# Earthquakes in Kansas Induced by Extremely Far-Field Pressure Diffusion

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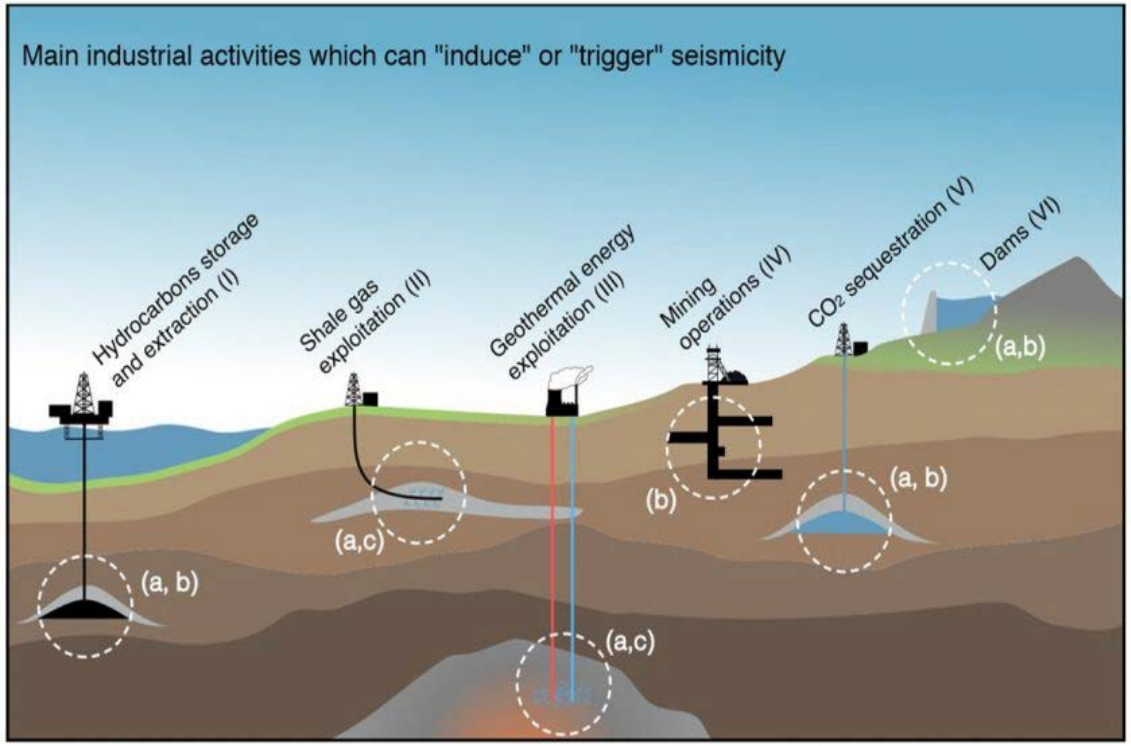
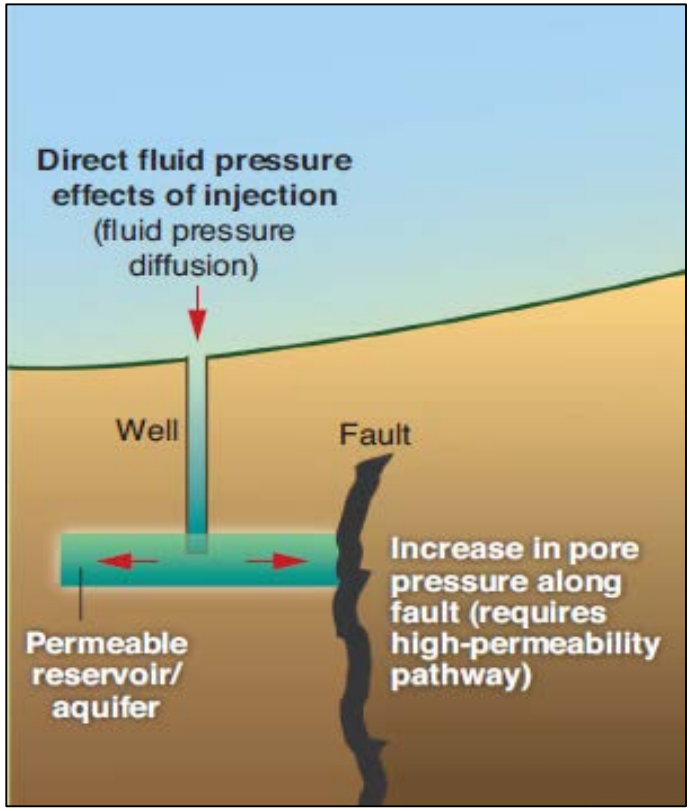
# What is Induced Seismicity?




*from Grigoli and Wiemer (2017)*

- Earthquakes caused by human activity
  - reservoir impoundment
  - mining
  - **injection**
    - geothermal stimulation
    - enhanced oil recovery
    - wastewater disposal
- Effects of induced seismicity
  - microearthquakes (M 2 or less)
  - a few cases of M 4 or M 5 (minor damage)
  - potential for a damaging event
  - important to understand mechanisms

# What is Induced Seismicity?

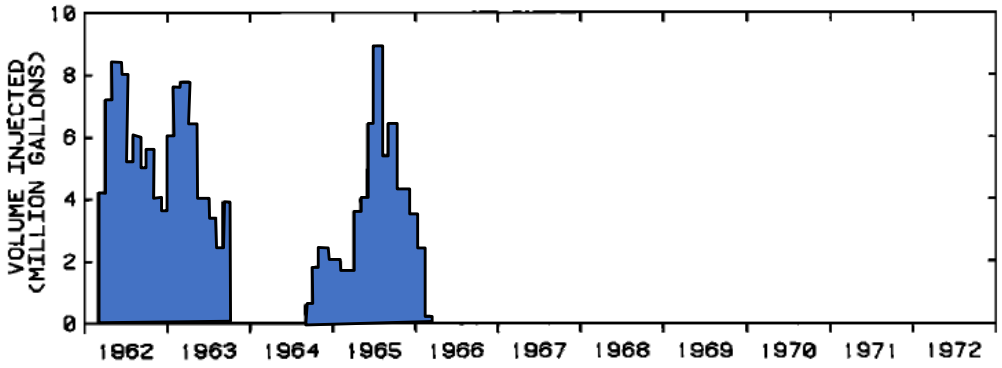



*from Ellsworth (2013)*

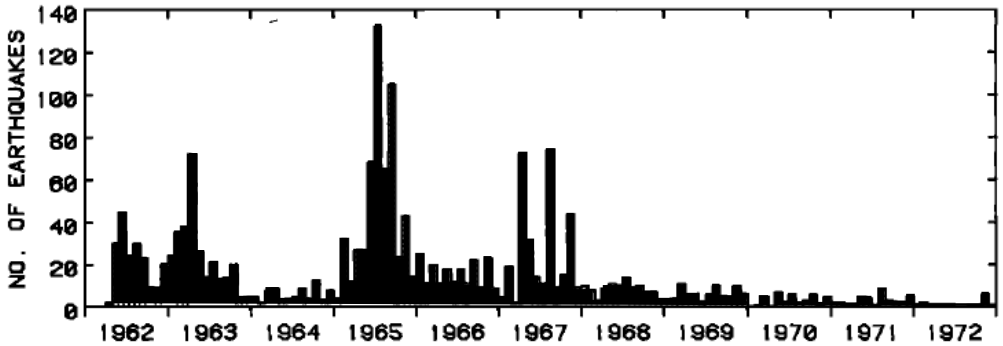
- Mechanism well understood
- Key factors:
  - existing fault
    - deep crystalline basement rocks
    - large crustal stresses
    - "critically stressed" faults
    - close to failure
    - small change in pressure
  - pore pressure
    - injection interval
    - reduces frictional resistance
    - 2-30 psi
- Traditional Model
  - one well, one series of earthquakes
  - begin near well
  - migrate away
    - pressure diffusion
    - pressure perturbation 5-10 km

# Case Study: Rocky Mountain Arsenal

*disposal volume*




*number of earthquakes*




- Denver, Colorado
- Wastewater disposal well
  - operated 1962-1967
  - terminated in basement
  - 7,000 bbl/day
- First earthquake within weeks
  - more than 1,500
  - three M 5
  - within 8 km
- Conclusion
  - direct correlation
  - pore pressures
  - basement faults
  - injection terminated
- Working hypothesis

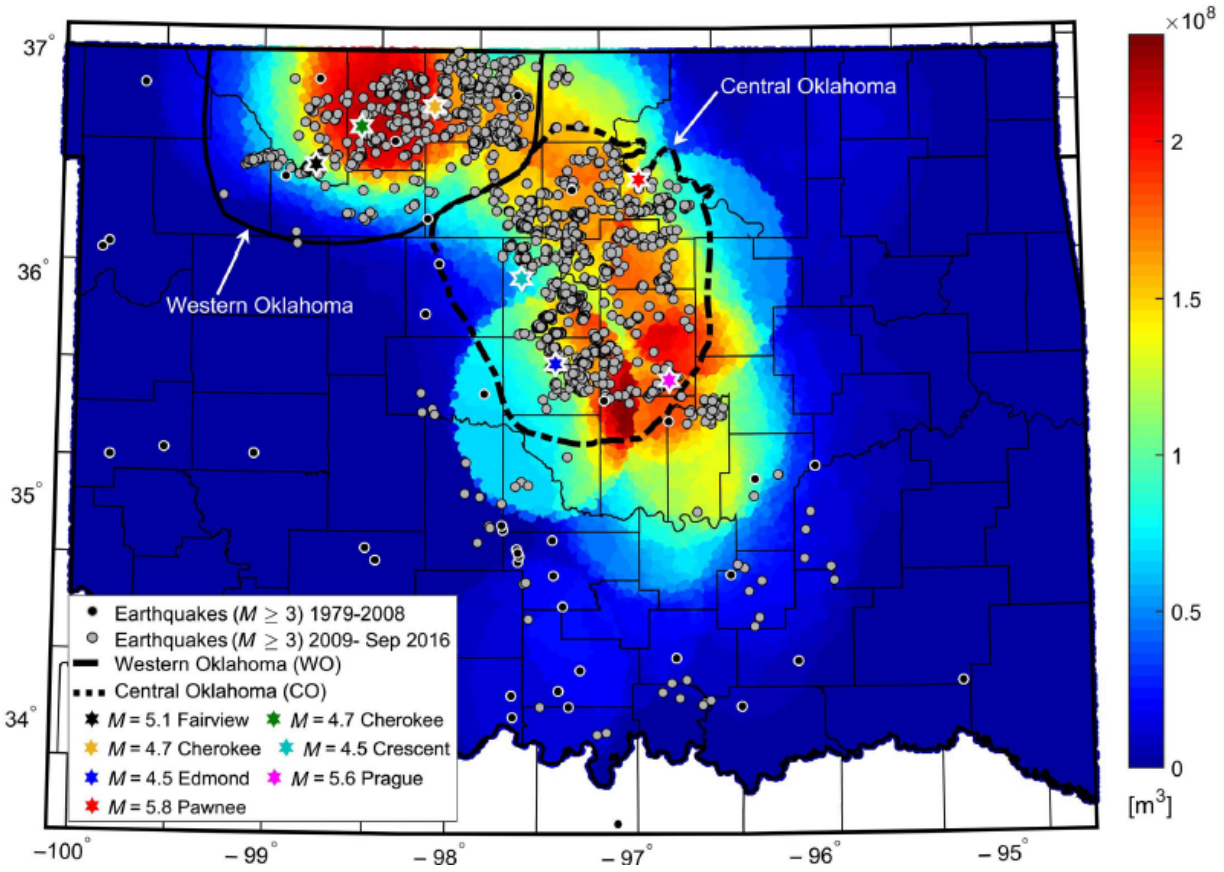
# Case Study: Oklahoma

- Mississippian limestone
  - oil bearing formation
  - not productive with conventional techniques
  - more economical with horizontal drilling
- Development
  - Oklahoma: 2009
  - Kansas: 2012
  - water bearing
  - large volumes formation water
  - Class II saltwater disposal wells
    - historic: 5,000 bbl/day
    - 10,000-30,000 bbl/day
- Arbuckle Group
  - basal aquifer
  - hydraulically connected to basement


*credit: Christopher Liner*

# Case Study: Oklahoma

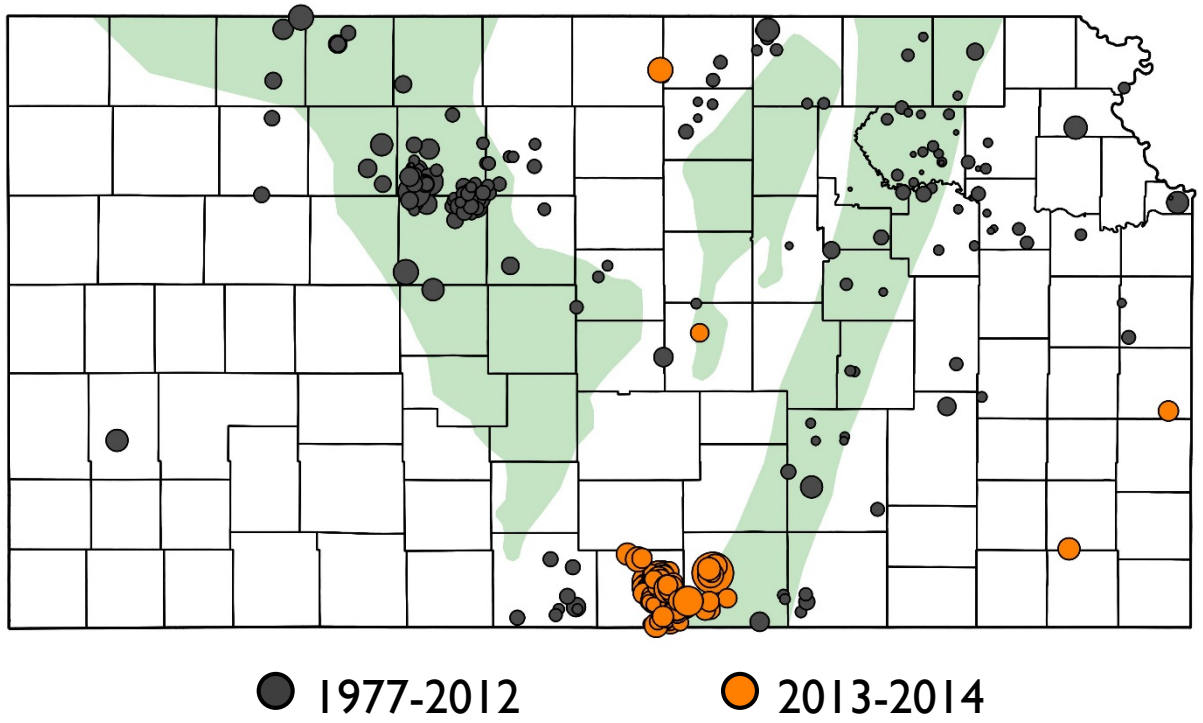
- Earthquake history
  - pre-2009: 1/year
  - 2009-present: hundreds/year
  - strong correlation
    - widespread earthquakes
    - regional saltwater disposal
    - Arbuckle Group
    - basement faults
- Doesn't fit the traditional model
  - little direct correlation
  - cumulative pressure effect
  - pressure diffusion up 20 km




*from Langenbruch and Zoback (2016)*

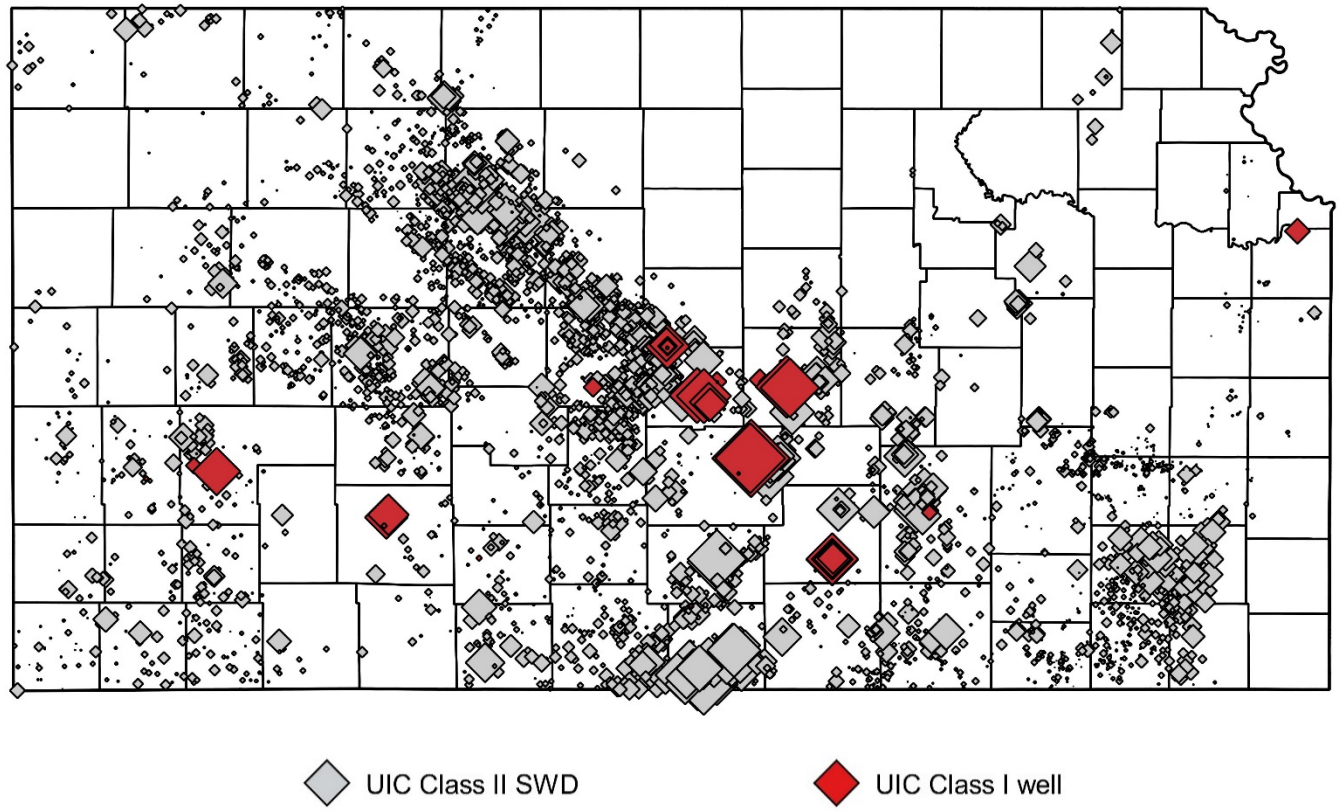
# Kansas Earthquake History

- Natural earthquakes
  - 1977 to 2012
  - mostly microearthquakes
  - basement structures
  - M 3 every 1-2 years
- Possibly induced seismicity
  - 2013-2014
  - increase in rate, magnitude
  - M 3 or larger = 44
  - Harper and Sumner
  - few historic earthquakes

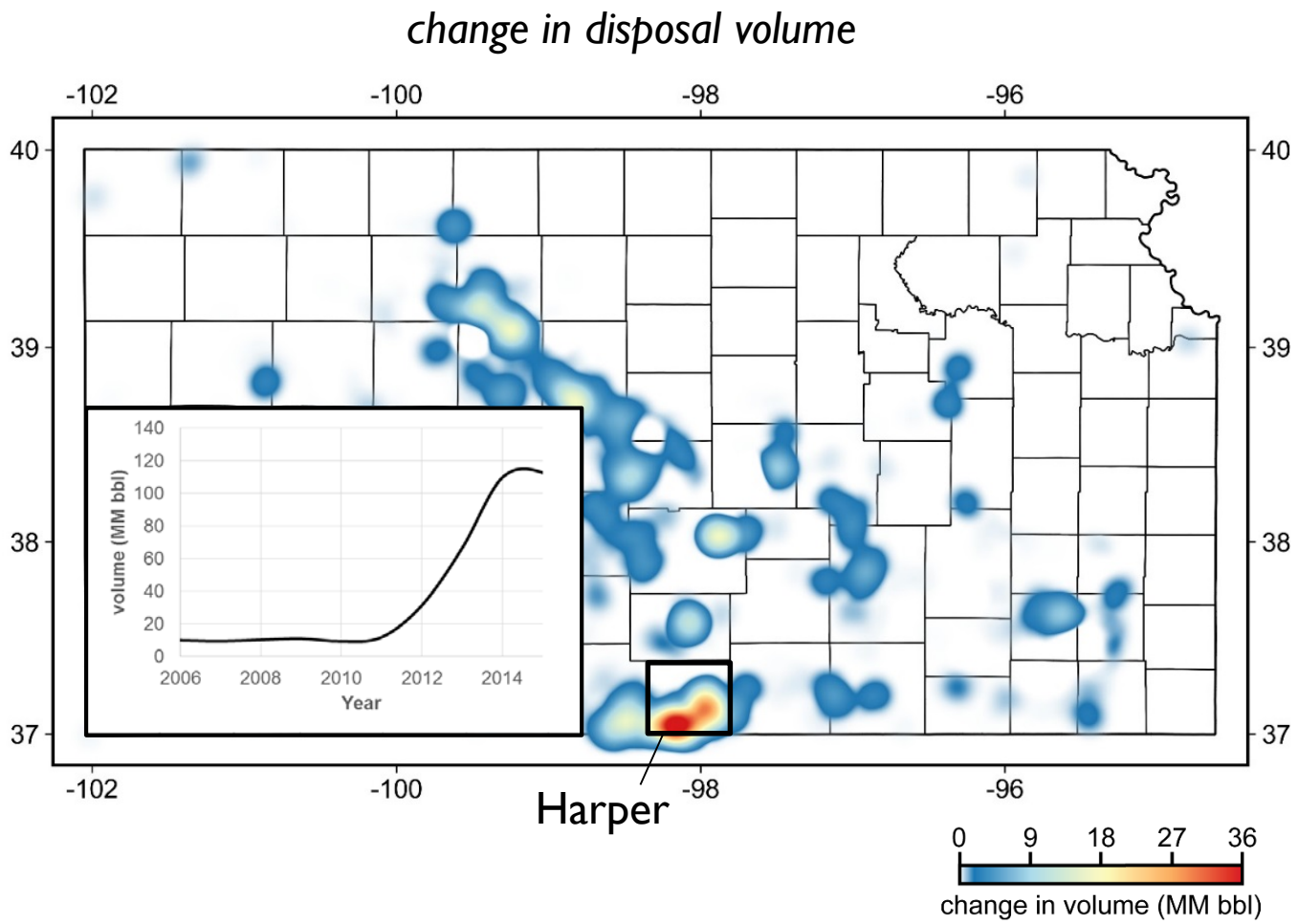


# Deep Fluid Disposal in Kansas

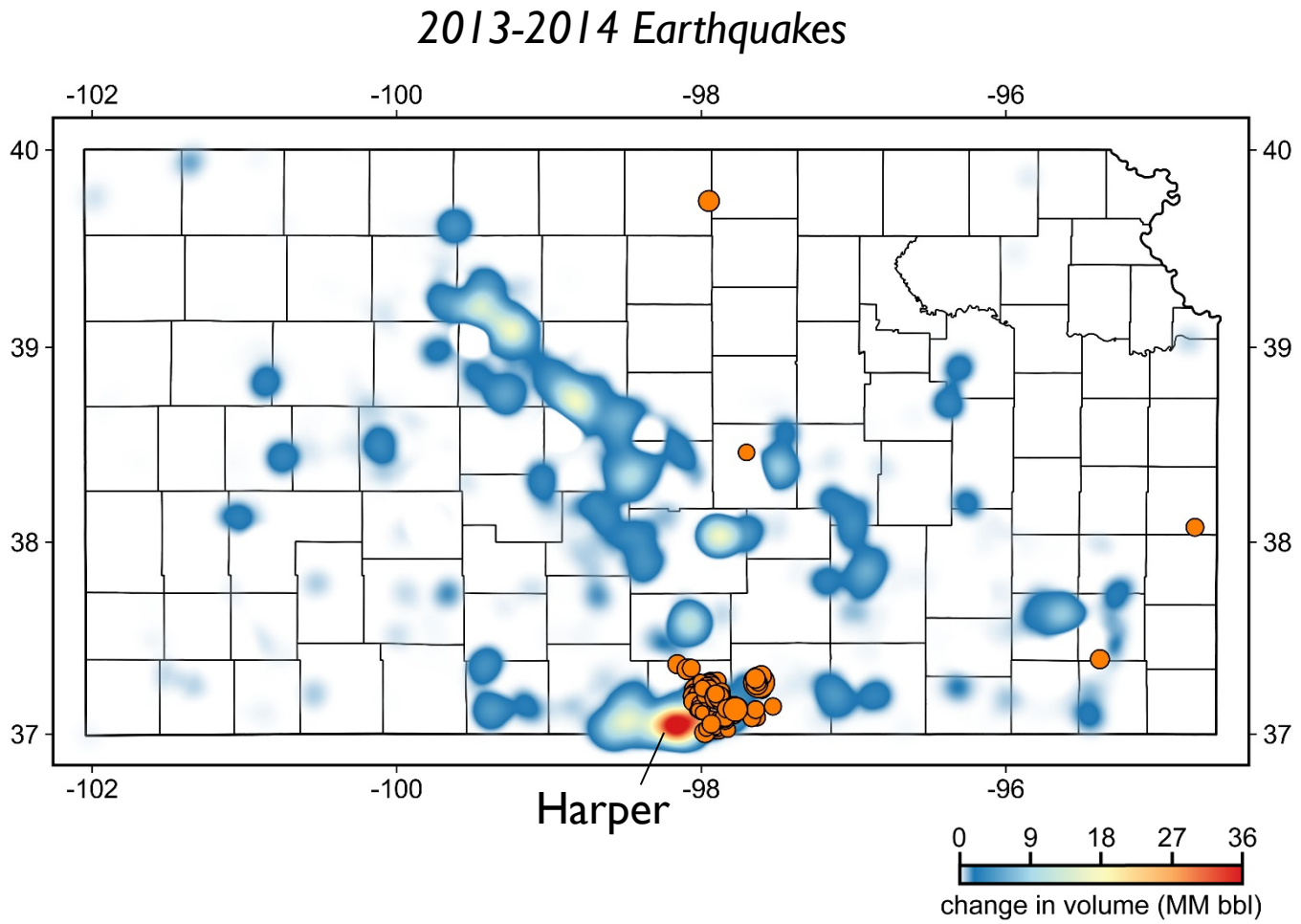
- Decades long history
- Class II
  - regulated by KCC
  - >5,000 SWD wells (gray)
  - scaled relative to volume
  - 50% Arbuckle Group
- Class I
  - regulated by KDHE
  - 50 wells (red)
  - Arbuckle
  - pressure falloff
    - fluid pressure
    - time history
    - regional pressure



# Increased Disposal Volume

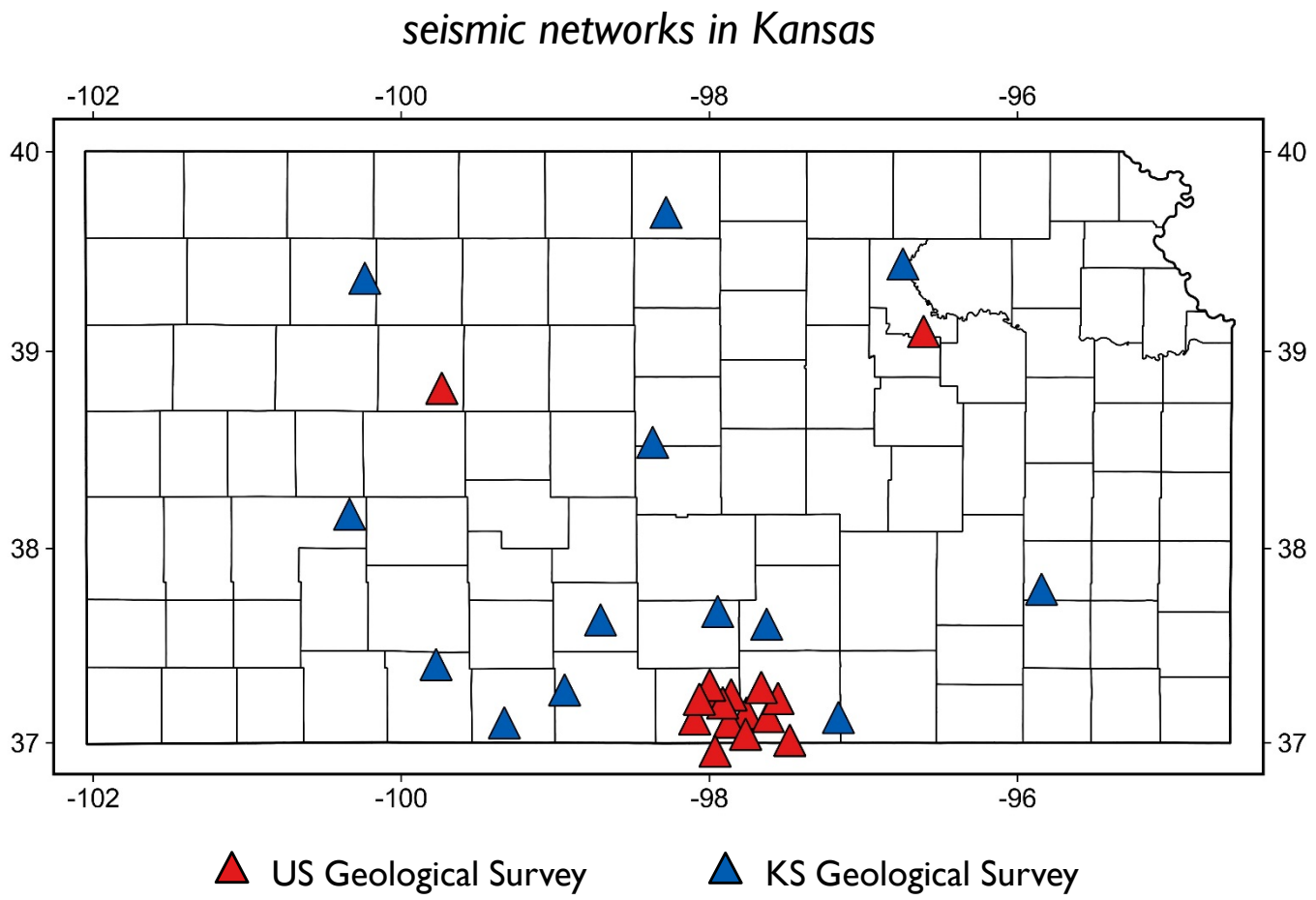


# Induced Seismicity

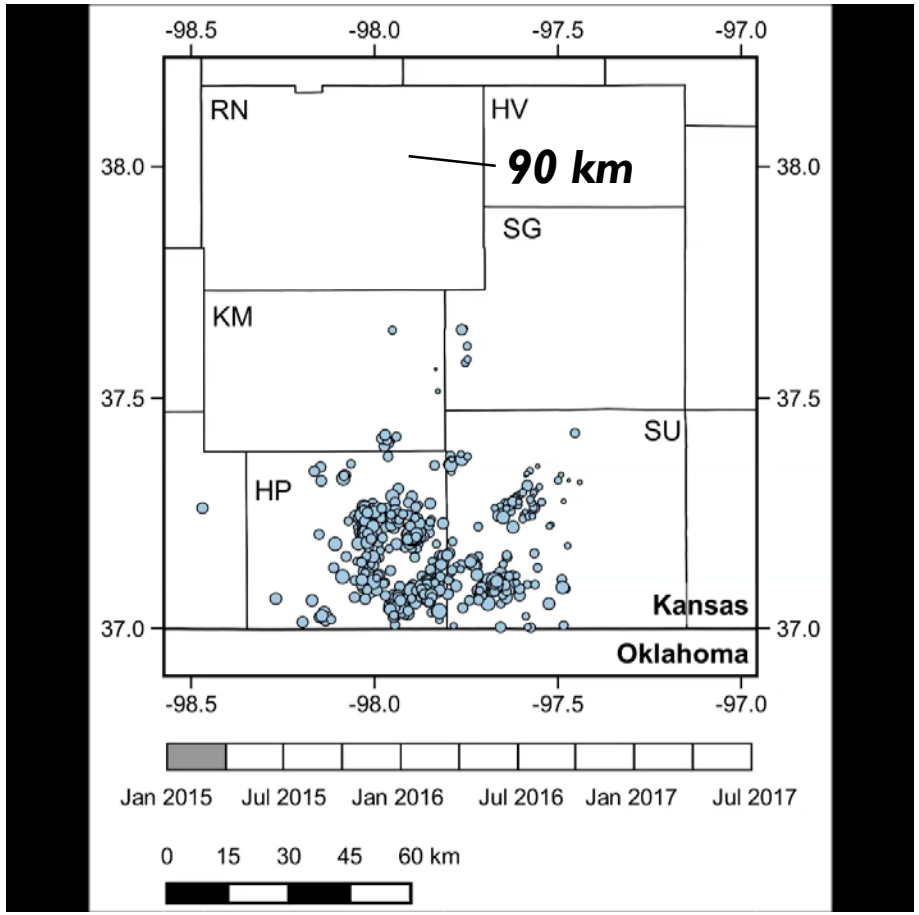



unique vantage to observe long-range effects

# Seismic Networks

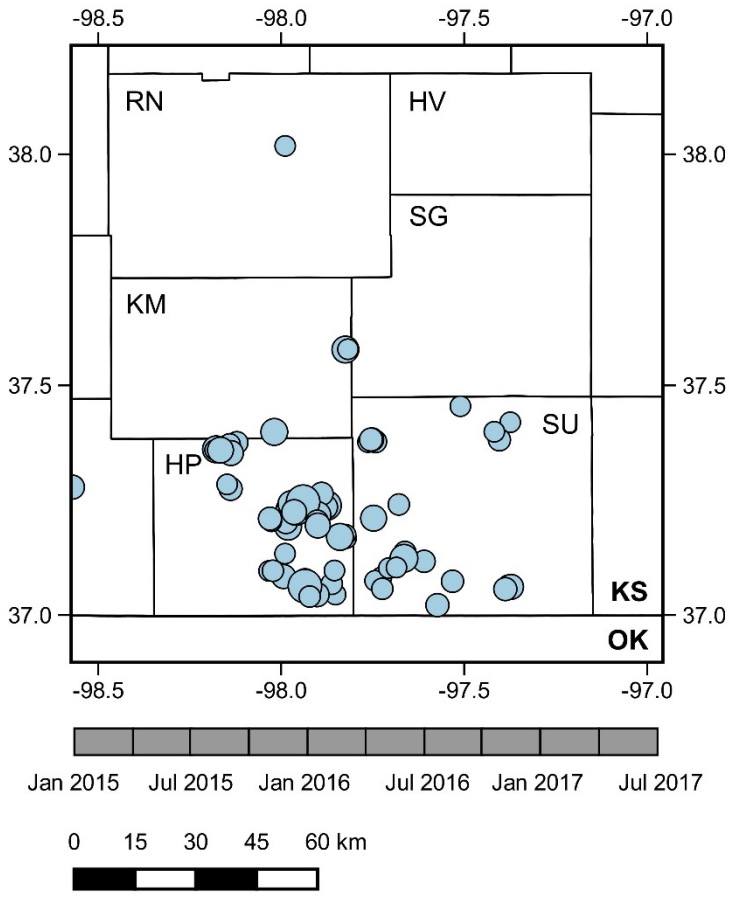


# Migration of Earthquakes



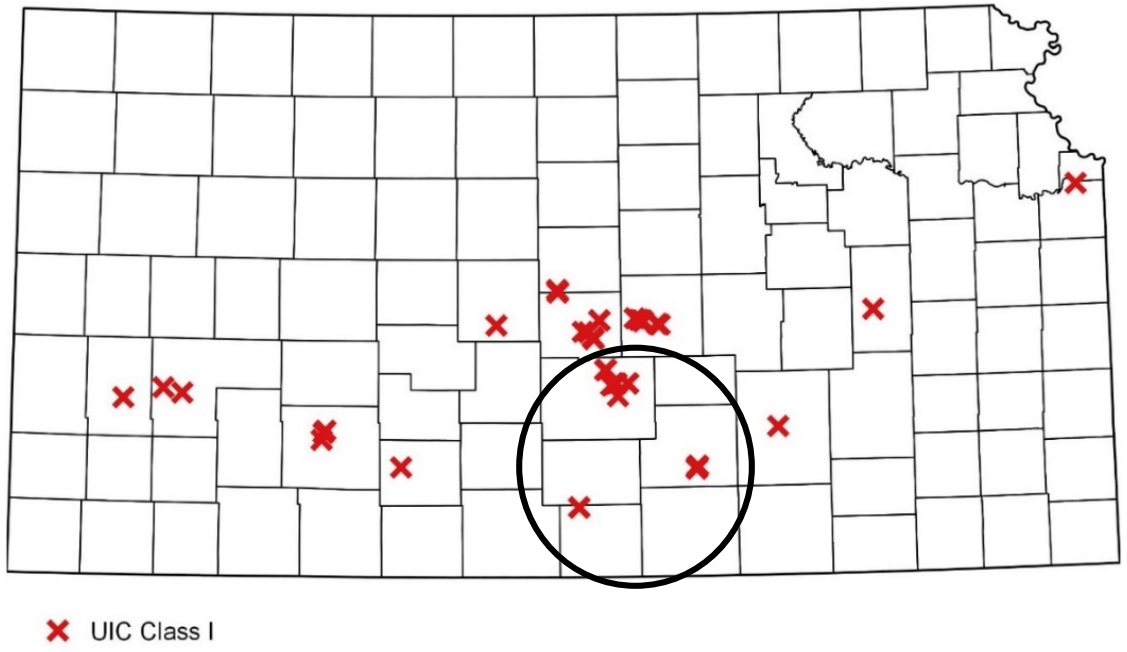

- Initially dense swarms
  - 2015-2016
  - Harper and Sumner
- Earthquake migration
  - 2016-2017
  - Persist in HP and SU
- Migrate progressively farther
  - radially away
  - up 90 km
  - challenges previous belief (20 km)

# Magnitude Distribution



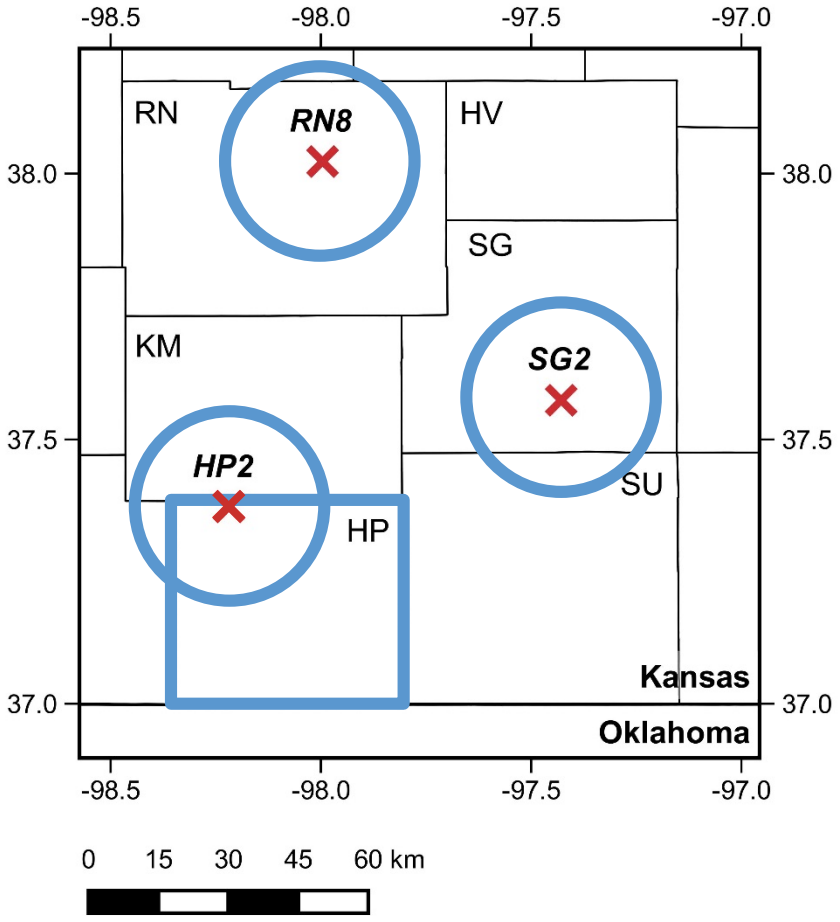

- Total earthquakes: 6,944
- Vast majority are microearthquakes
  - M < 2 = 4,958 (70%)
  - M 2-3 = 1,912
  - M ≥ 3 = 74
- Regional network (USGS) M~3
  - no obvious trend
  - isolated, unrelated
- Value of local network
  - microearthquake data
  - improved understanding
  - insight into causal factors

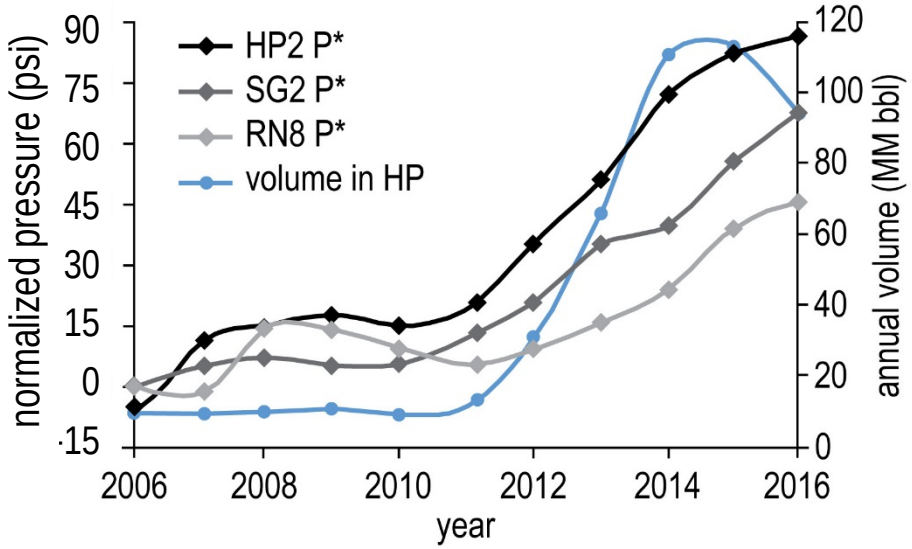
# Arbuckle Fluid Pressure




- Correlation with SWD
  - what's the driver?
    - pore pressure
    - other effects
- Geomechanical modeling
  - estimate pressure and stress
  - time intensive
  - difficult
  - expensive
  - non-unique
- Direct P* measurements
  - Class I PFO
  - time history
  - several in study area

# Arbuckle Fluid Pressure



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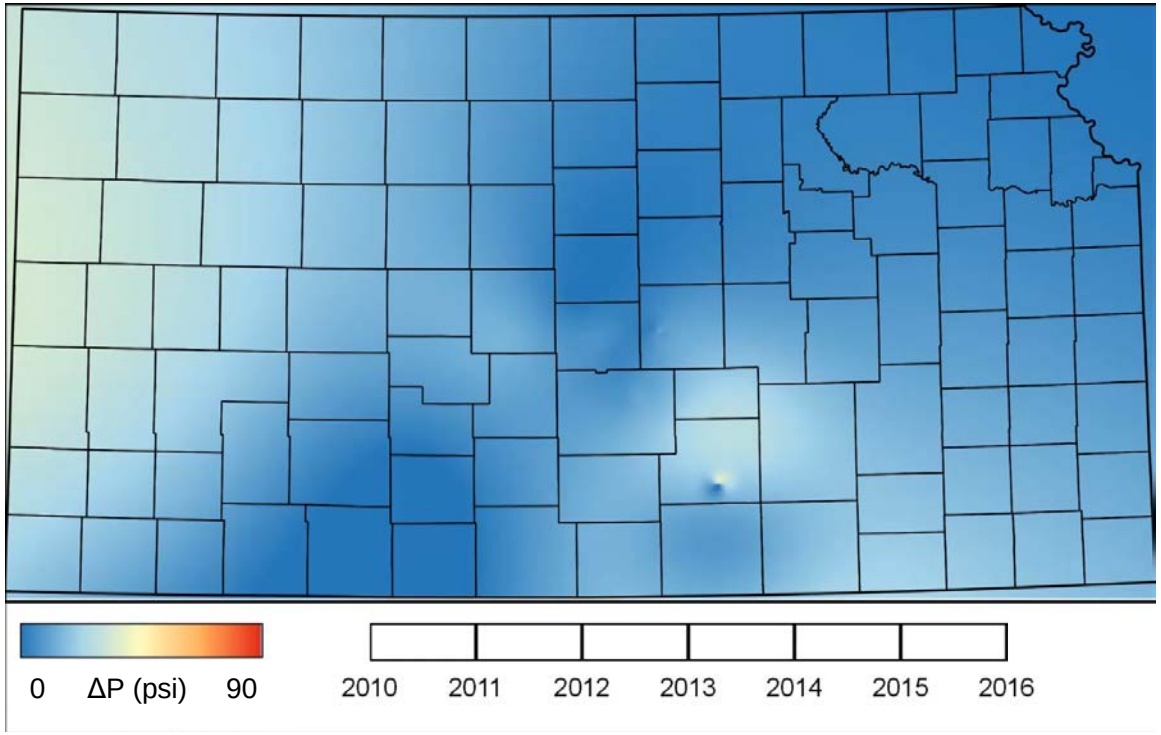
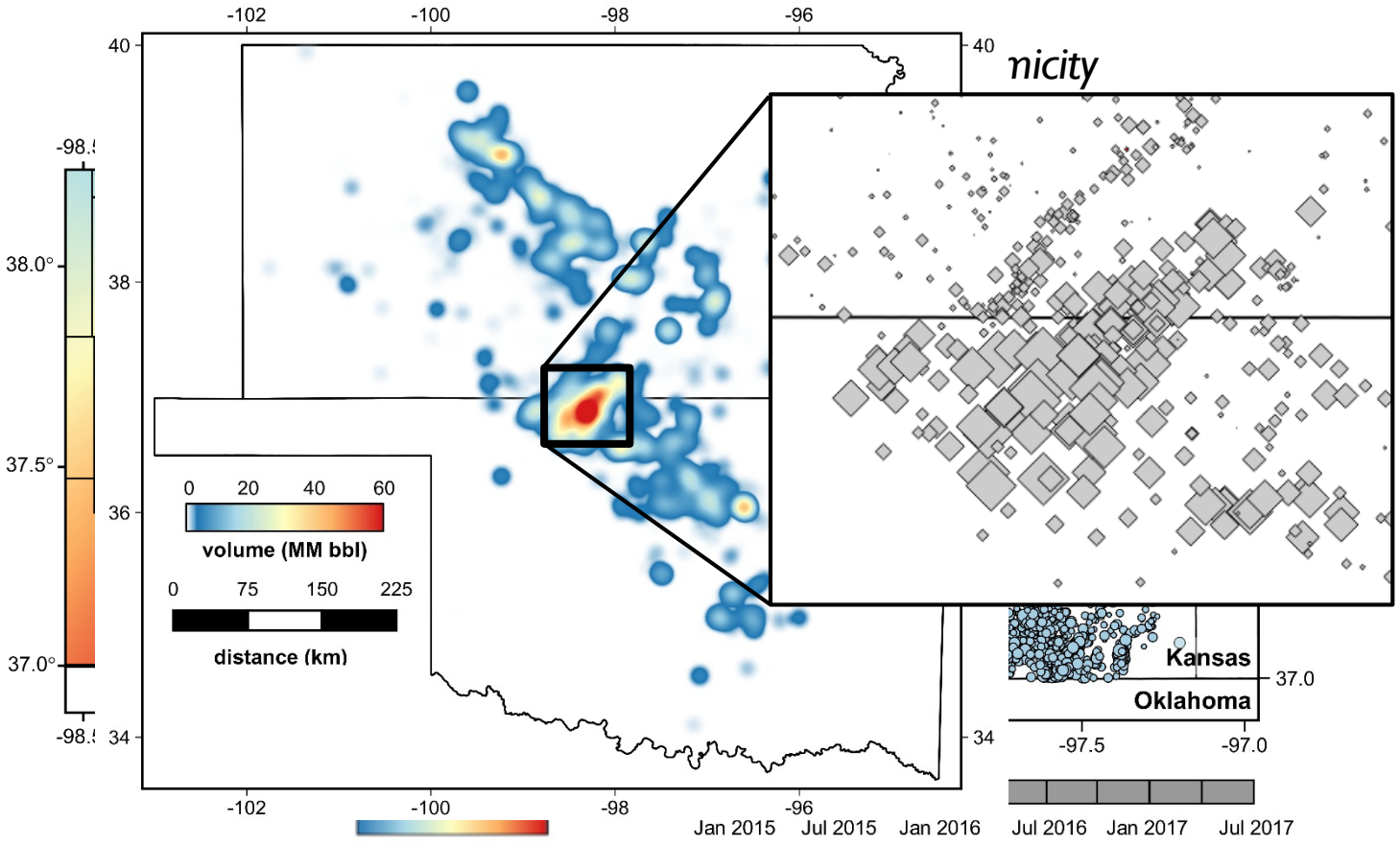



- Preliminary regional map
  - sparse statewide measurements
  - interpolate
  - limited local detail
  - insights into regional pressure
- Normalized pressure
  - absolute pressure varies
  - change in pressure
  - relative to baseline (2002)
- Insight into pressures affecting basement faults

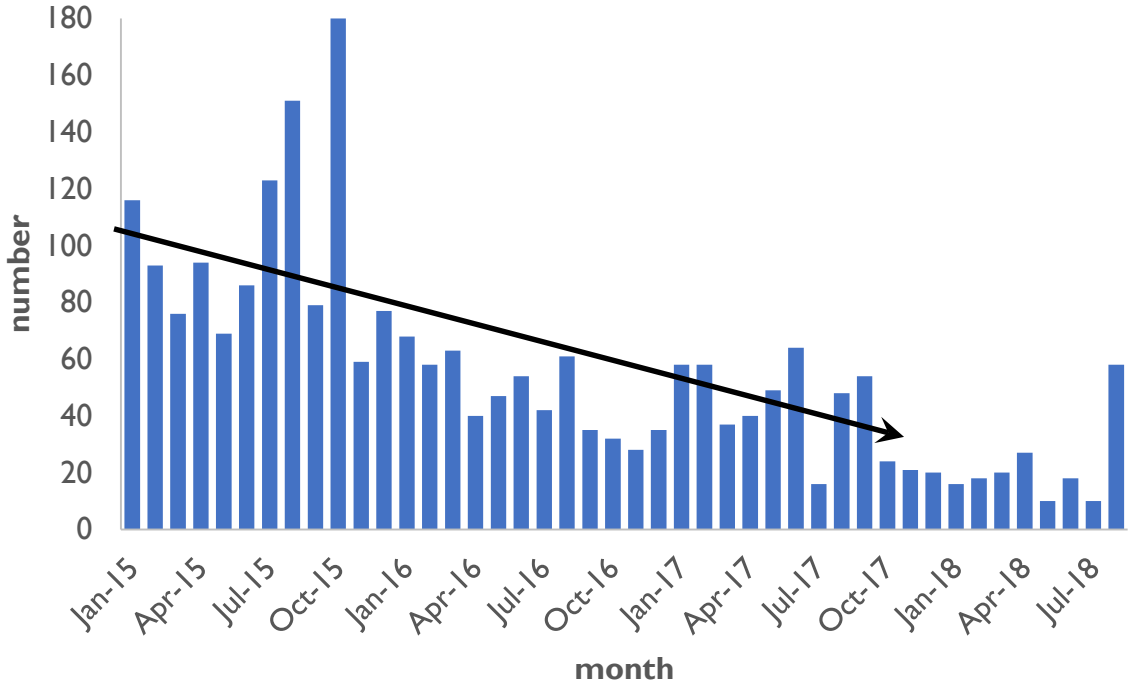
# Arbuckle Fluid Pressure



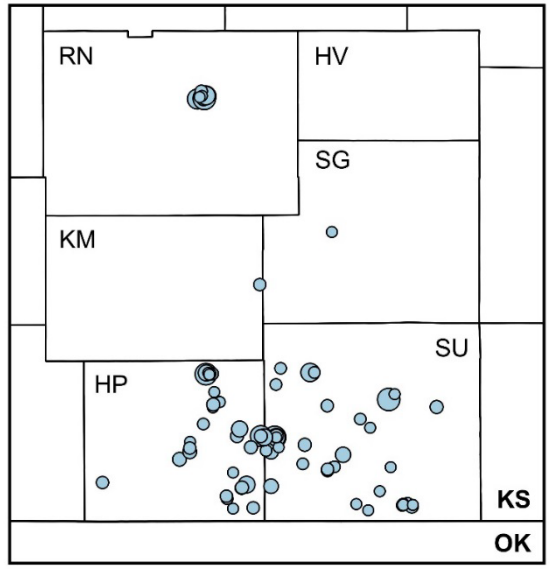

- Earthquake consistent with pressure
  - supports cumulative effect
  - pore pressure primary driver
- Previous studies
  - a few high-volume wells
  - 10,000 bbl/day
- Kansas
  - spatially dense group
  - dozens of high-volume wells (4 km)
    - 500 MM bbl in 2015
    - equivalent to >100 wells
- Unprecedented

# What's happening now?

*Earthquakes M ≥ 2*

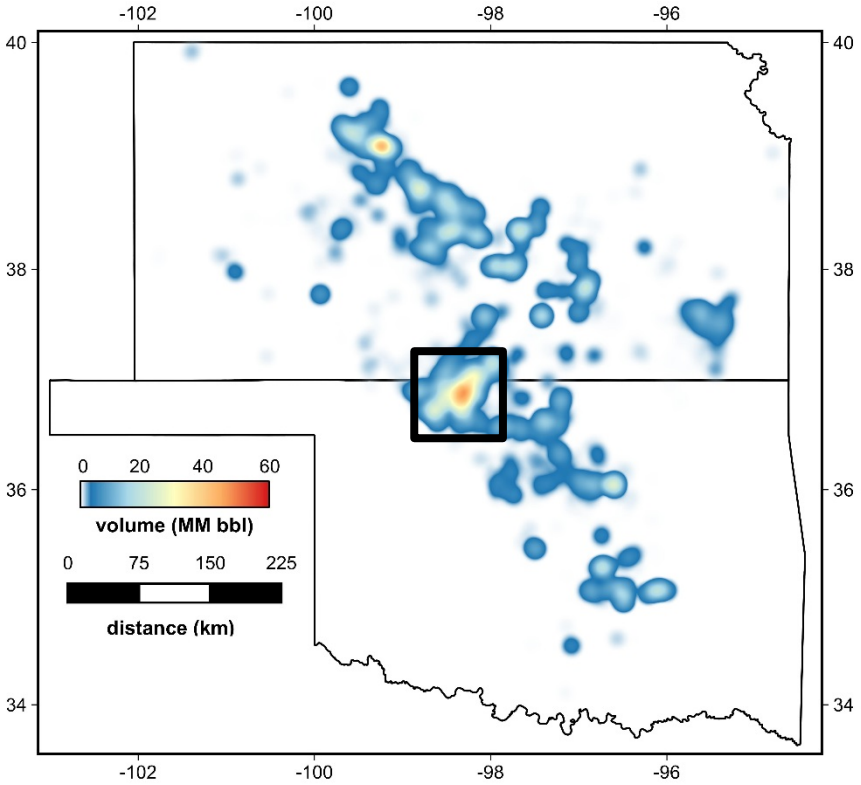



*M≥2 Jan-Jun 2018*

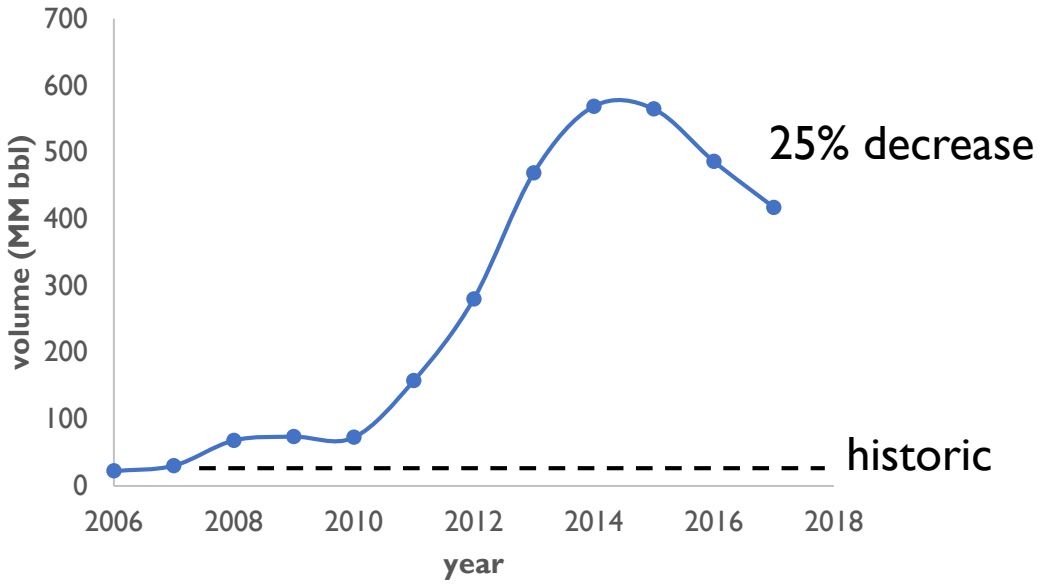


# What's happening now?

*disposal volume (2017)*




*Arbuckle disposal volume*



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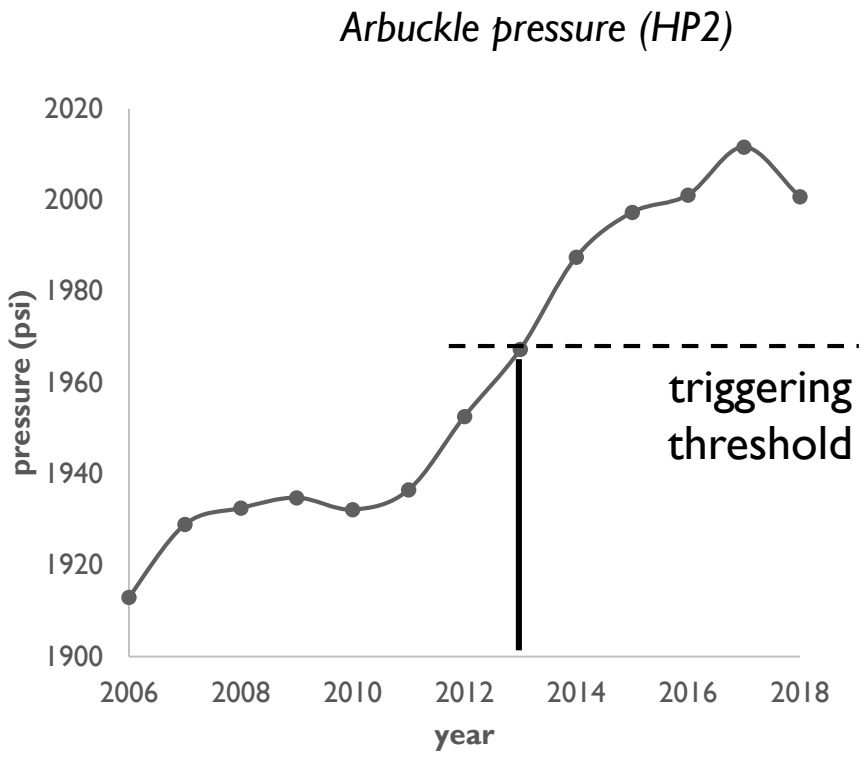
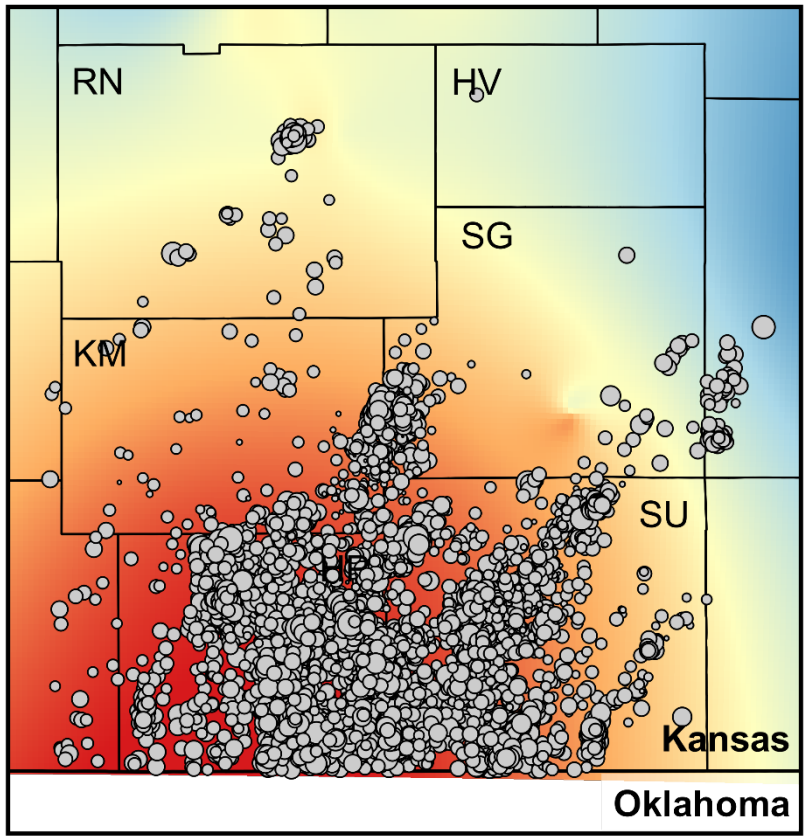



- Regional Arbuckle pressure
  - continued to climb in 2017
  - 2018
    - stabilizing in Harper county
    - elsewhere unclear
- Exceed triggering threshold
  - 30 psi above
  - faults will be sensitive
    - small fluctuations
    - operations previously tolerated
- "The new normal"
  - could take years
  - maintain pressure

# Conclusions

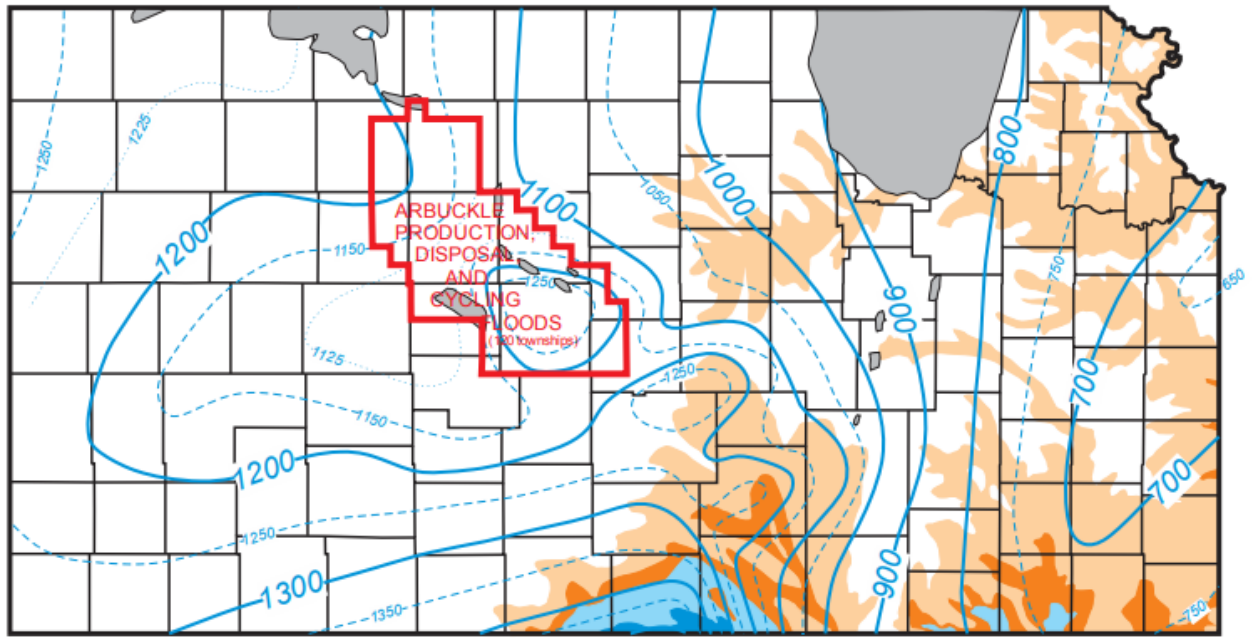
- Summary
  - increased high-volume SWD
  - regionally elevated pressure
  - migration of seismicity
- Regional pore pressure change
  - affecting basement faults
  - primary driver of seismicity
  - farther than previously observed
    - 90 km
    - studies in OK suggest 20 km limit
    - challenge previous
  - value of local monitoring
- Implications
  - "the new normal"
  - rising fluid levels

*Arbuckle fluid pressure*



# *Ongoing Research*: Arbuckle Fluid Levels

*elevation of hydrostatic surface (freshwater)*



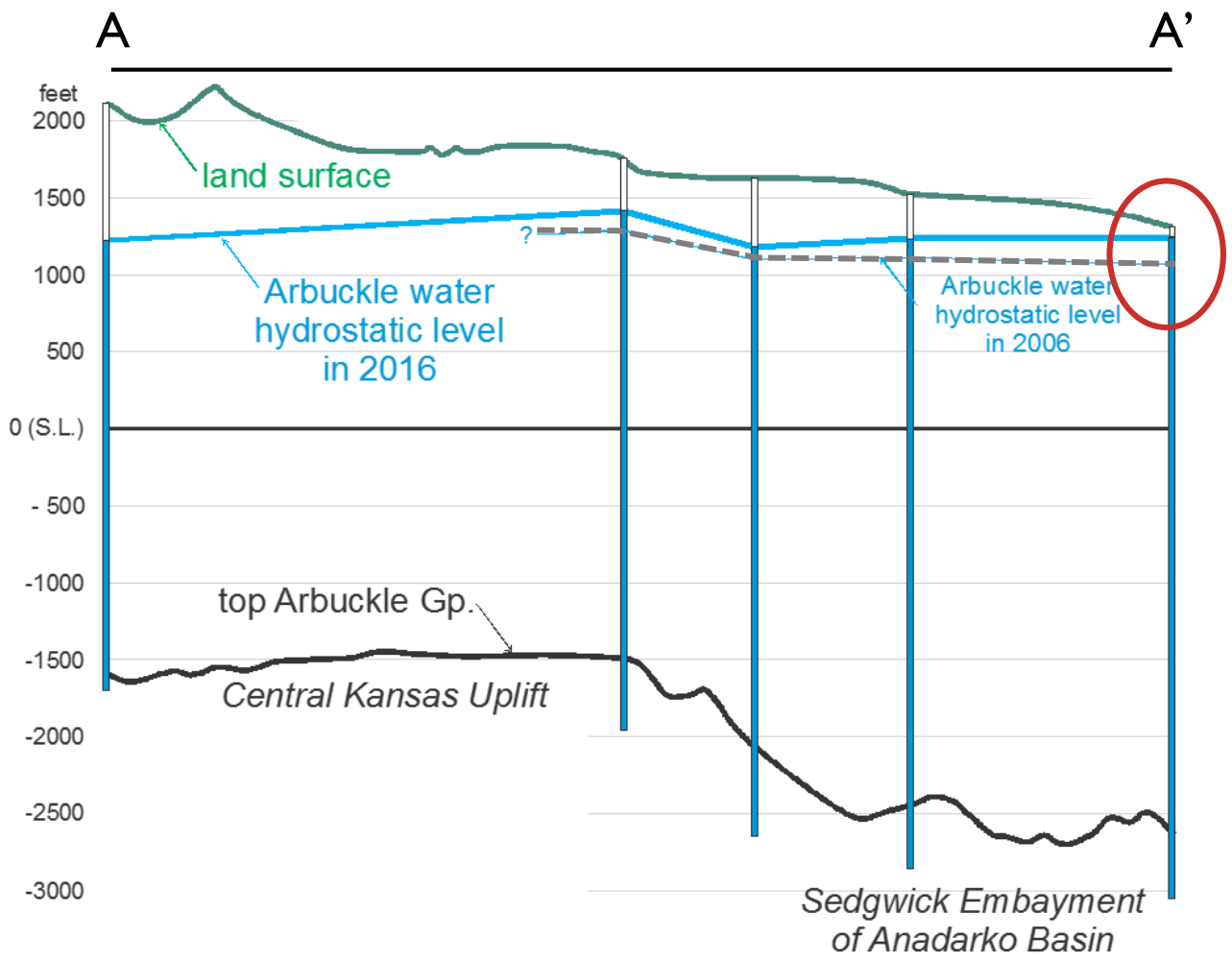

fluid level related to pressure:

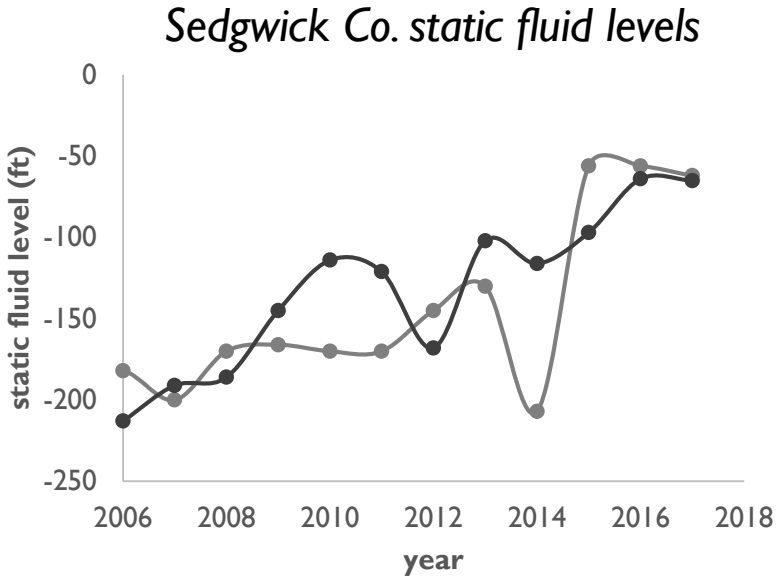
$$P = \rho g h$$

ρ = density
g = gravitational acceleration
h = height of fluid column

- < 300 ft
- < 100 ft
- 0 ft – hydrostatic level at land surface
- 200 ft head required for gravity feed

# *Ongoing Research*: Arbuckle Fluid Levels




within 50' of surface

< 5 years

# Acknowledgements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- KGS field crew
  - Brett Bennett
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  - Joe Anderson
- Earthquake analysts
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