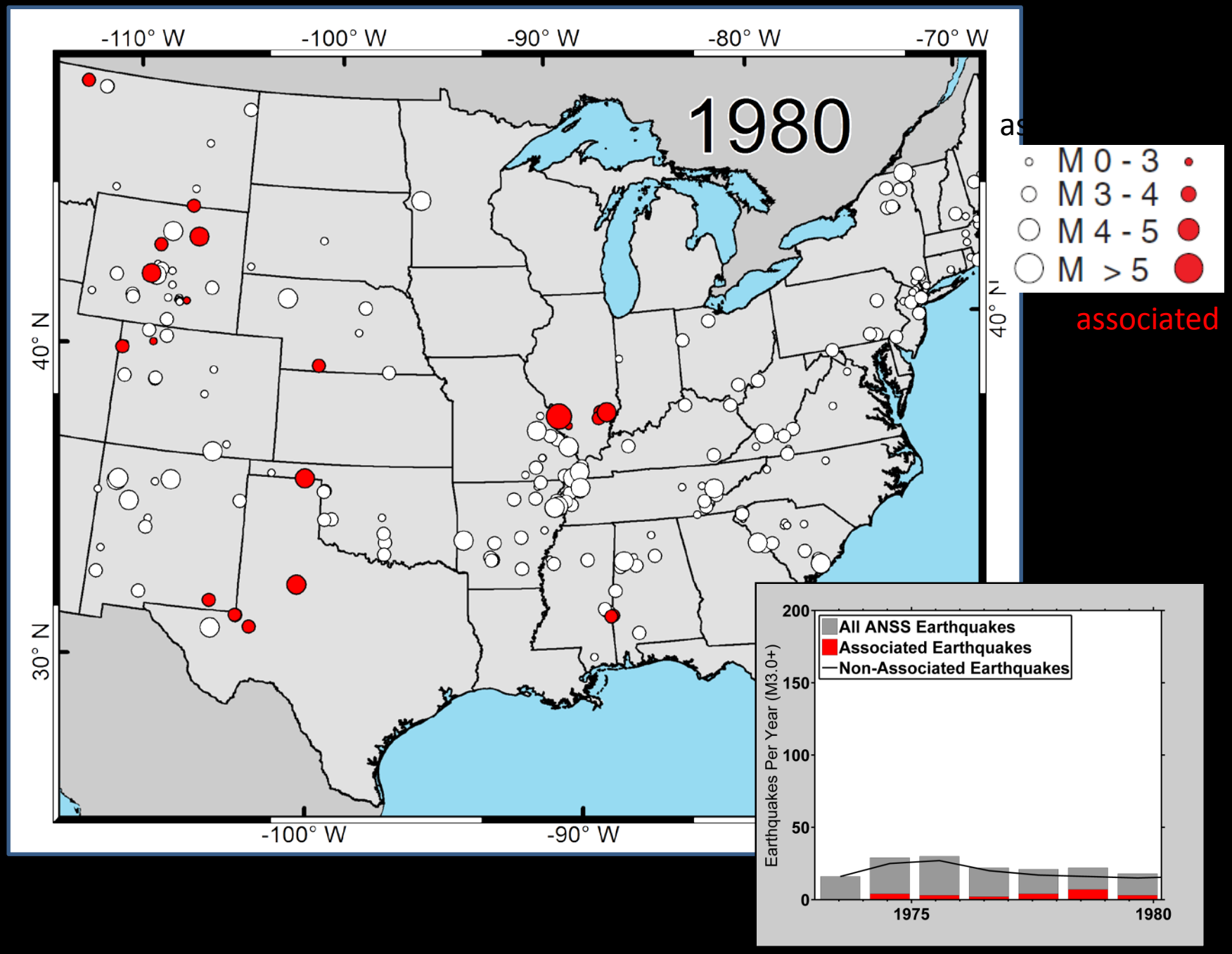


18,757 associated
~ 10% of all wells

~85% in Oklahoma, Texas, Kansas

Earthquakes associated with injection through time…..


-110° W
-100° W
-90° W
-80° W
-70° W
1975
40° N
30° N
M 0 - 3
M 3 - 4
M 4 - 5
M > 5
associated
All ANSS Earthquakes
Associated Earthquakes
Non-Associated Earthquakes
Earthquakes Per Year (M3.0+)
200
150
100
50
0
1975
1980


-110° W
-100° W
-90° W
-80° W
-70° W
1980
40° N
30° N
M 0 - 3
M 3 - 4
M 4 - 5
M > 5
associated
All ANSS Earthquakes
Associated Earthquakes
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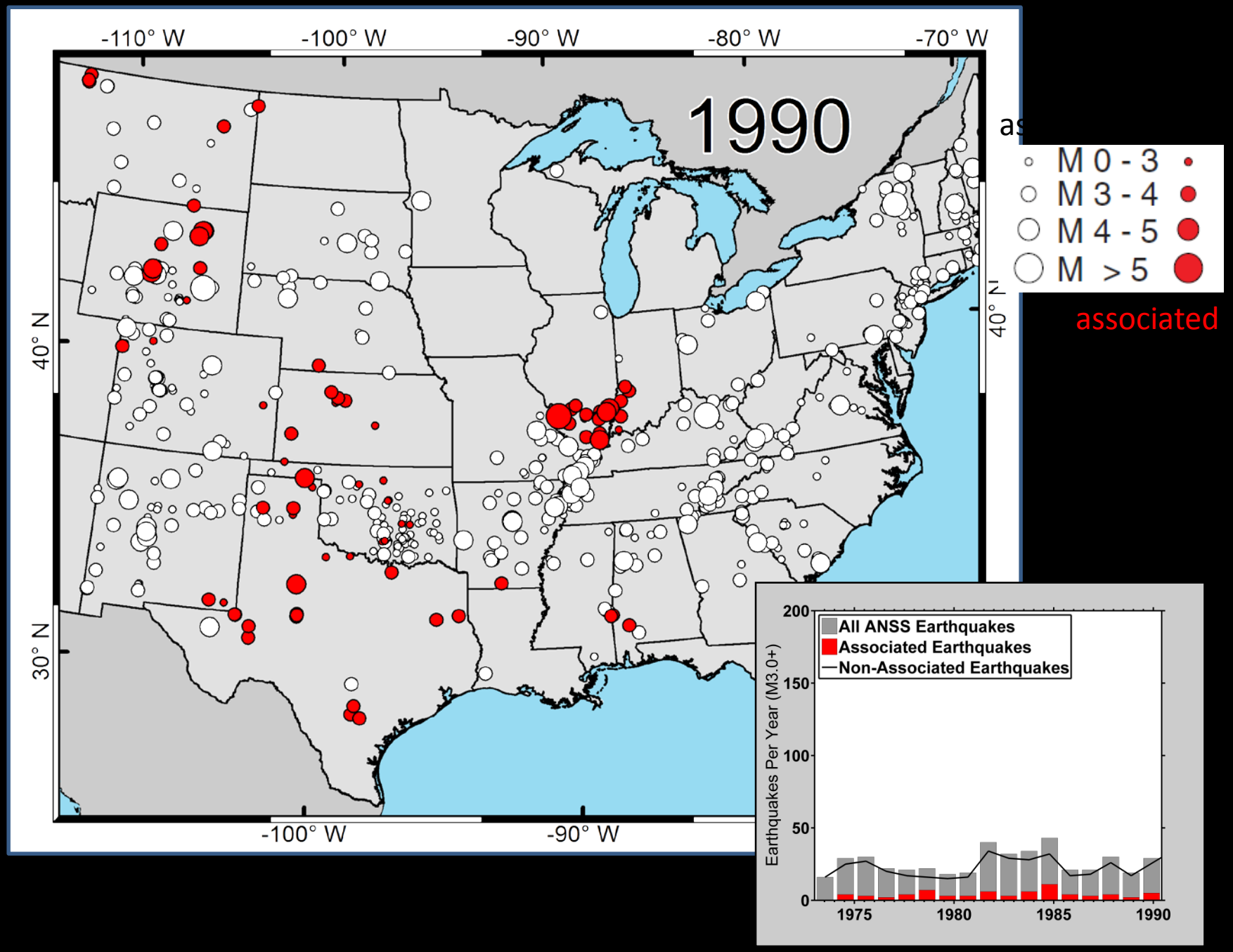
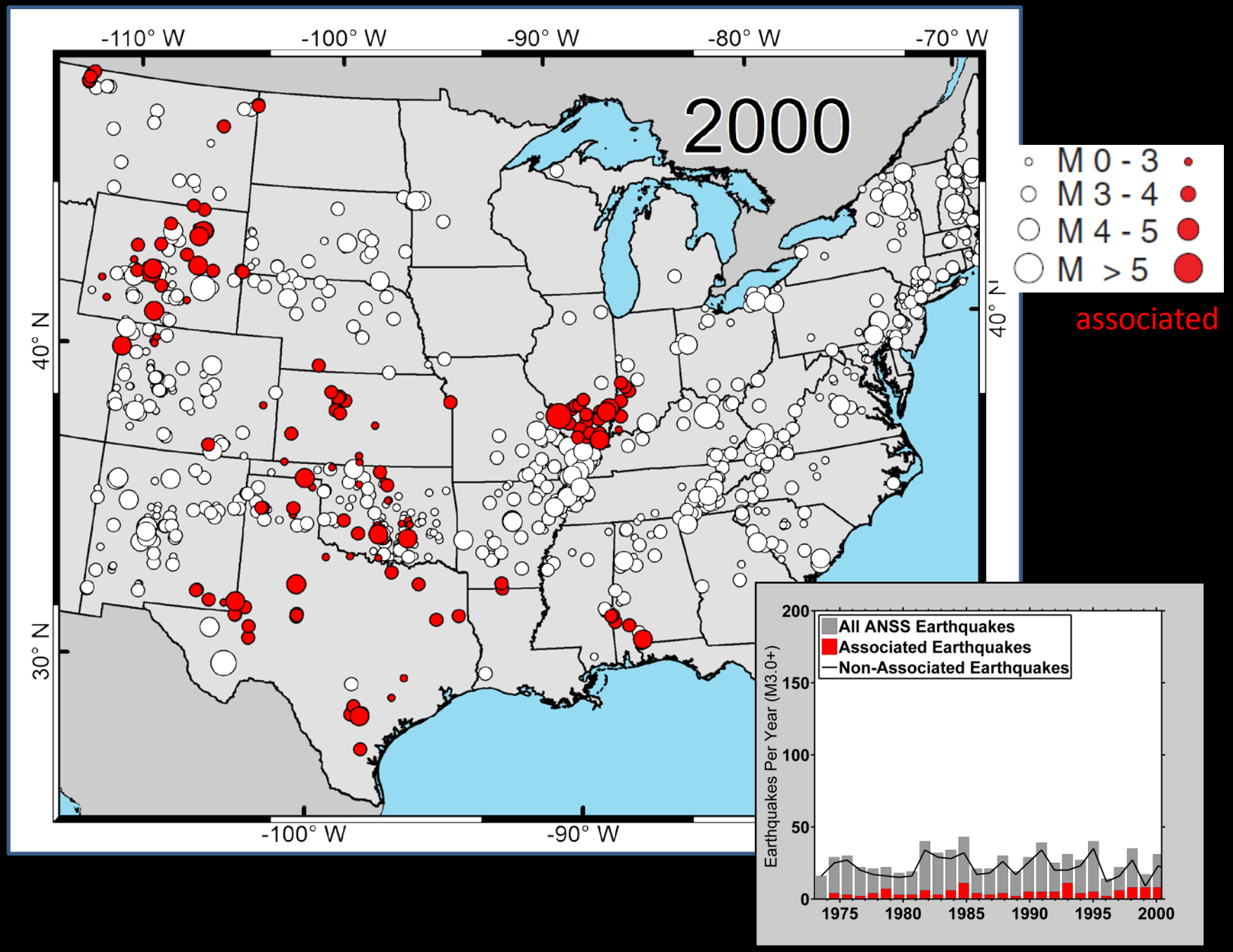
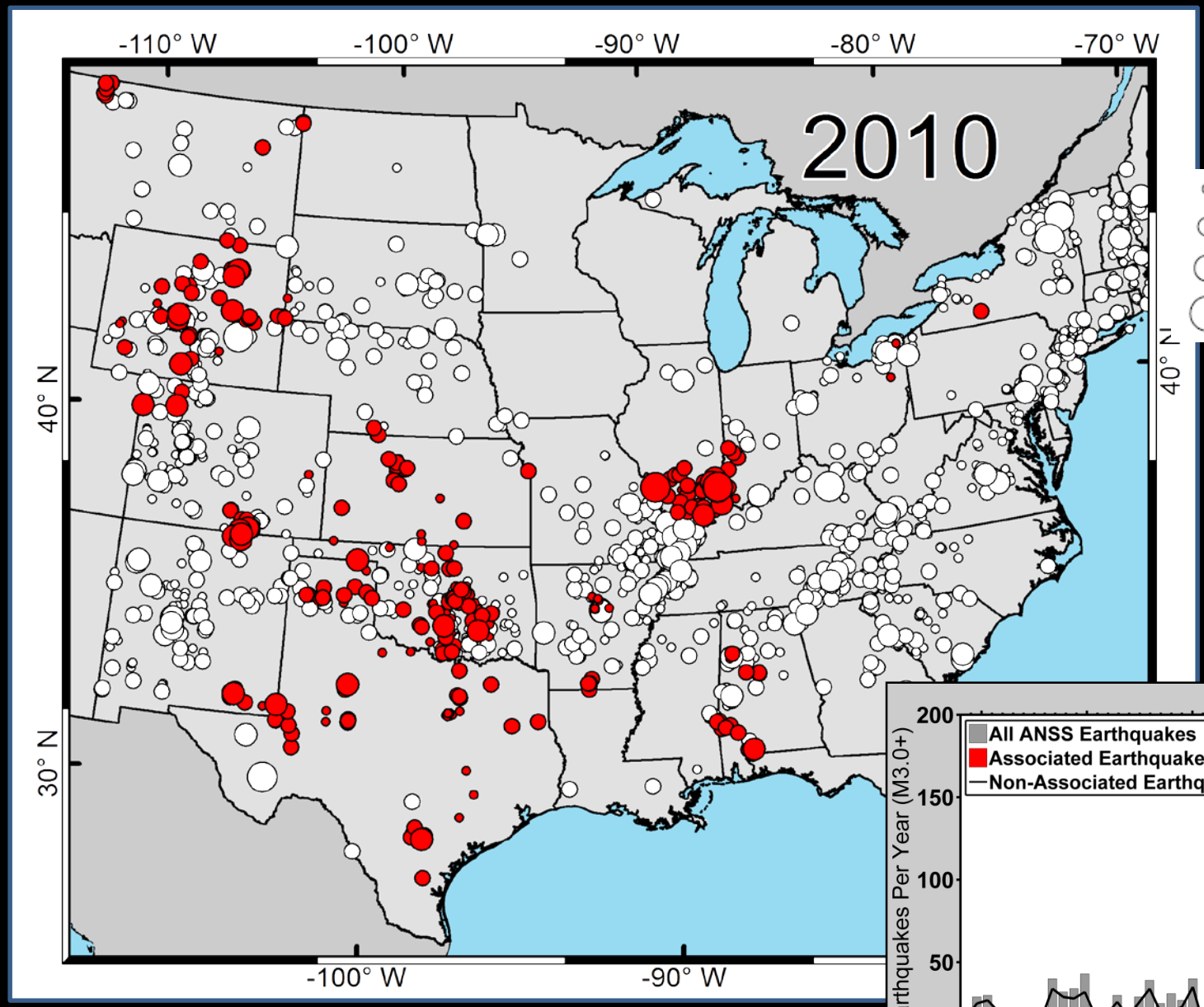
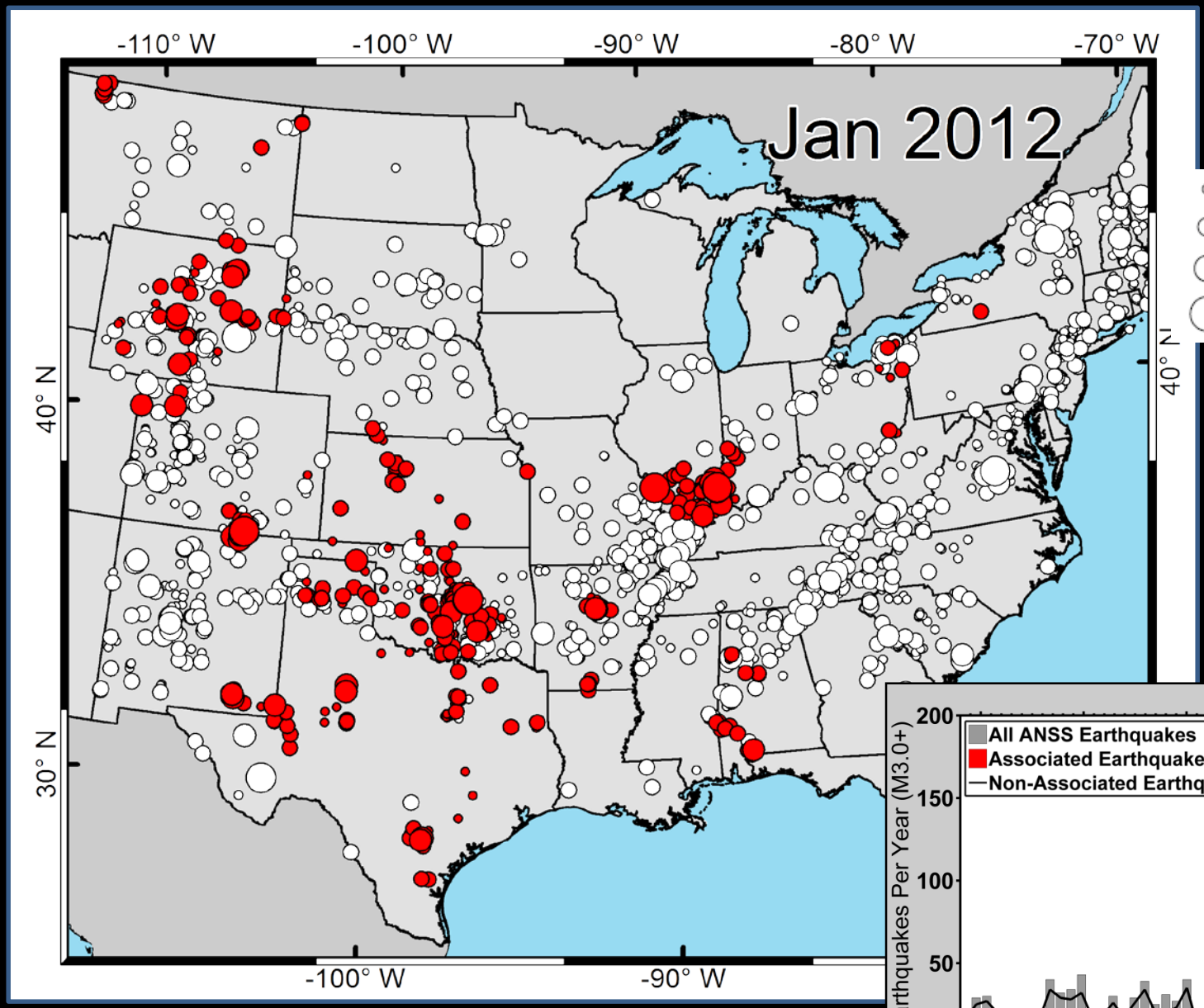
Earthquakes Per Year (M3.0+)
200
150
100
50
0
1975
1980


-110° W
-100° W
-90° W
-80° W
-70° W
1990
40° N
30° N
M 0 - 3
M 3 - 4
M 4 - 5
M > 5
associated
All ANSS Earthquakes
Associated Earthquakes
Non-Associated Earthquakes
Earthquakes Per Year (M3.0+)
200
150
100
50
0
1975
1980
1985
1990

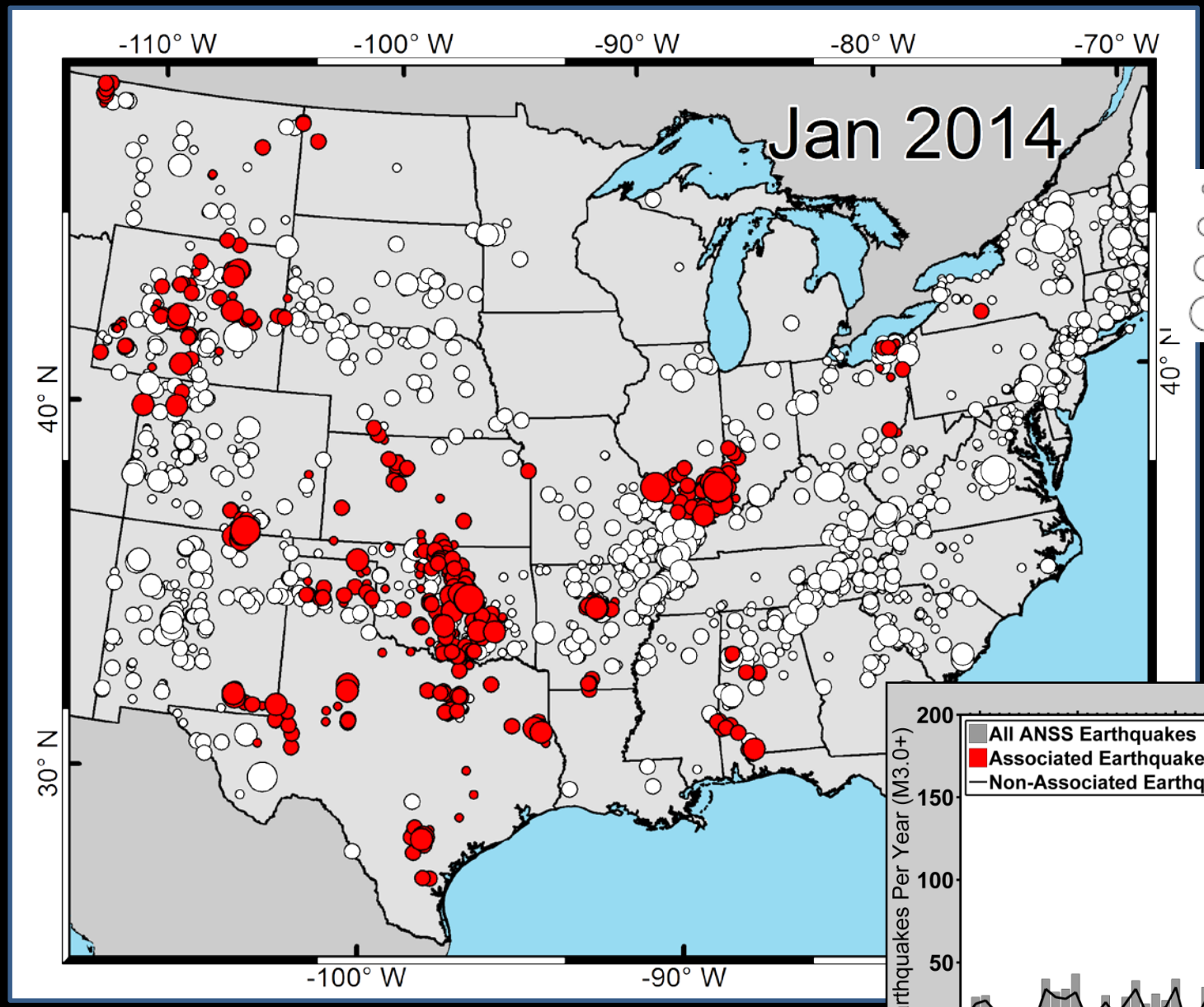

-110° W
-100° W
-90° W
-80° W
-70° W
40° N
30° N
2000
M 0 - 3
M 3 - 4
M 4 - 5
M > 5
associated
All ANSS Earthquakes
Associated Earthquakes
Non-Associated Earthquakes
Earthquakes Per Year (M3.0+)
200
150
100
50
0
1975
1980
1985
1990
1995
2000



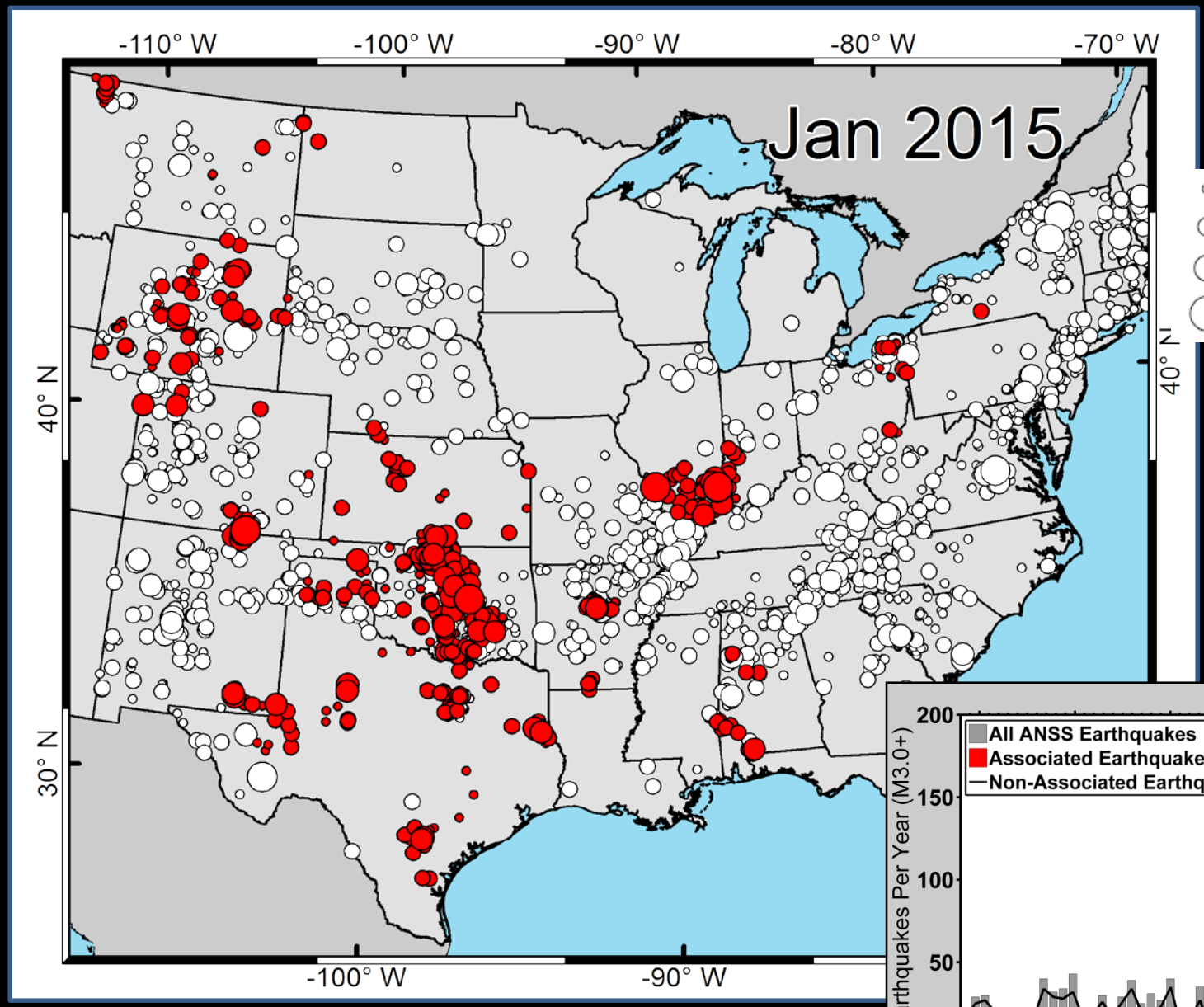
Increased seismicity started

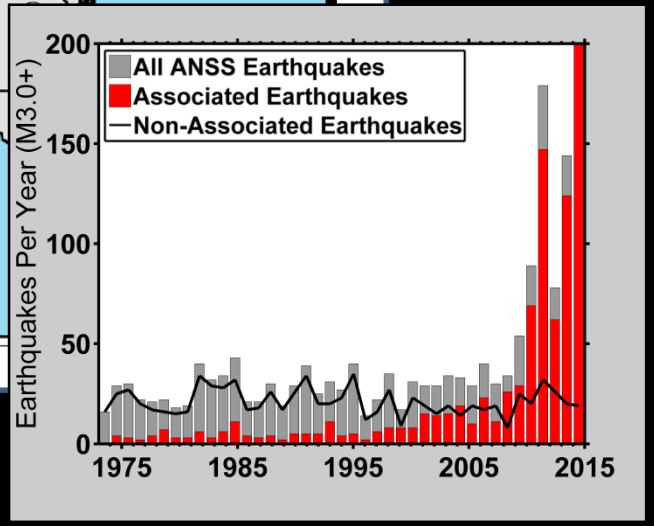


Increased seismicity continued



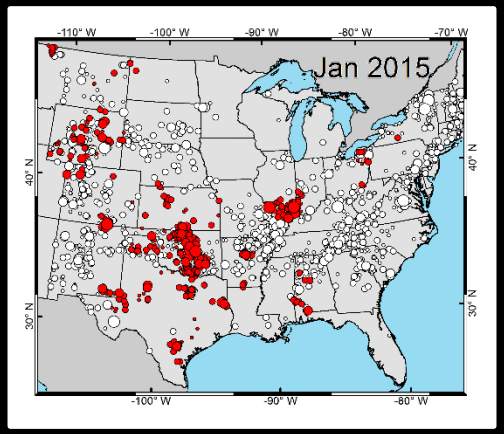
Increased seismicity continued





Increased seismicity continued

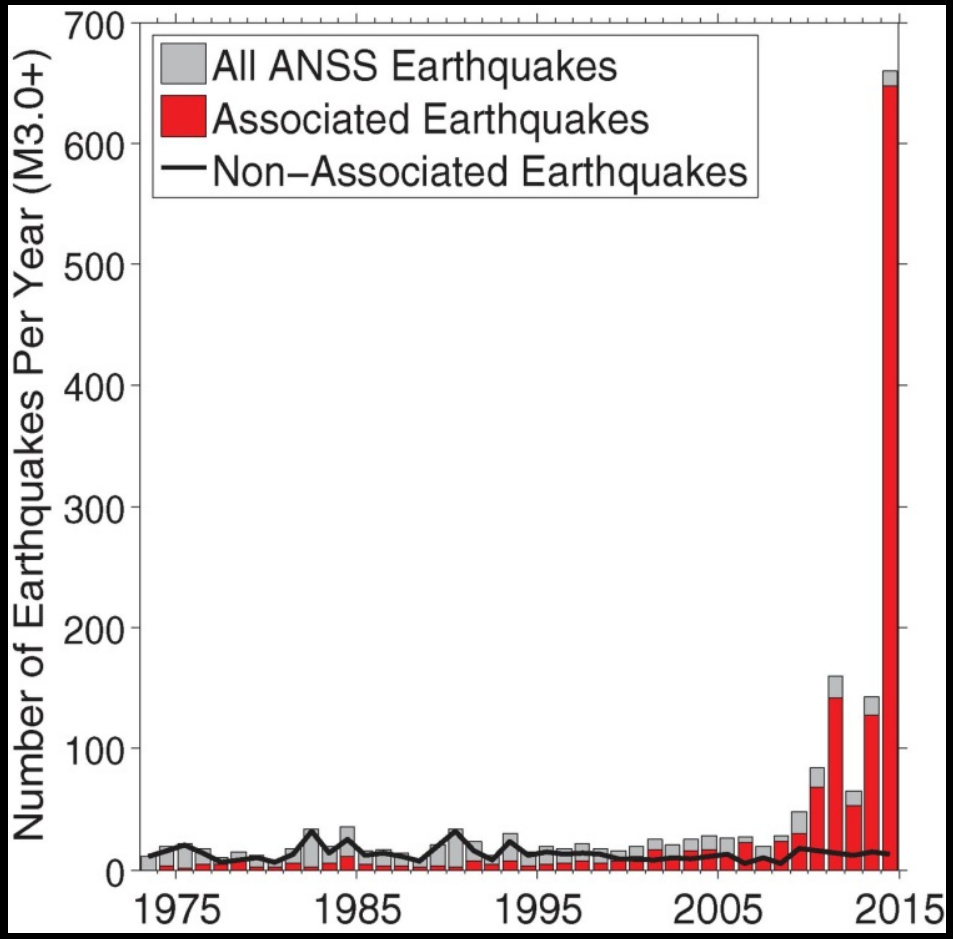
Associated Earthquakes, 1973 - 2015



Non-associated earthquakes stayed at 10 – 25/year

Associated earthquakes rose:

a few	tens	> 650
1970s	early 2010s	2015

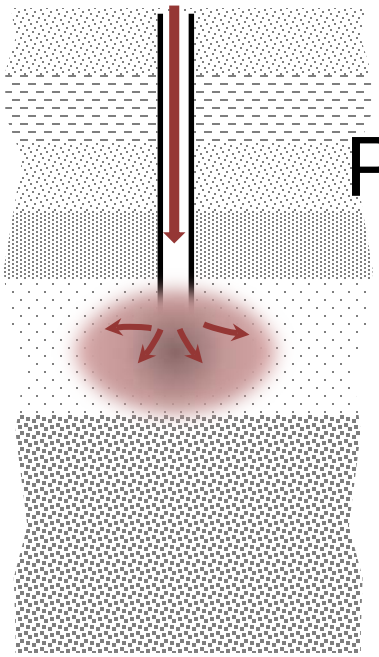


Increased seismicity in recent years in U.S. mid-continent is associated with injection wells

Spatiotemporal correlations

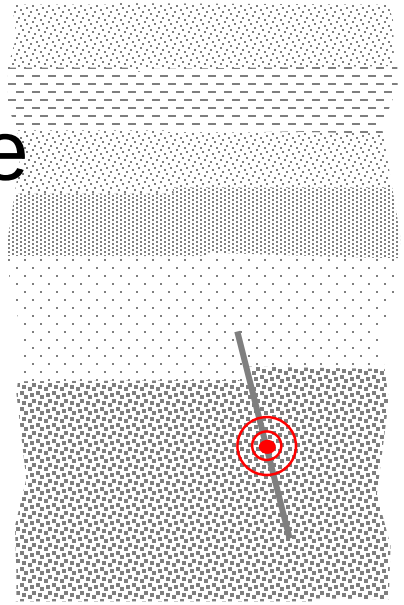
Causation

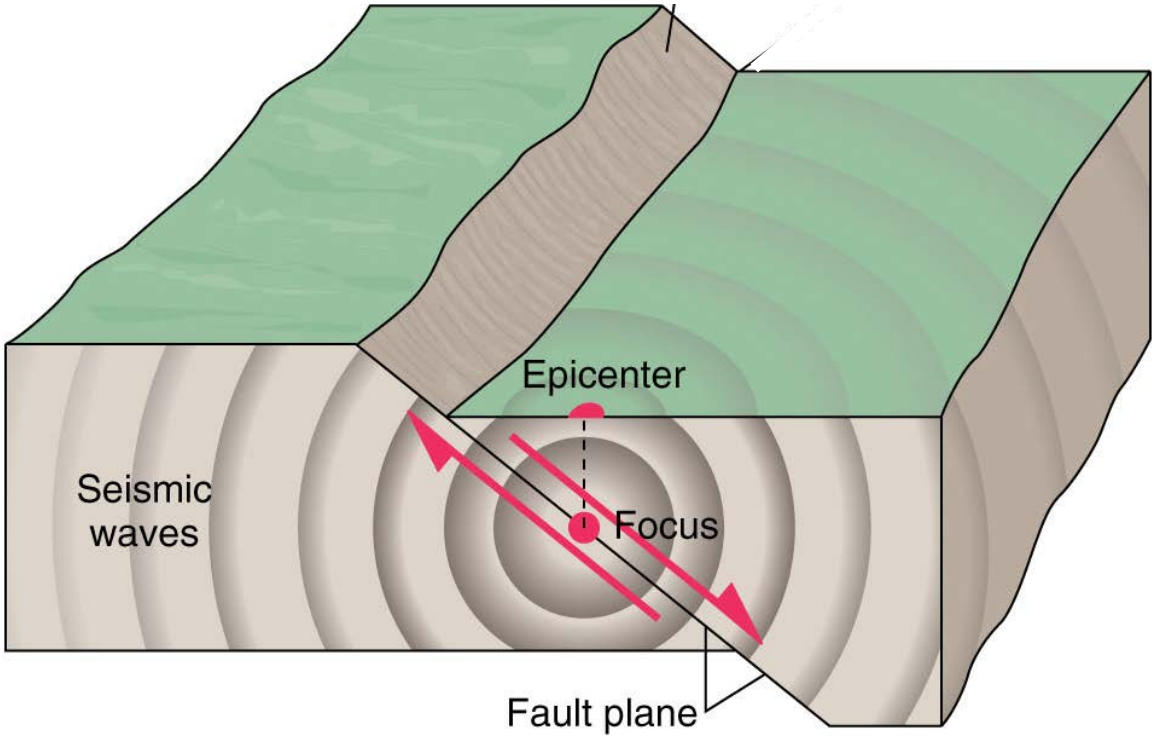
Wastewater Injection Induced earthquakes



Pore pressure dynamics

a key link

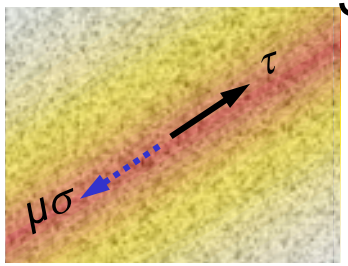



Epicenter
Seismic
waves
Focus
Fault plane

Coulomb stress

(Byerlee 1978,..)

Shear stress : τ



Frictional resistance : $\mu\sigma$

Coulomb stress: $S = \tau - \mu\sigma$

S < 0, Shear stress < Frictional resistance, stable

S > 0, Shear stress > Frictional resistance, unstable

S = 0, Shear stress ~ Frictional resistance, critically stressed

[e.g., Lin and Stein, 2004]

Pore Pressure Influences Coulomb stress

beer can experiment

(Hubbert and Rubey, 1959)

$$\Delta S = \Delta\tau - \mu\Delta\sigma$$

need a steeper angle

larger friction resistance

room temperature

need a gentle slope

smaller friction resistance

$$\Delta S = \Delta\tau - \mu(\Delta\sigma - \Delta P)$$

freezer chilled

Coulomb stress change

$$\Delta S = \Delta\tau - \mu\Delta\sigma + \mu\Delta P$$

$\Delta S < 0$, stable

$\Delta S > 0$, unstable slip

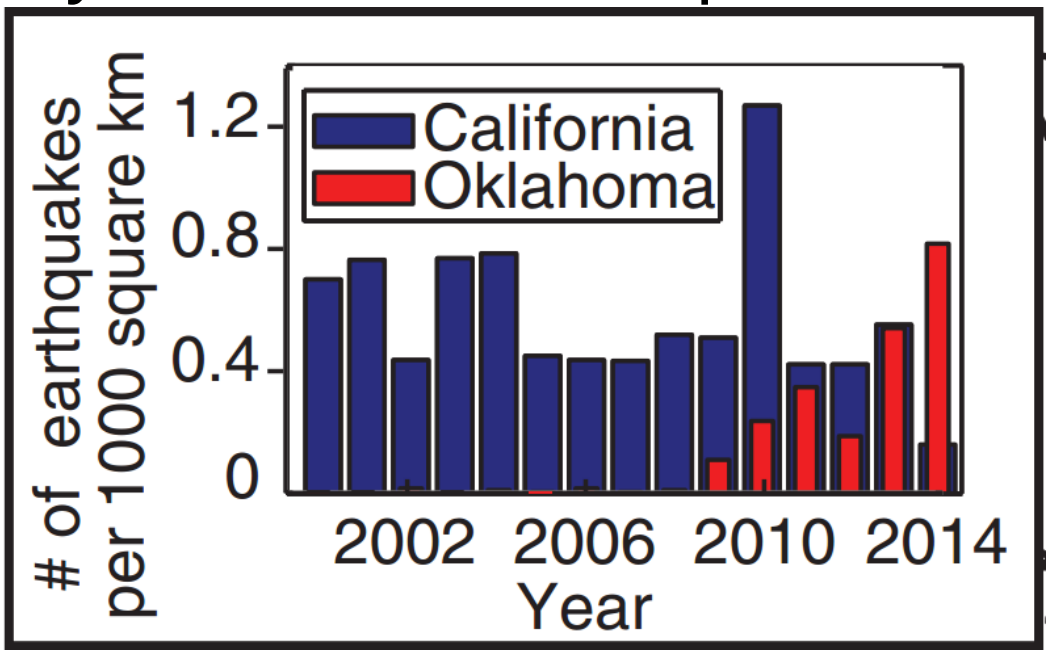
$\Delta S = 0$, in equilibrium

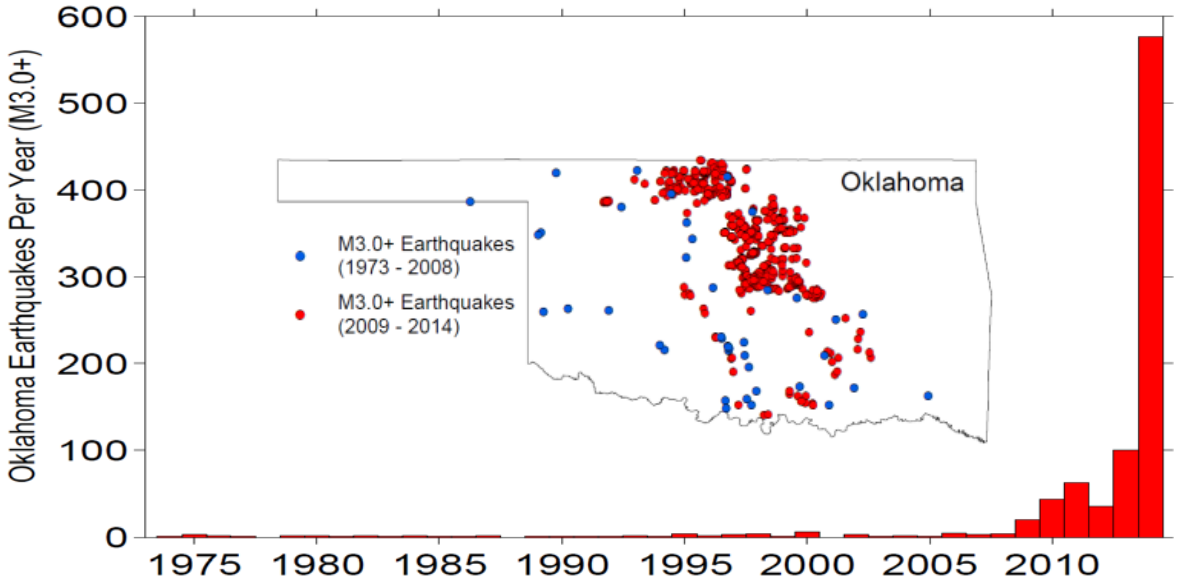
Pore pressure increases always lead to larger ΔS

Pore pressure is the variable that changes with time

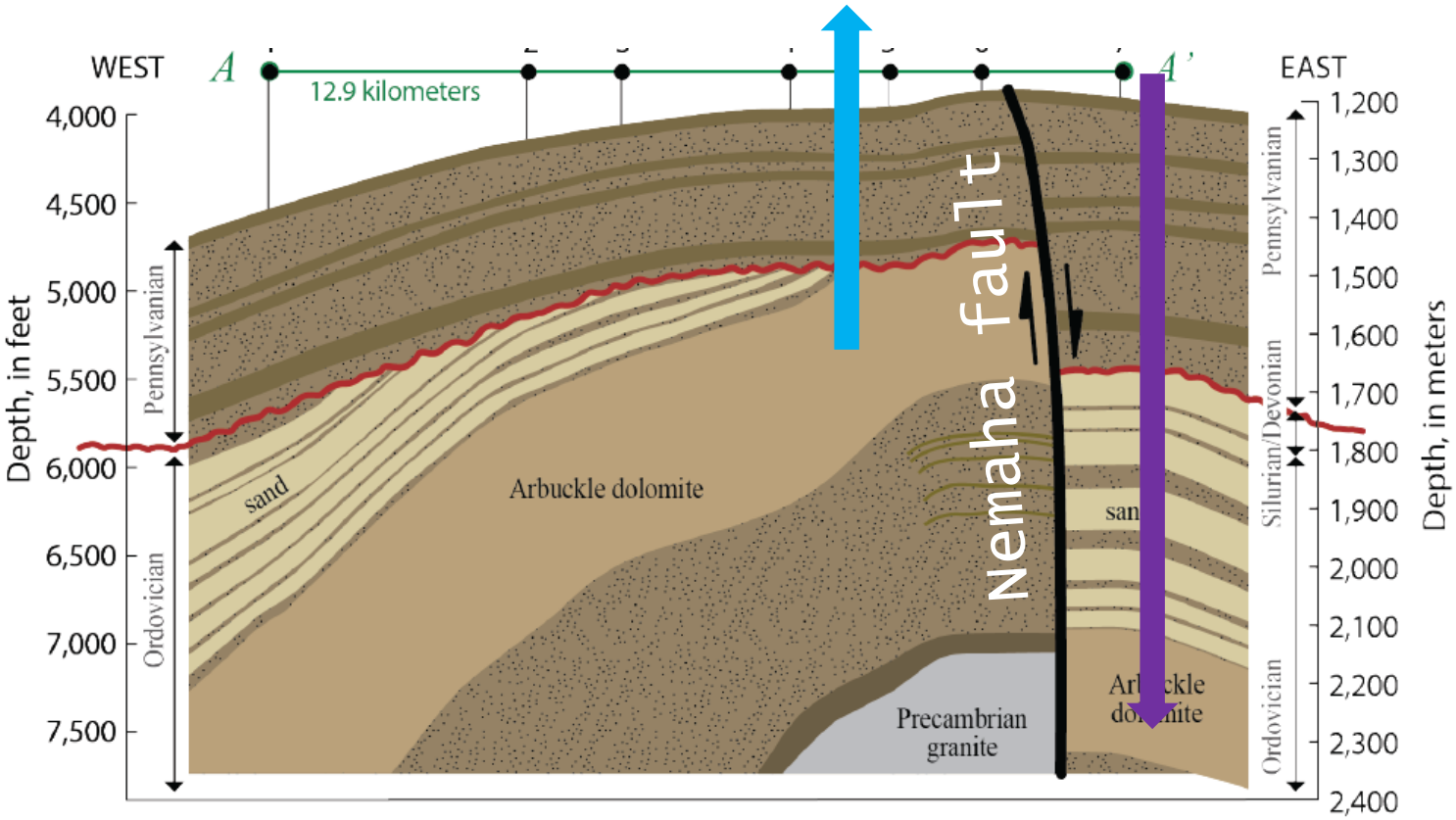
P = f(x, y, z, t, injection rate, hydraulic diffusivity)

The seismicity rate in OK is comparable to that in CA

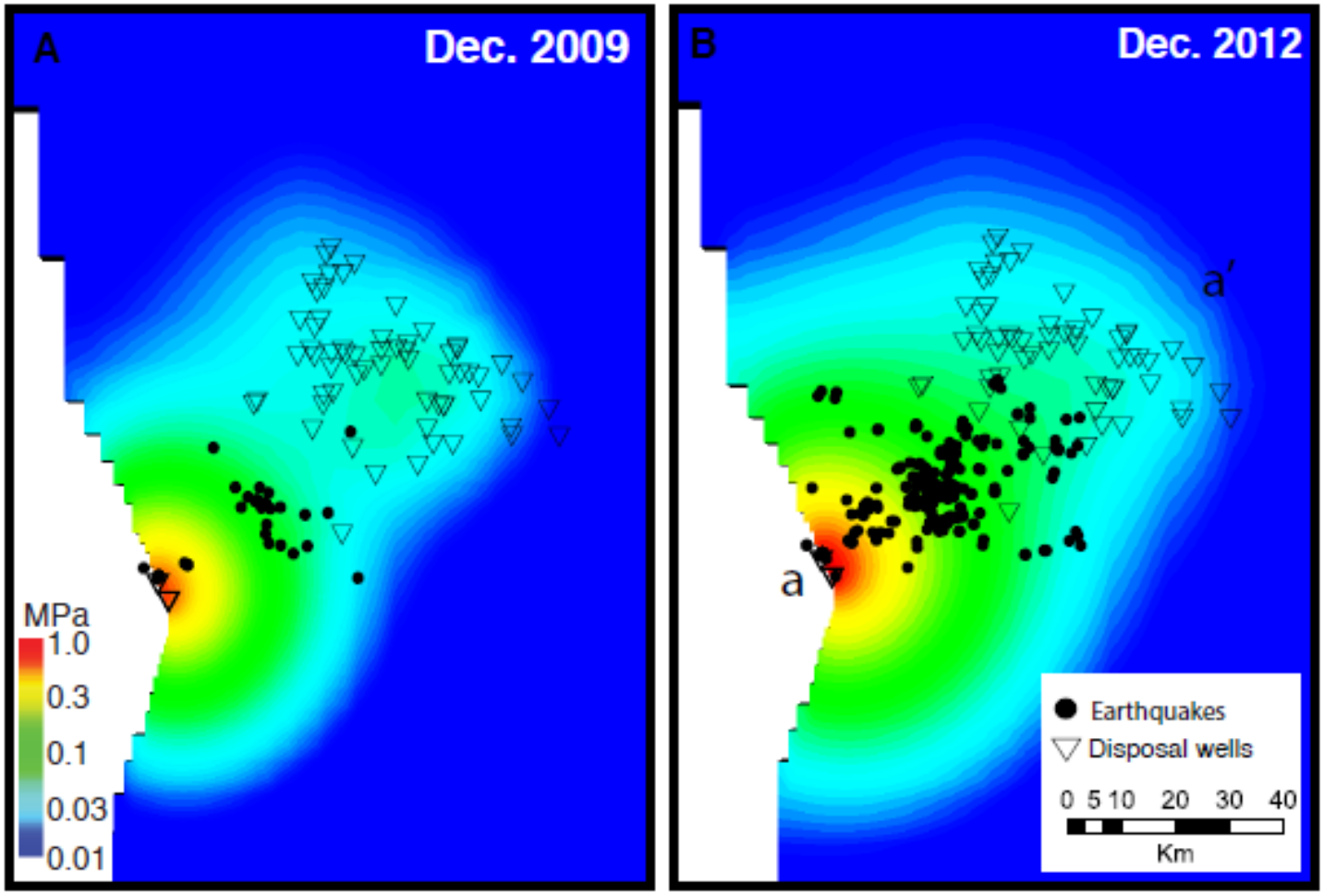




Dewatering production and disposal

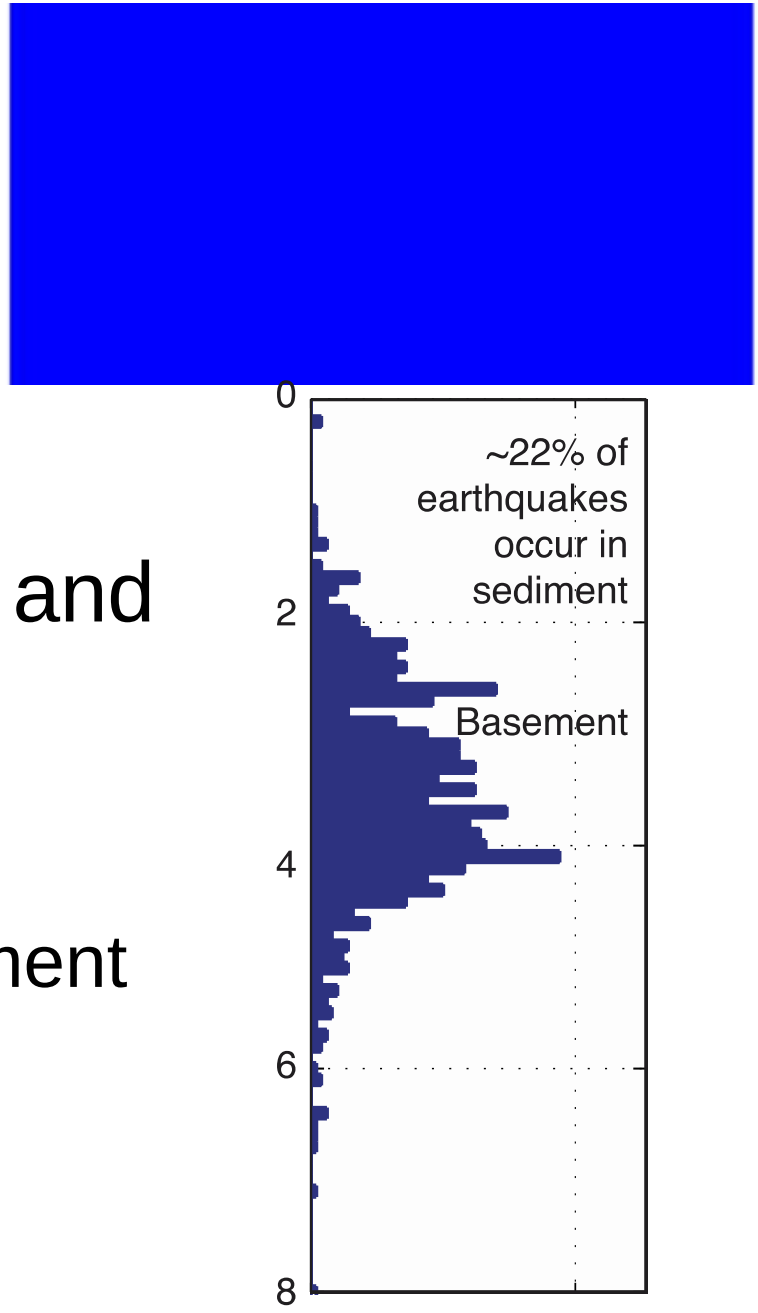


Modeled pressure increases over a large area, 10s km

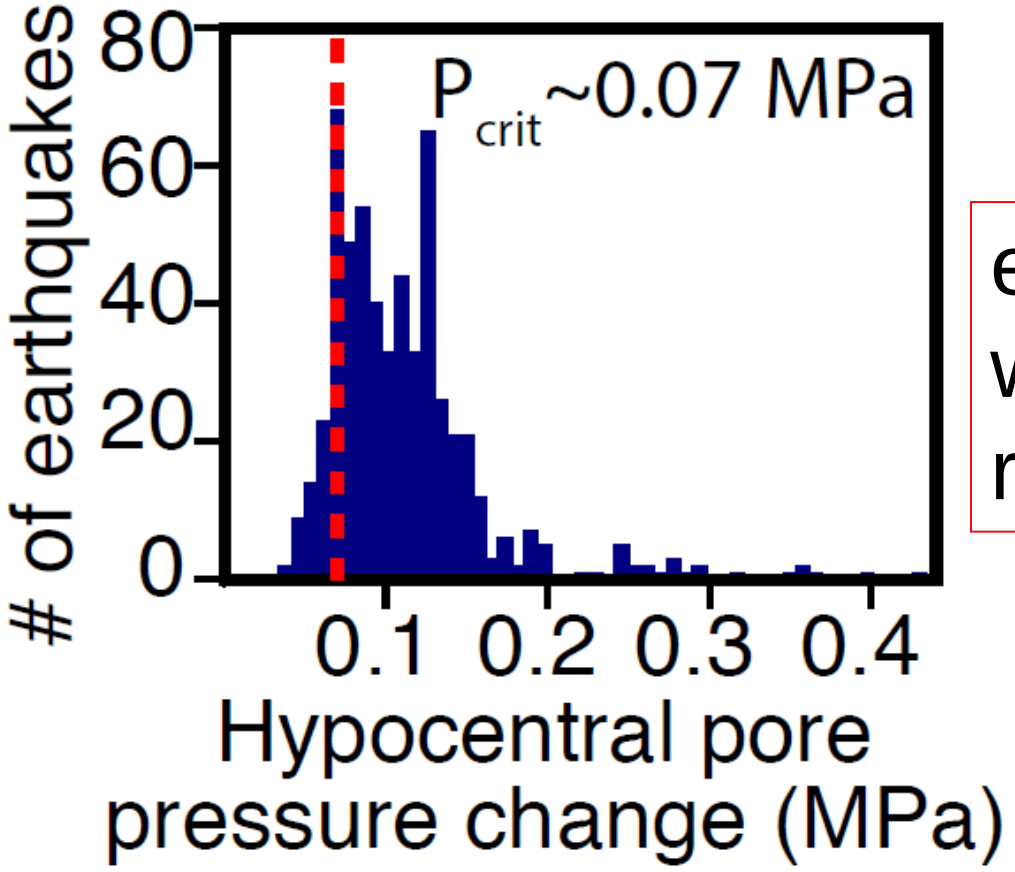


Pore pressure increase and earthquake depth are consistent

- Arbuckle and upper basement
- 2-5 km depth

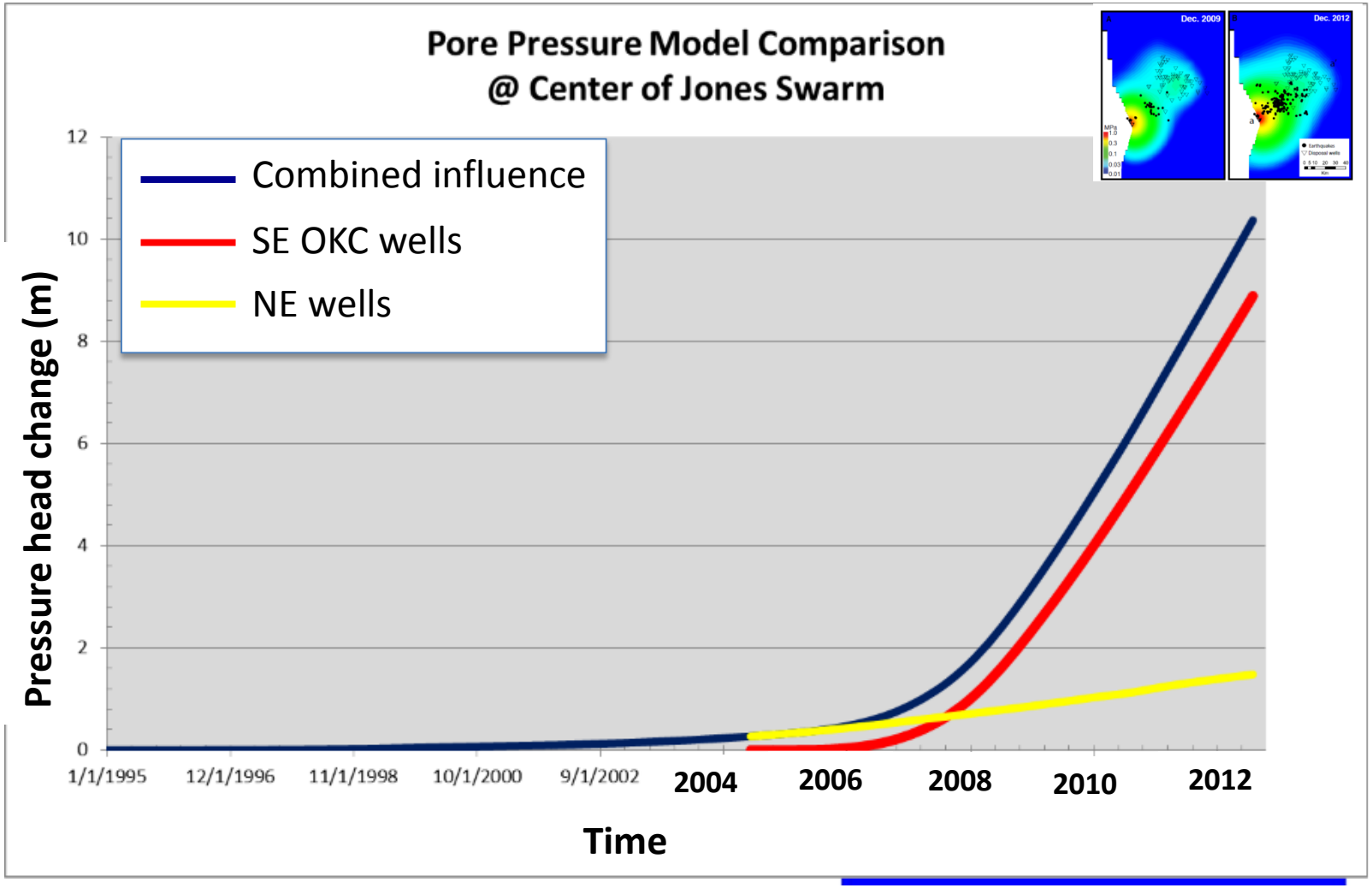


How much did pore pressure rise at time & location of each earthquake?

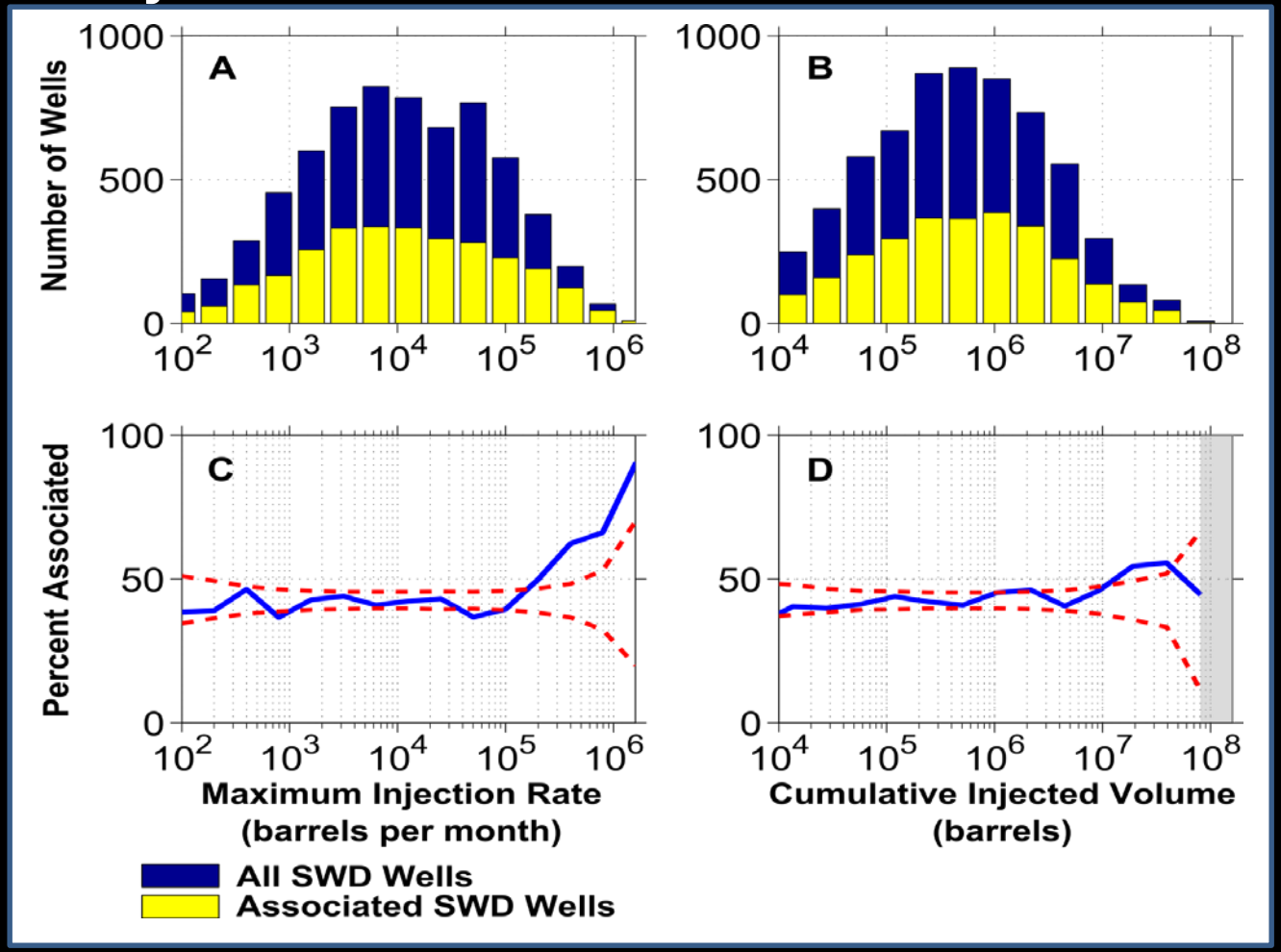


earthquakes occur when pressure reaches ~0.07 MPa

Wells in SE OKC contribute a large fraction of pore pressure increase



Injection Rate Cumulative Volume

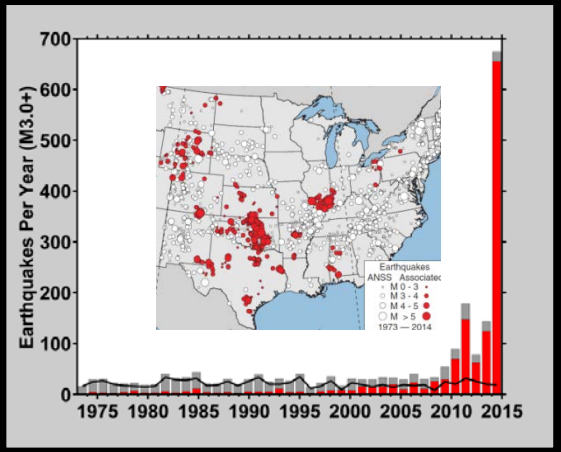


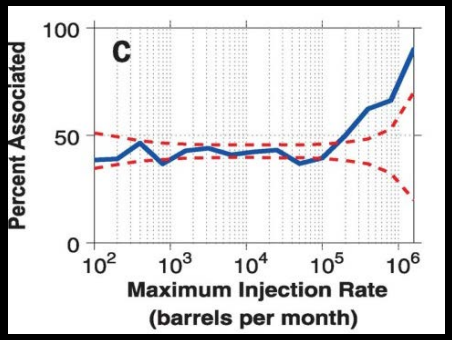
% of wells associated with earthquakes increases with injection rate

No such a trend for cumulative volume

Summary

The recent increase in seismicity is associated with wastewater injection





High-rate injections are more likely to be associated with earthquakes

High rate injection – major contributing factor for generating higher pore pressure