Regional trends in Kansas seismicity, formation pressure, and fluid levels

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RISC Webinar
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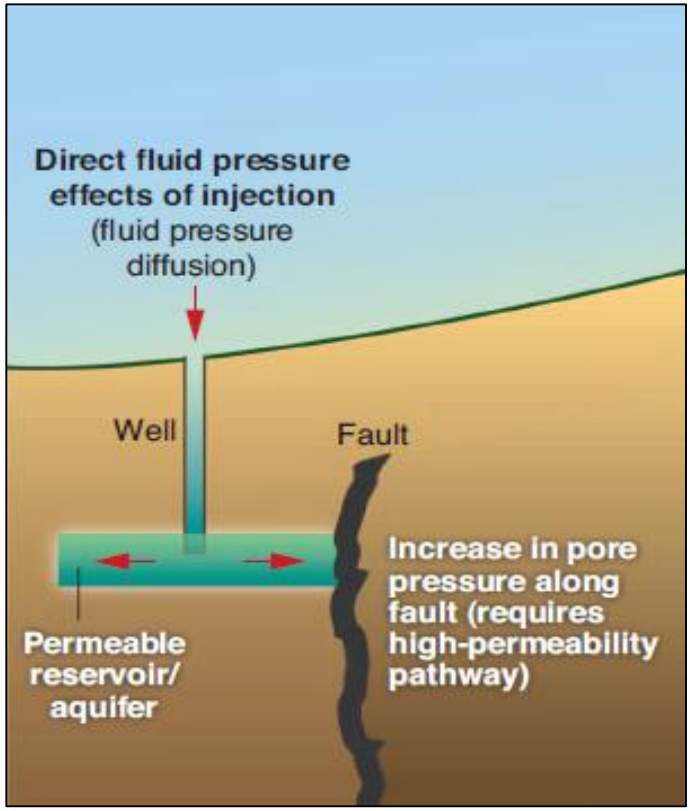
Induced Seismicity Mechanism



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

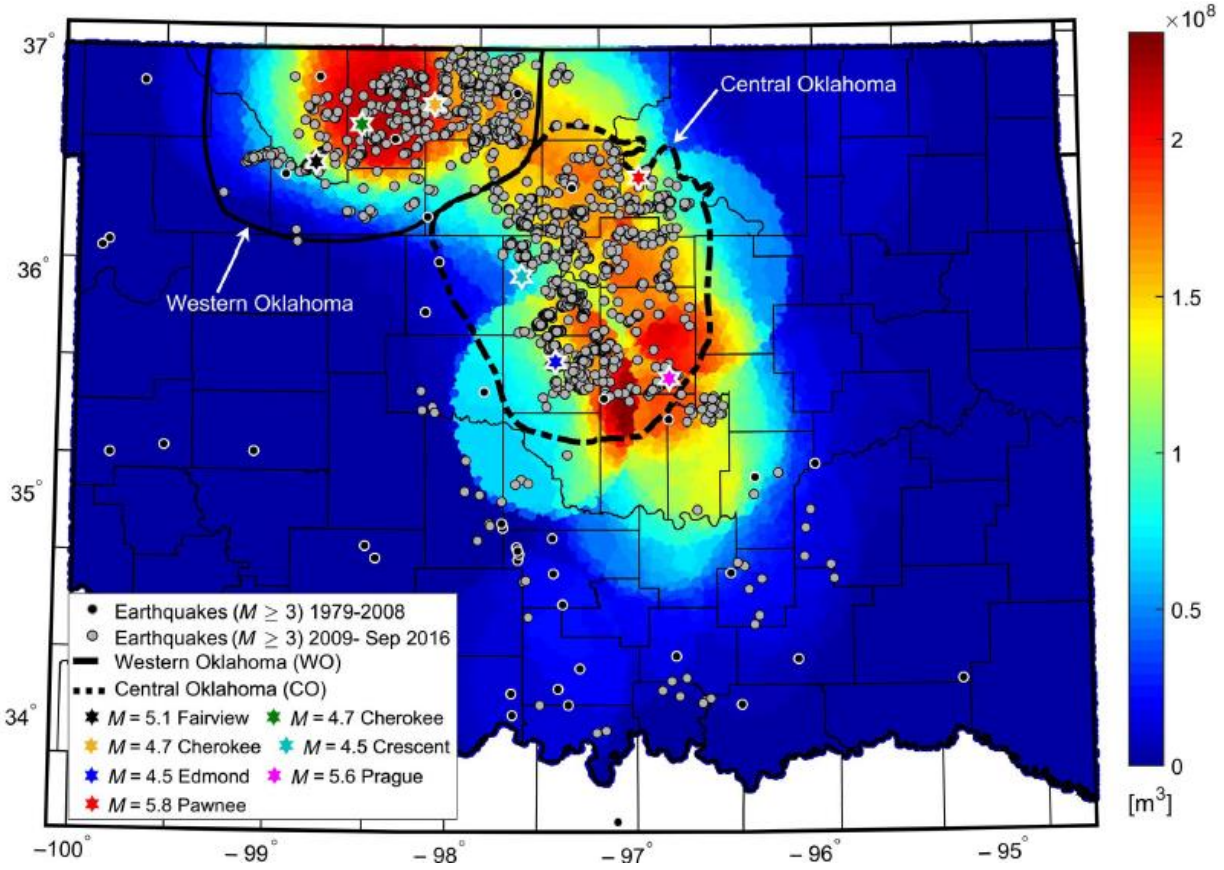
Mississippian Limestone

- Mississippian limestone
  - oil bearing formation
  - not productive with conventional techniques
  - more economical with horizontal drilling
- Development
  - Oklahoma: 2009
  - Kansas: 2012
  - large volumes formation water
  - Class II saltwater disposal wells
    - historic: ~1,000 bbl/day
    - 10,000-30,000 bbl/day
- Arbuckle Group
  - basal aquifer
  - 1000 ft thick, ~4000 ft deep
  - hydraulically connected to basement

credit: Christopher Liner

Observations from Oklahoma

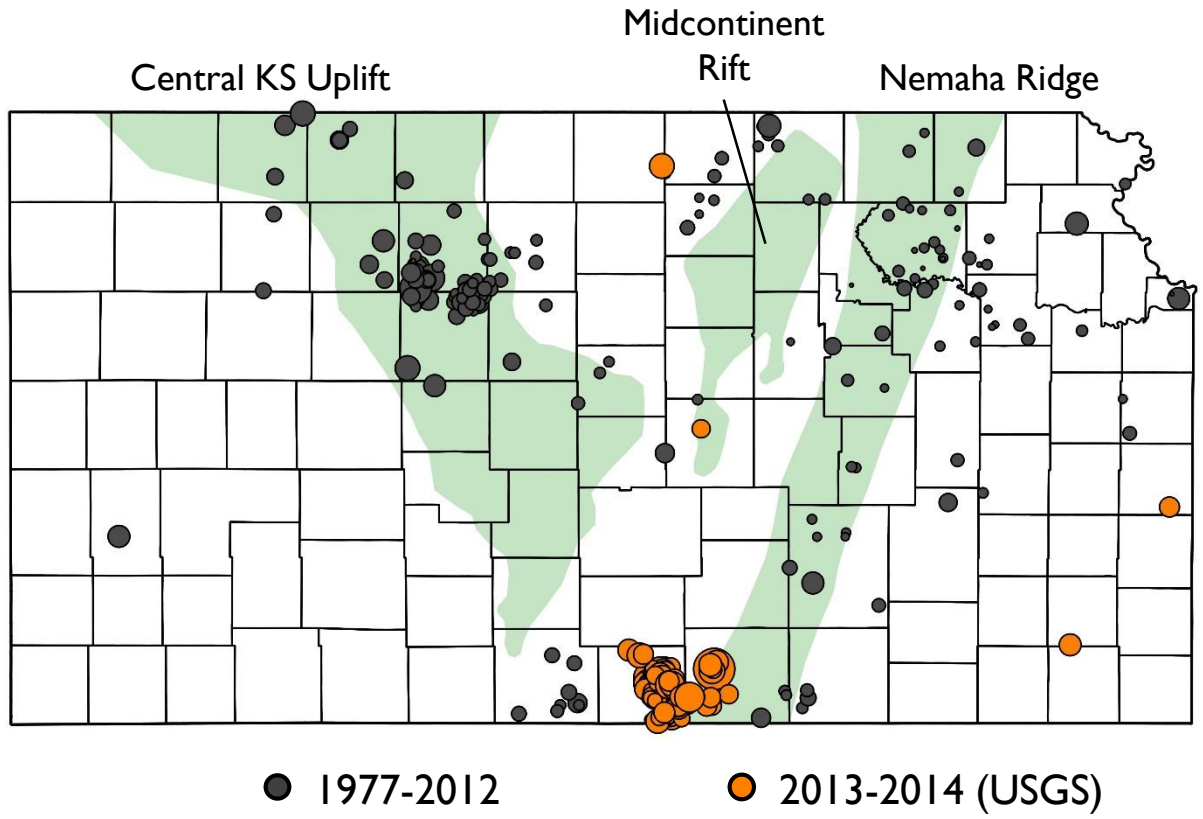
- Earthquake history
  - pre-2009: 1/year
  - 2009-present: hundreds/year
  - strong correlation
    - widespread earthquakes
    - regional saltwater disposal
    - Arbuckle Group
    - basement faults
- Doesn't fit the traditional model
  - little direct correlation
  - cumulative pressure
  - pressure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



from Langenbruch and Zoback (2016)

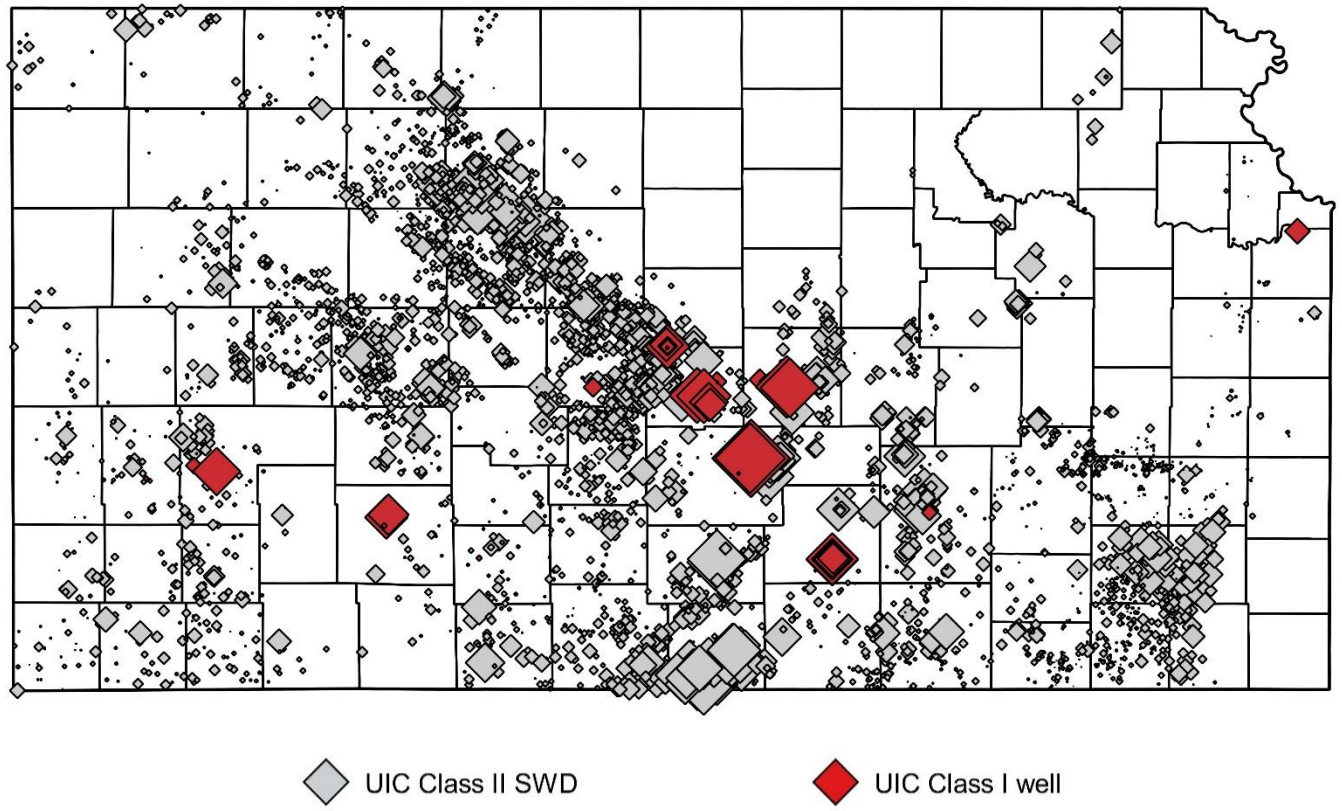
Kansas Earthquake History

- Natural earthquakes
  - 1977 to 2012
  - mostly microearthquakes
  - basement structures
  - M 3 every 2 years
- Possibly induced seismicity
  - 2013-2014
  - increase in rate, magnitude
  - >100 earthquakes
    - M 3 or larger = 44
    - Harper and Sumner
    - few historic earthquakes

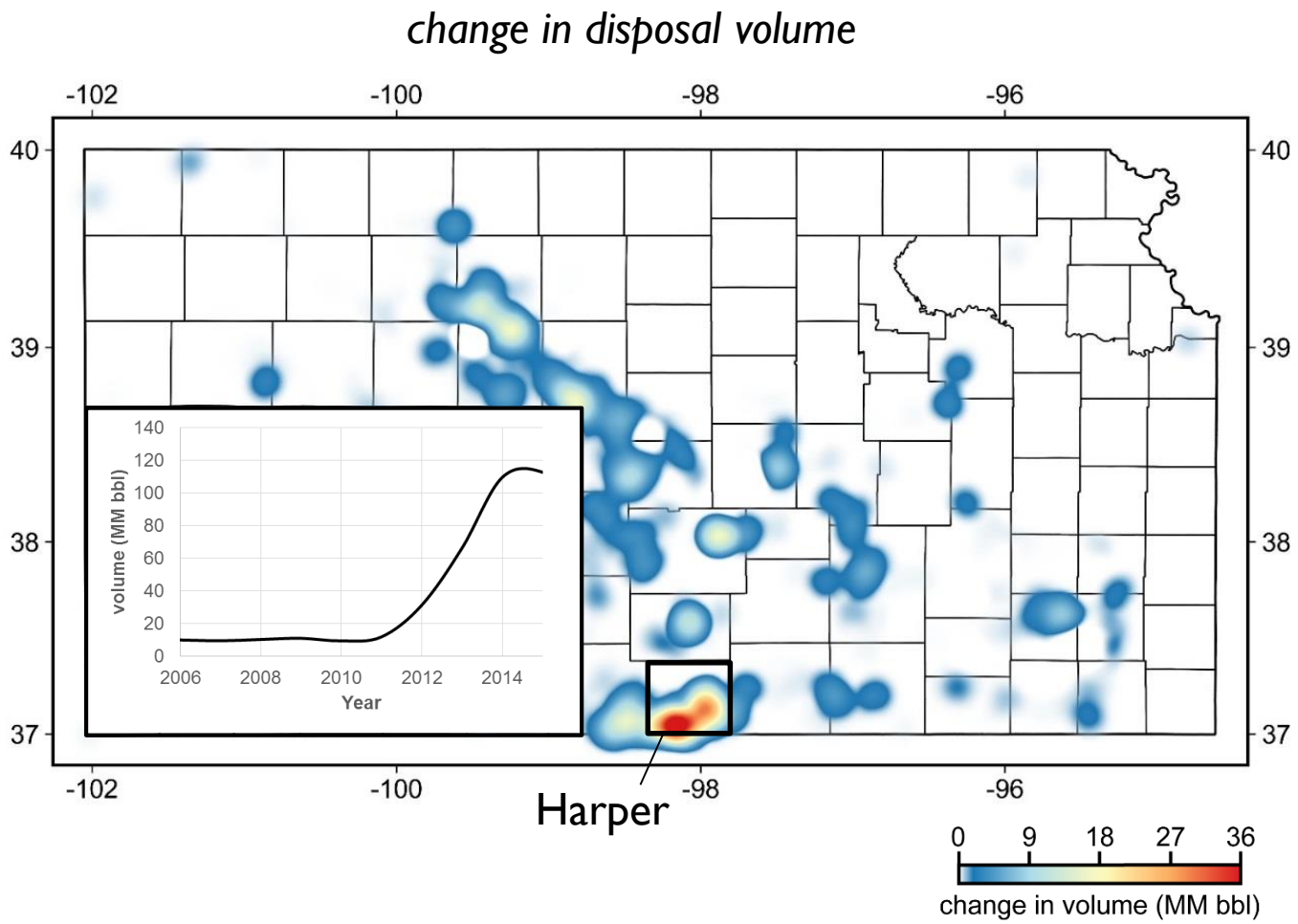


Deep Fluid Disposal in Kansas

- Decades long history
- Class II
  - regulated by KCC
  - >5,000 SWD wells (gray)
  - 50% Arbuckle Group
- Class I
  - regulated by KDHE
  - industrial wastewater
  - range of industries
  - 50 wells (red)
  - Arbuckle
  - pressure falloff tests
    - time history
    - regional pressure

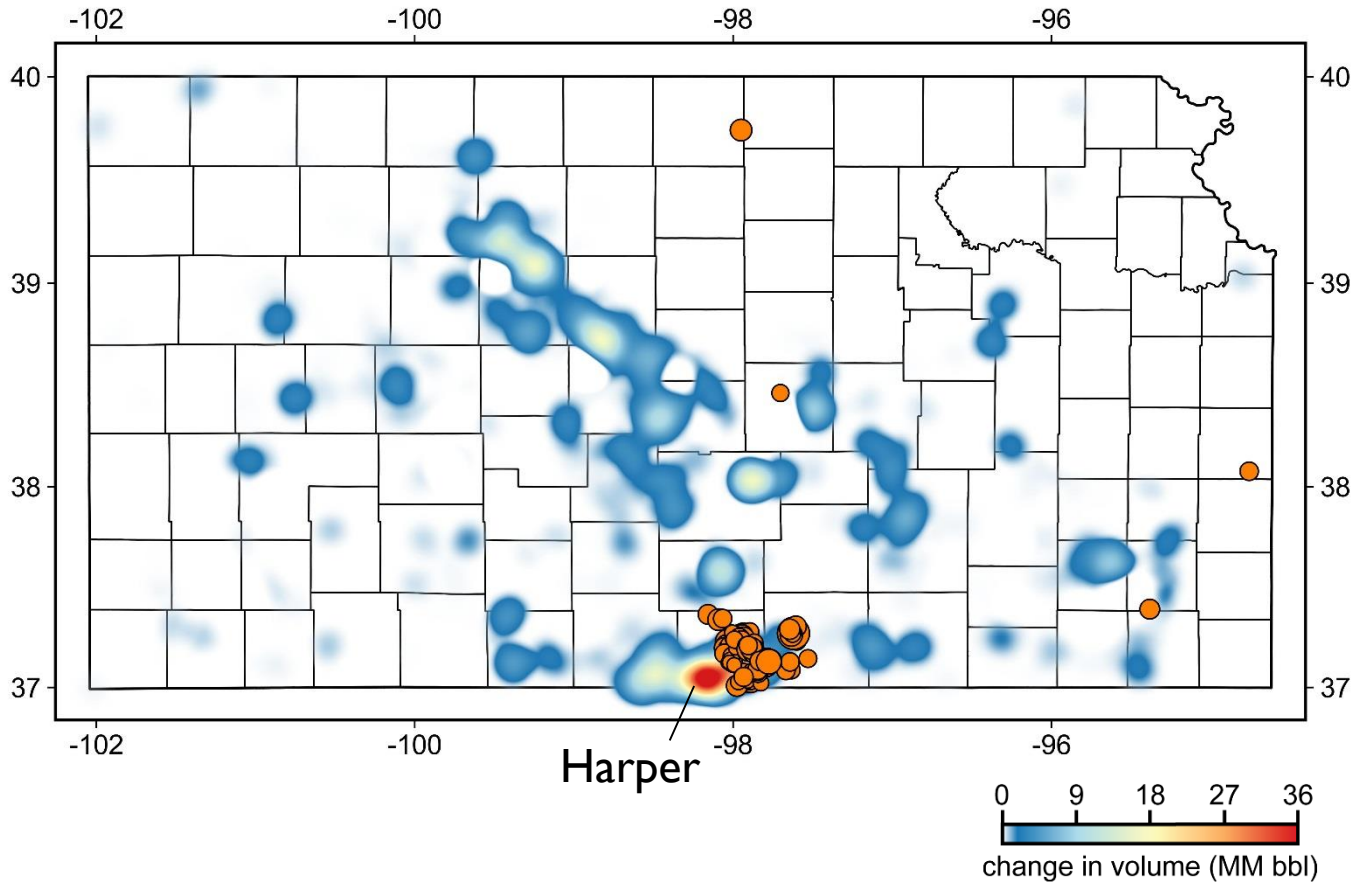


Increased Disposal Volume



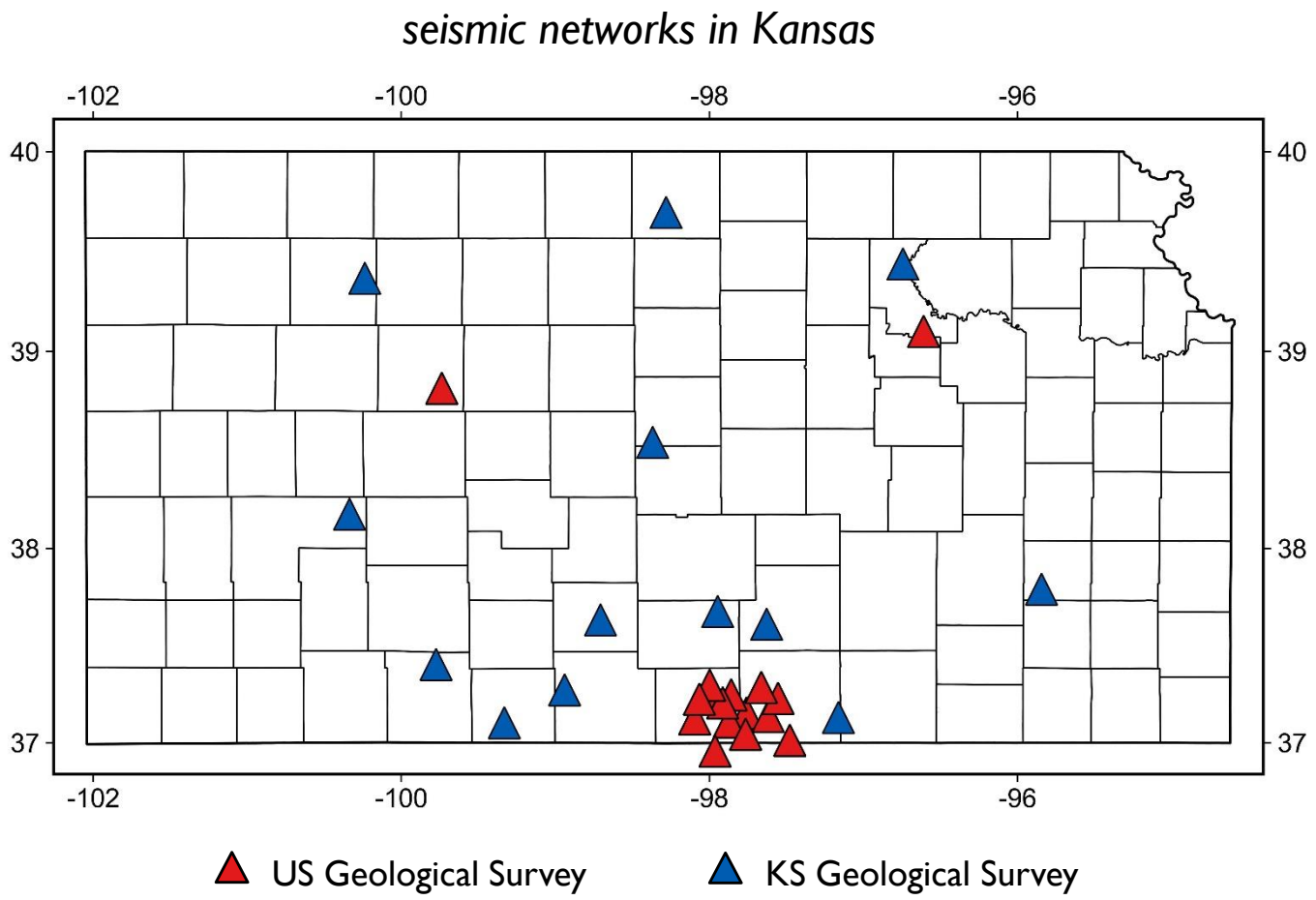
Induced Seismicity

2013-2014 Earthquakes (USGS)



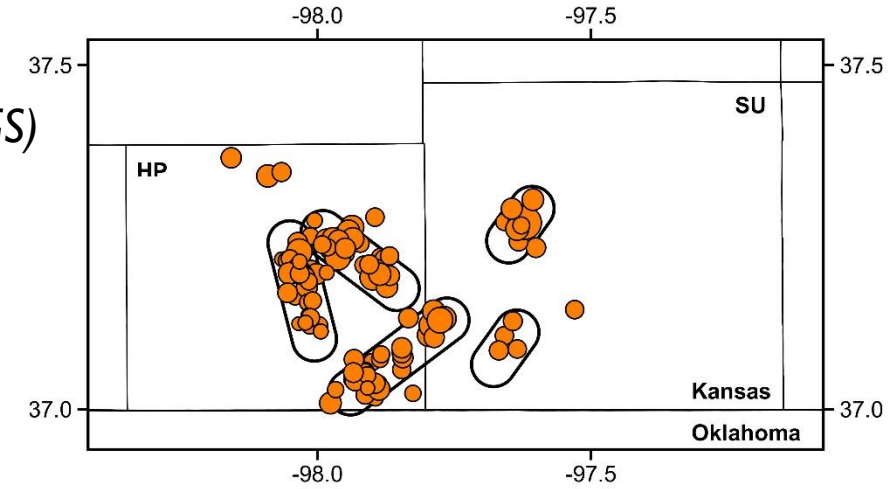
unique vantage to observe long-range effects

Seismic Networks

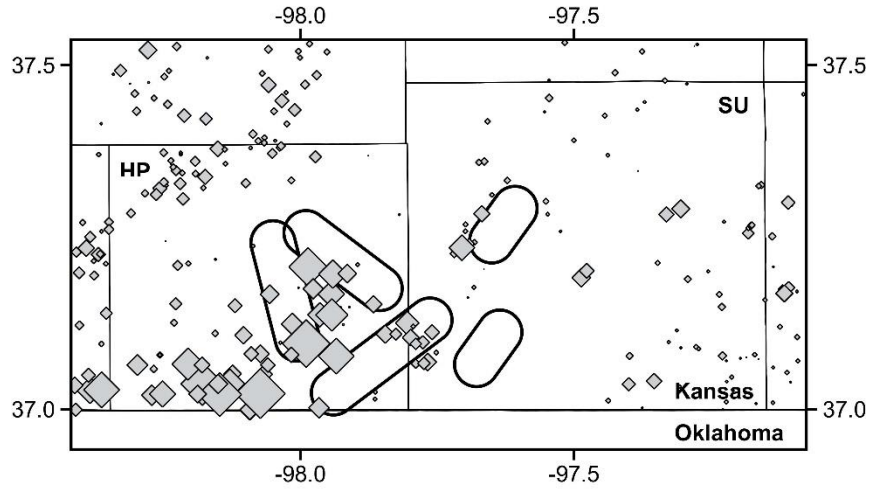


Mitigation Efforts

2013-2014 Earthquakes (USGS)



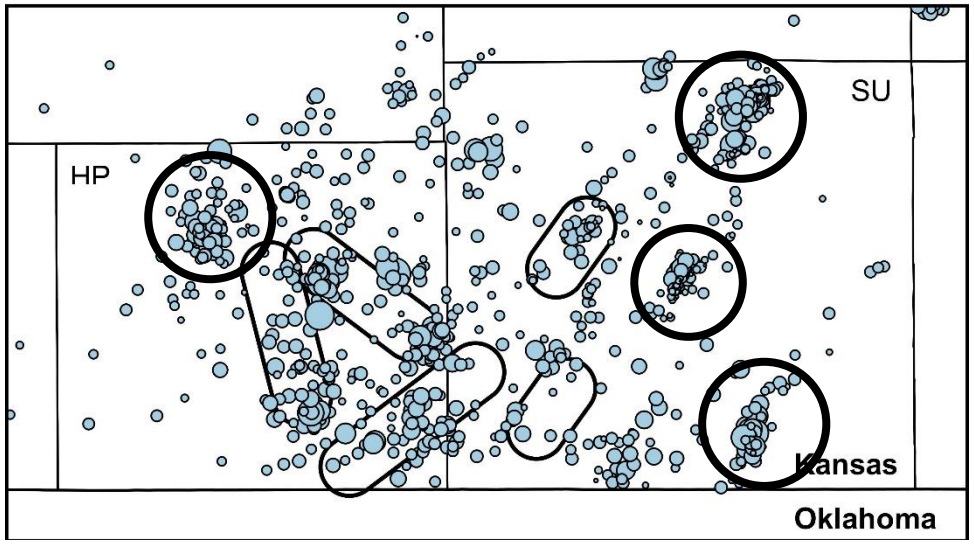
Class II SWD



- General strategies: well-based
- Kansas Corporation Commission
  - geologically based approach
  - reduce pore pressure
  - initial earthquakes
- Ordered phased reduction
  - regulation footprint
  - 20,000 → 8,000 bbl/day
  - July 2015
- Generally reduced
  - decline in oil prices
  - regulation in Oklahoma

Migration of Earthquakes

Jan to Jun 2017



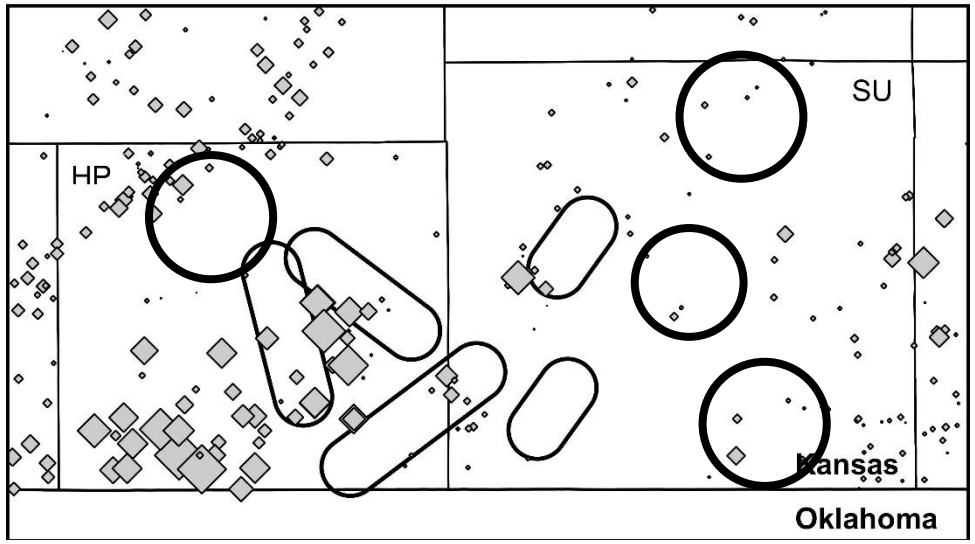
earthquake (KGS)

KCC regulation area

0 10 20 30 40

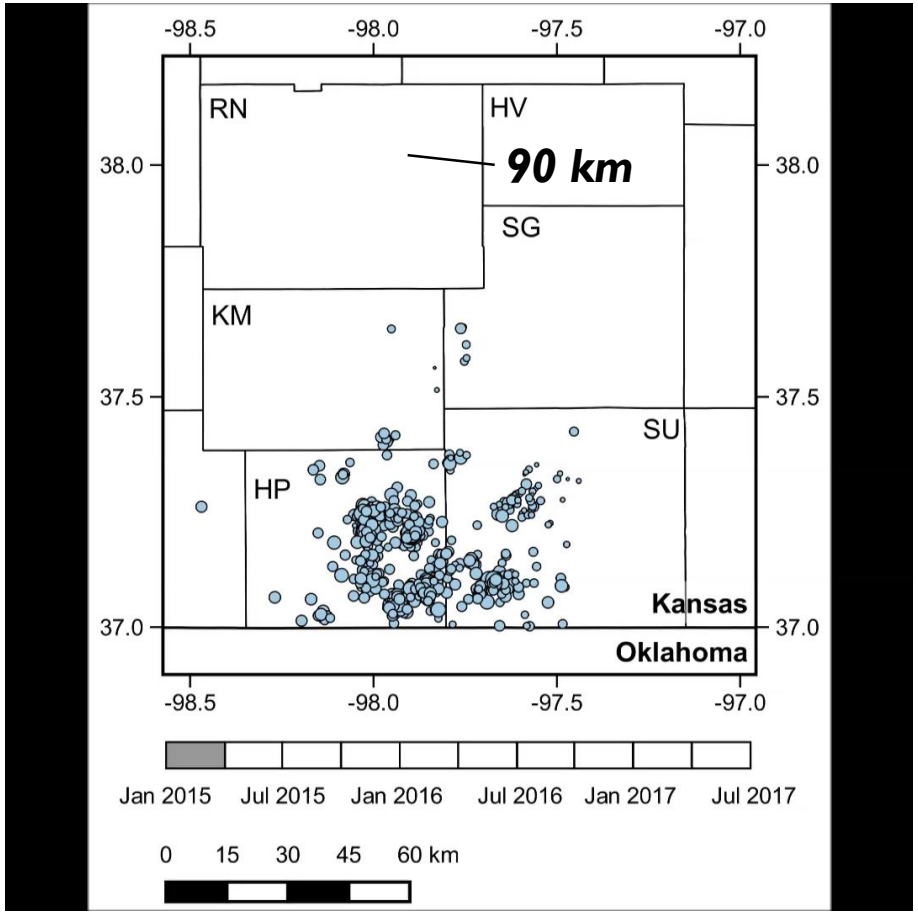
distance (km)

Class II SWD and Class I wells (2017)



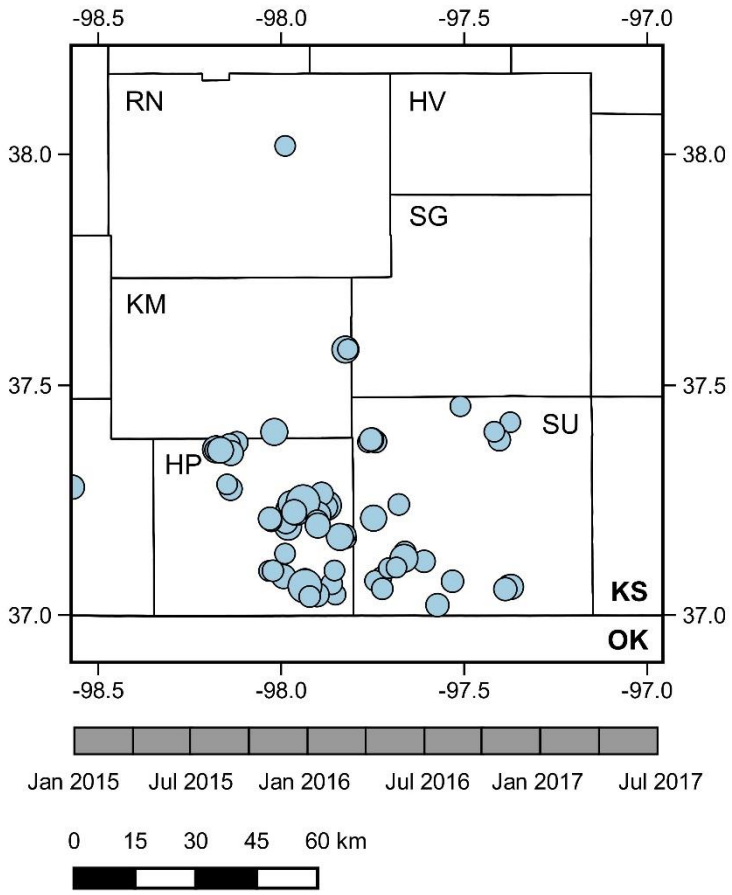
local injection likely not the cause

Migration of Earthquakes



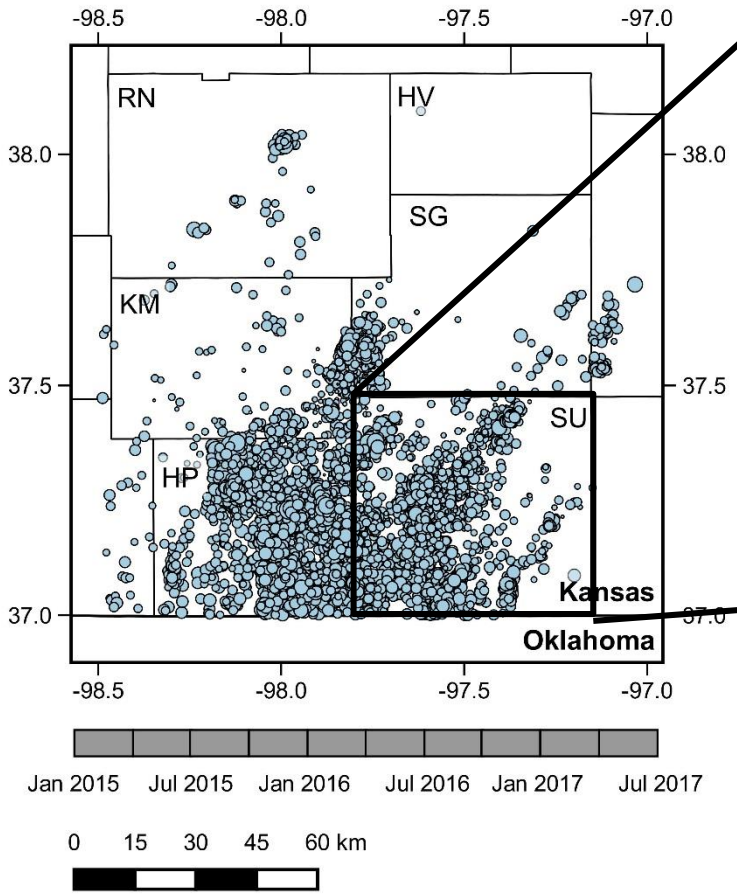
- Initially dense swarms
  - 2015-2016
  - Harper and Sumner
- Earthquake migration
  - 2016-2017
  - Persist in HP and SU
- Migrate progressively farther
  - radially away
  - up 90 km
  - challenges previous belief (20 km)

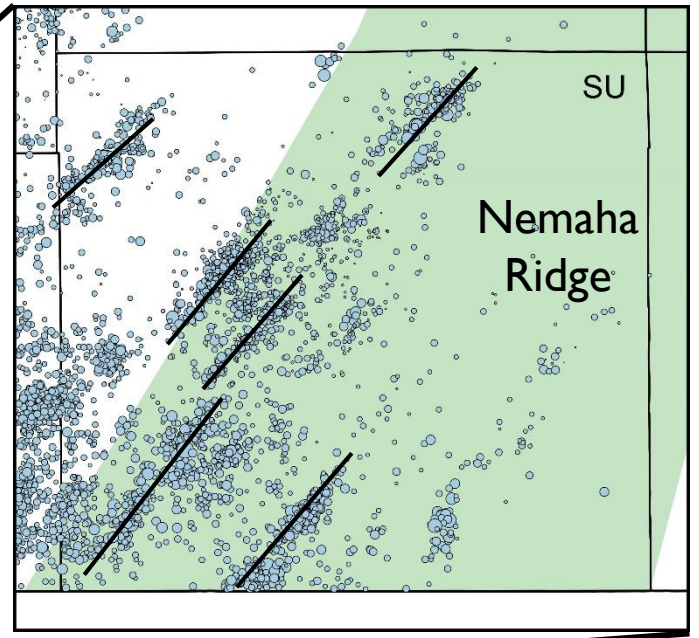
Magnitude Distribution



- 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

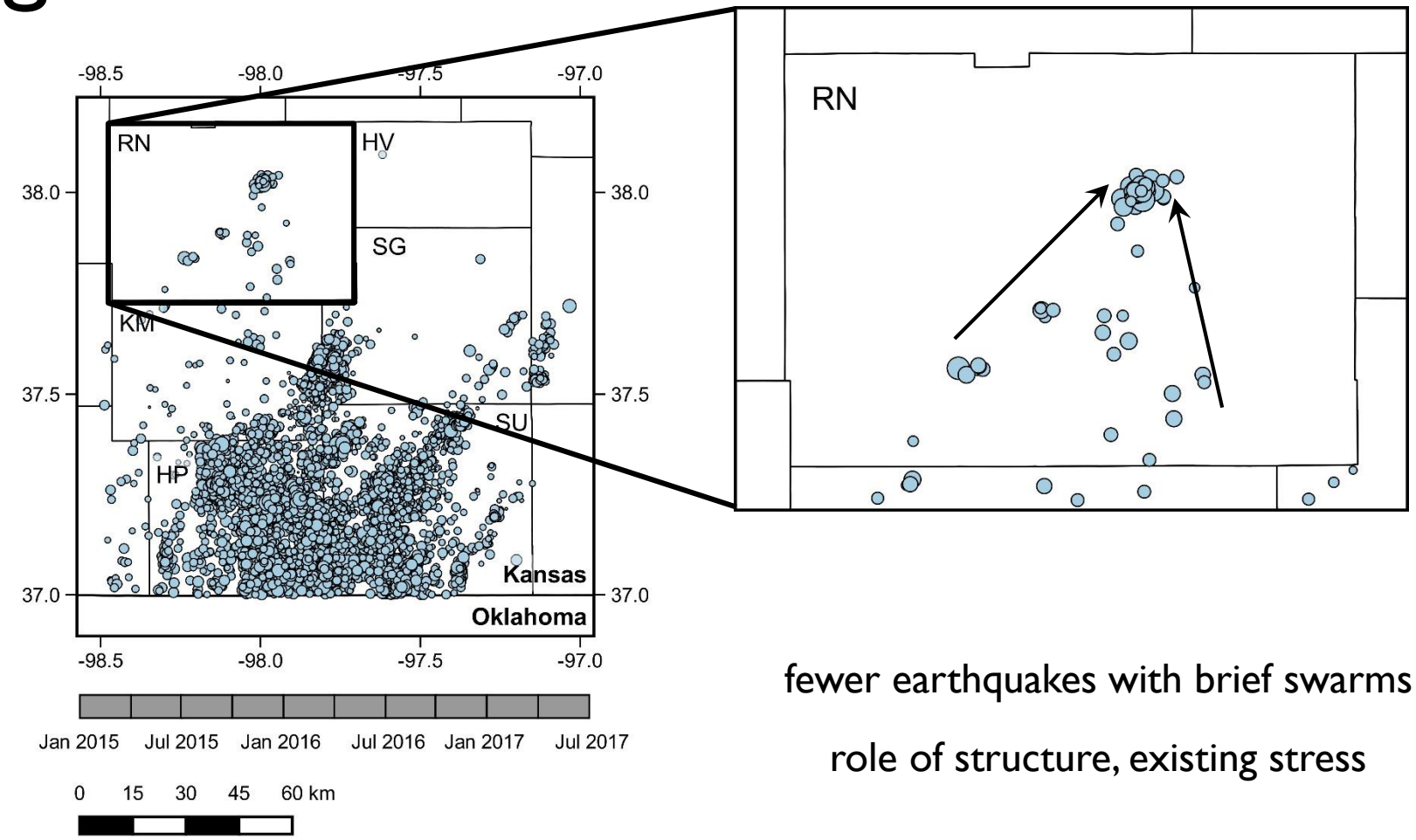
Migration Patterns





fluid migration along permeable faults

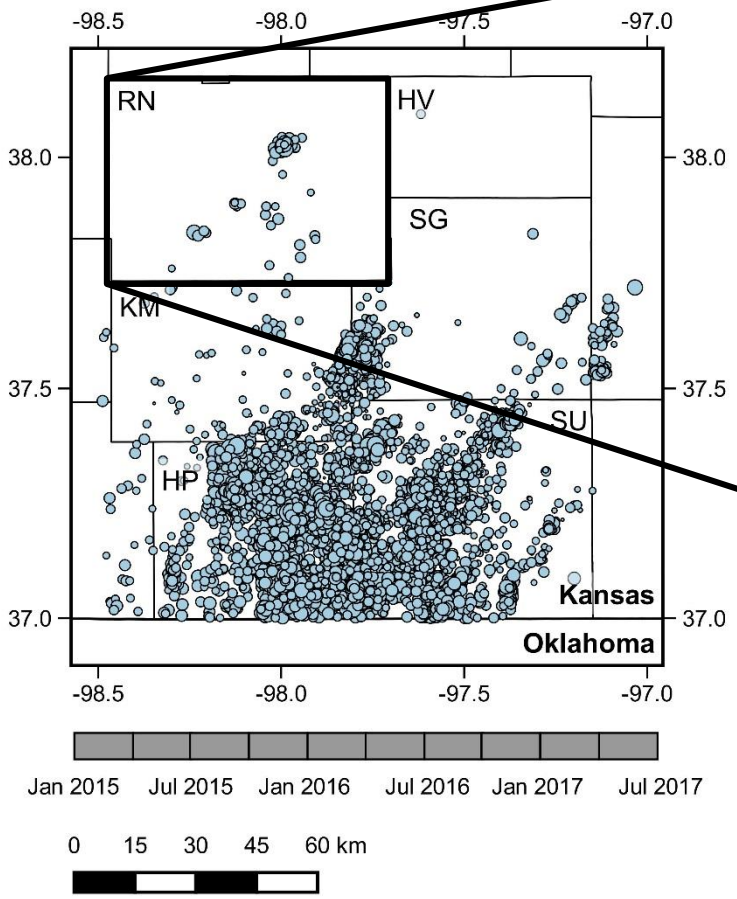
Migration Patterns

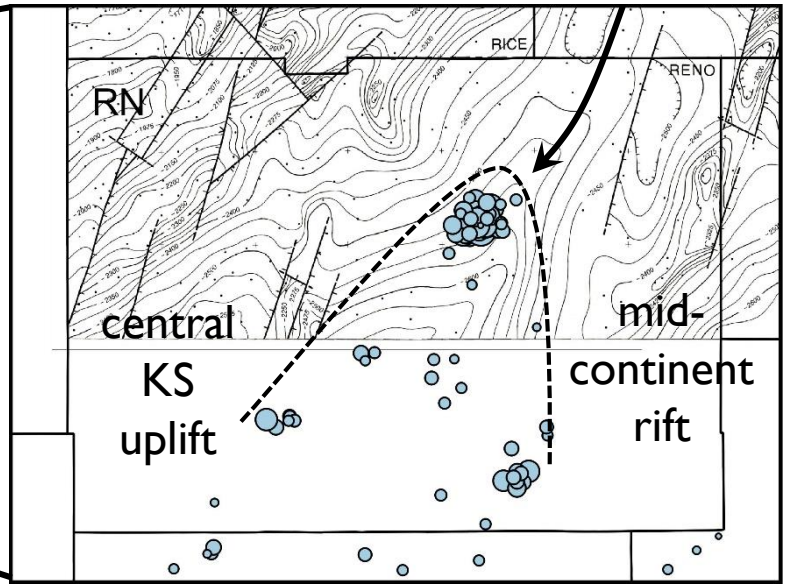


fewer earthquakes with brief swarms

role of structure, existing stress

Migration Patterns



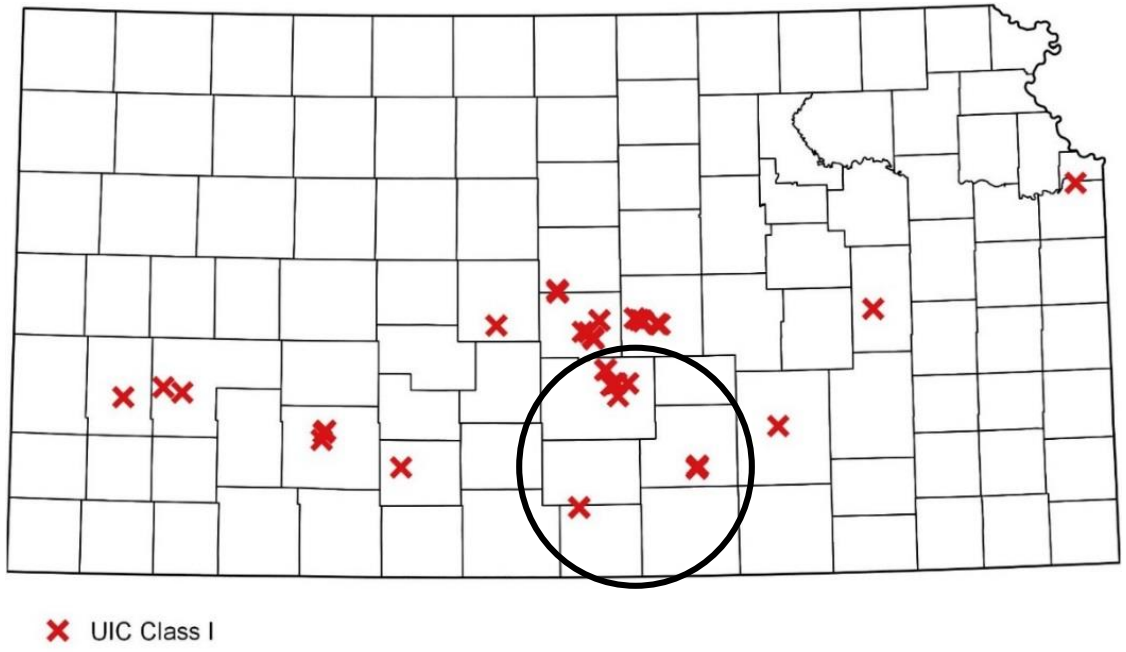


Arbuckle Structural Contours

fewer earthquakes with brief swarms

role of structure, existing stress

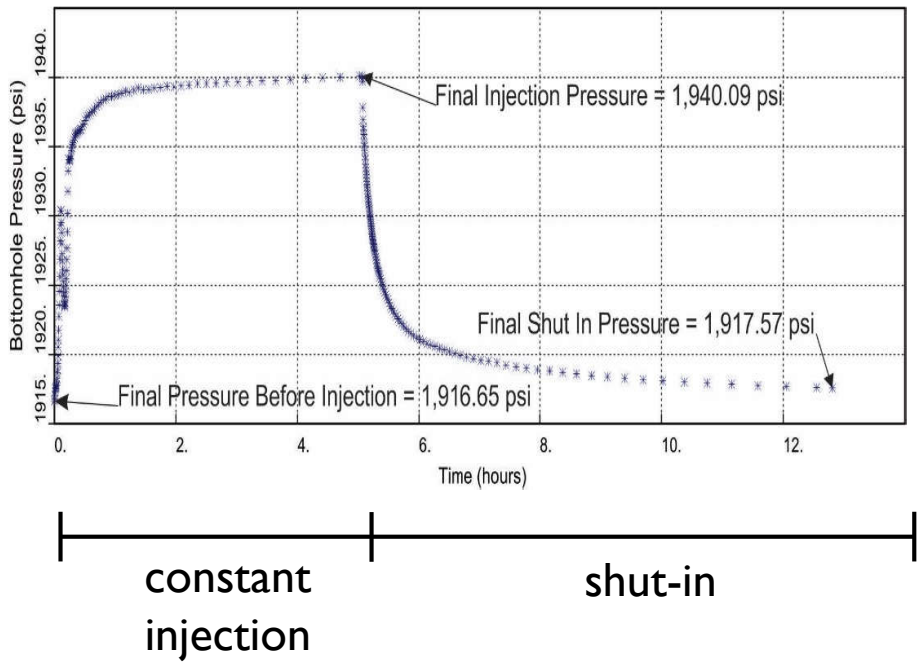
Arbuckle Fluid Pressure



- Correlation with SWD
  - what's the driver?
    - pore pressure
    - poroelastic stress
    - combination
- Modeling
  - estimate pressure and stress
  - time intensive
  - difficult
- Direct P* measurements
  - Class I PFO
  - time history
  - several in study area

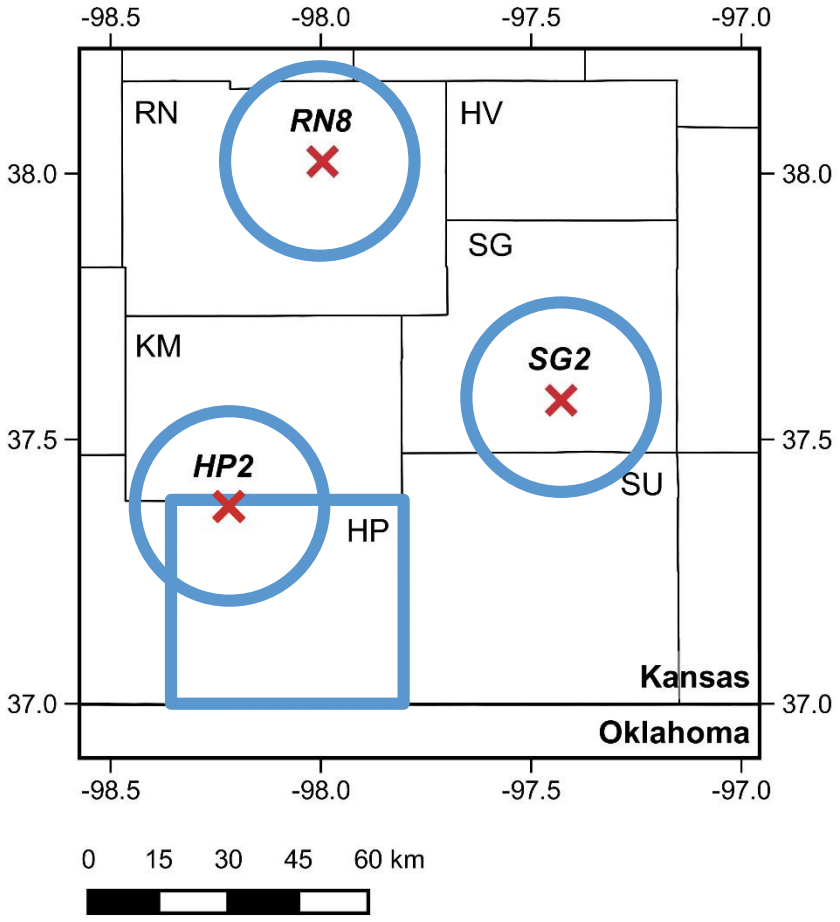
Pressure Falloff Test

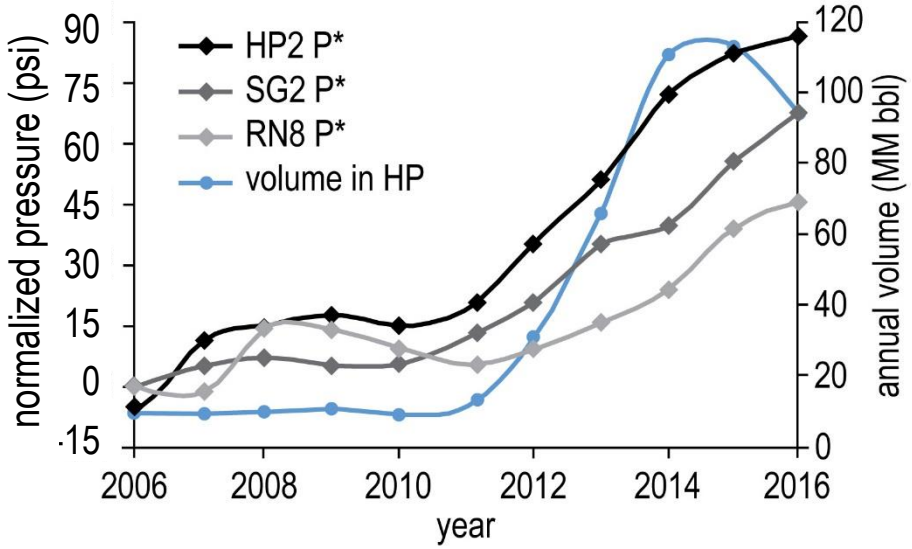
pressure vs. time



- Required by KDHE
  - annual testing
  - evaluate reservoir conditions
- During the test
  - pressure sensor
  - constant rate injection
  - shut-in
  - pressure monitored
- Pressure transient analysis
  - porosity
  - permeability
  - **formation pressure**

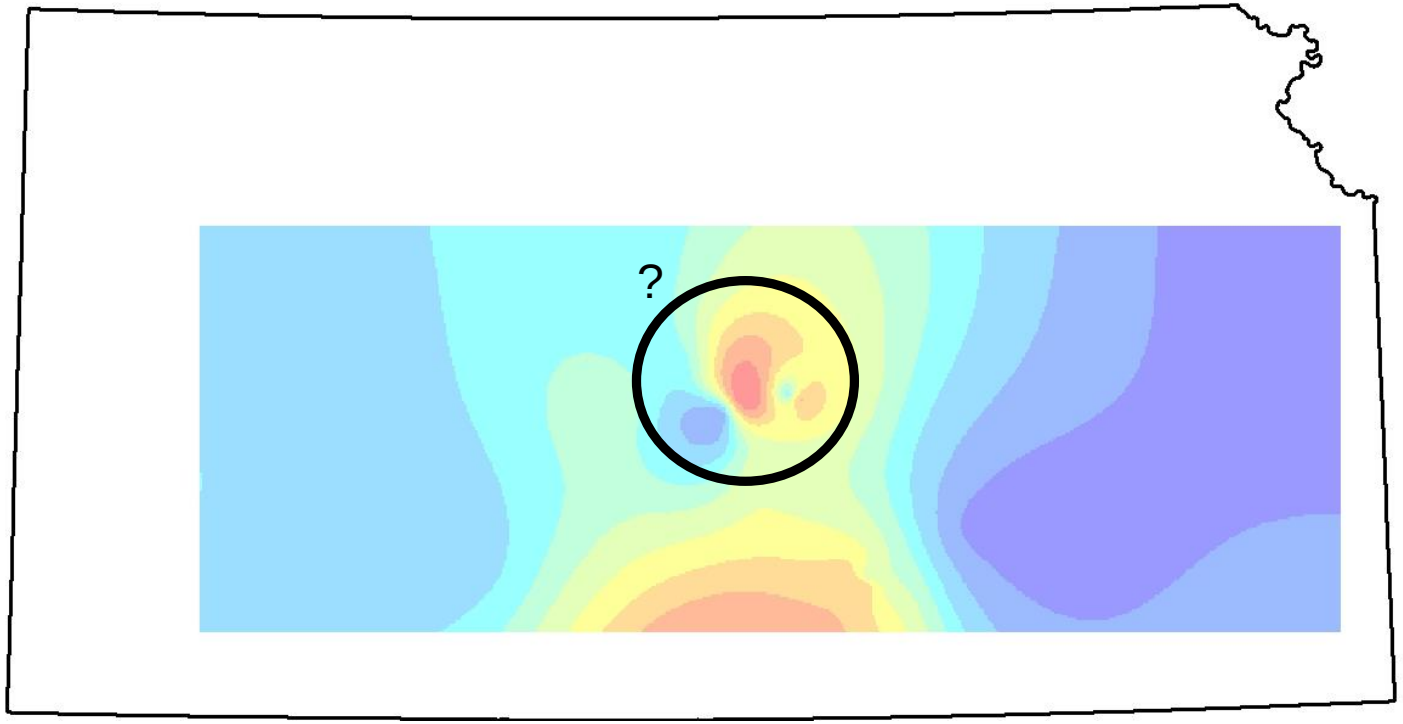
Arbuckle Fluid Pressure





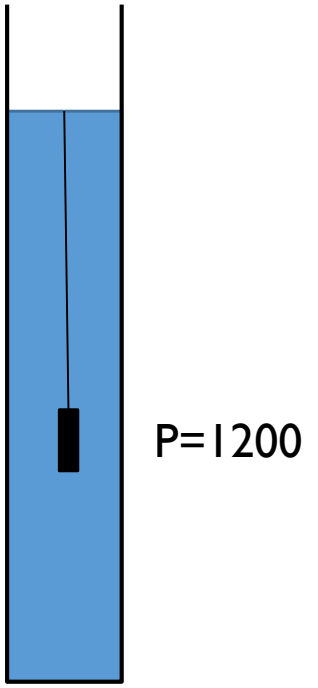
Regional Pressure Change Map

interpolate sparse measurements



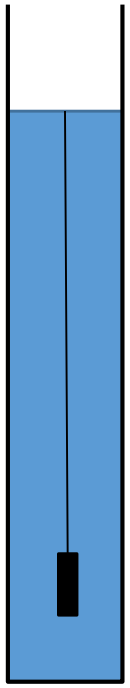
Tool Depth Changes

2011



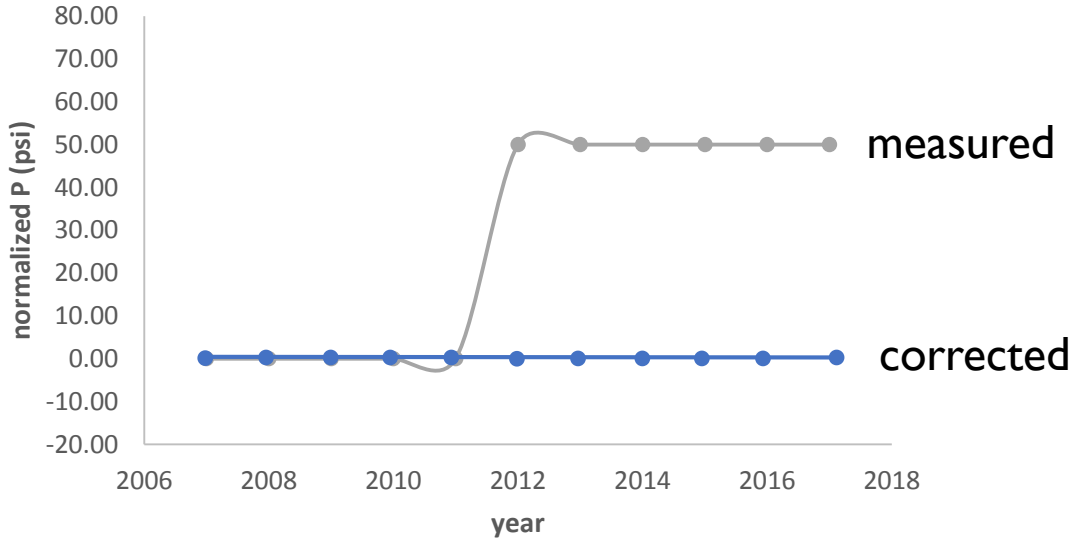
P=1200

2012



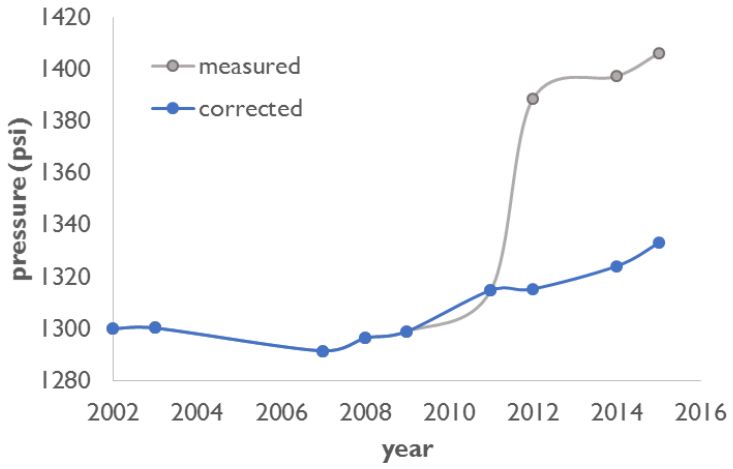
P=1250

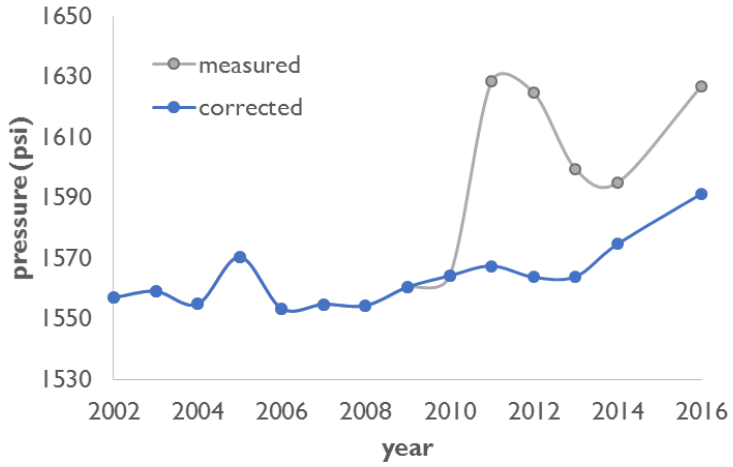
apparent ΔP



$$P_{corrected}(z_0) = \mathrm{P}_{measured} - \frac{dP}{dz}(z_0 - z_{actual})$$

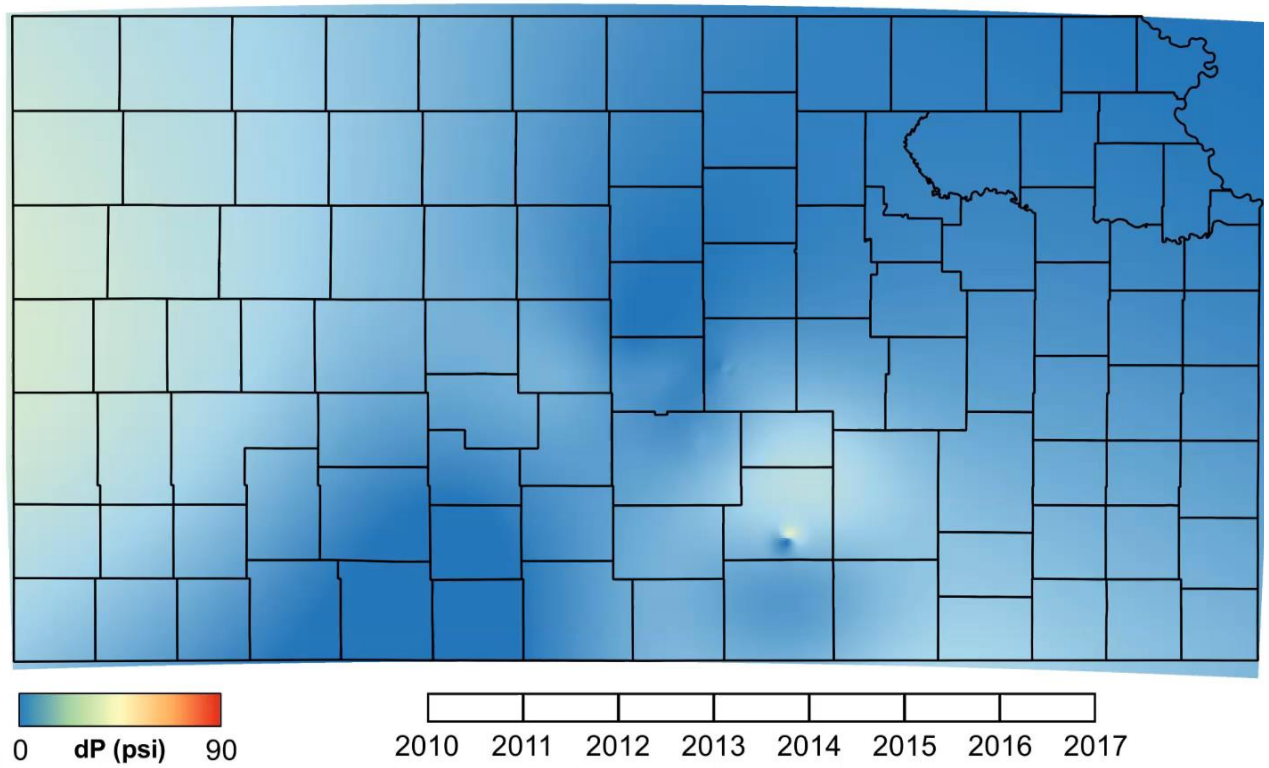
Tool Depth Changes





- *Examples:* apparent 100 psi increase
- To obtain tool depth
  - paper reports
  - 1,300 scanned files
    - meaningless name
    - upside down
  - PFO are not standardized
- Correct for depth changes
  - accurate time history
  - true pressure

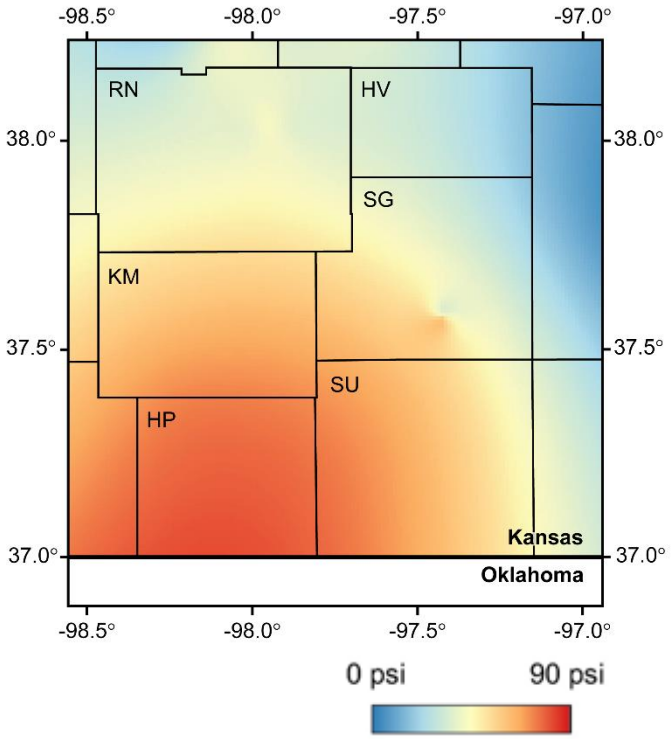
Arbuckle Fluid Pressure



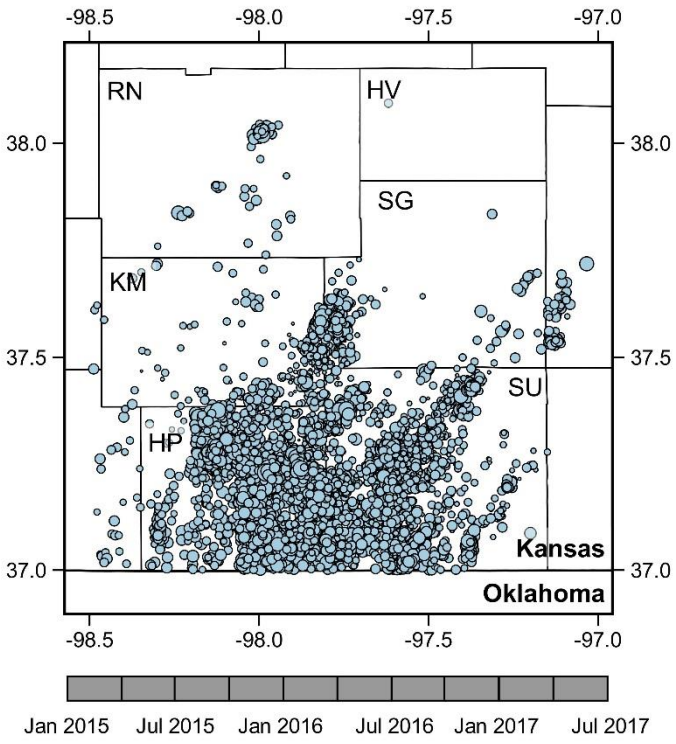
- Regional map
  - sparse statewide measurements
  - interpolate
  - limited local detail
- Pressure change
  - absolute pressure varies
  - relative to baseline (2002)
- Insight into pressure affecting basement faults

Arbuckle Fluid Pressure

Arbuckle pressure

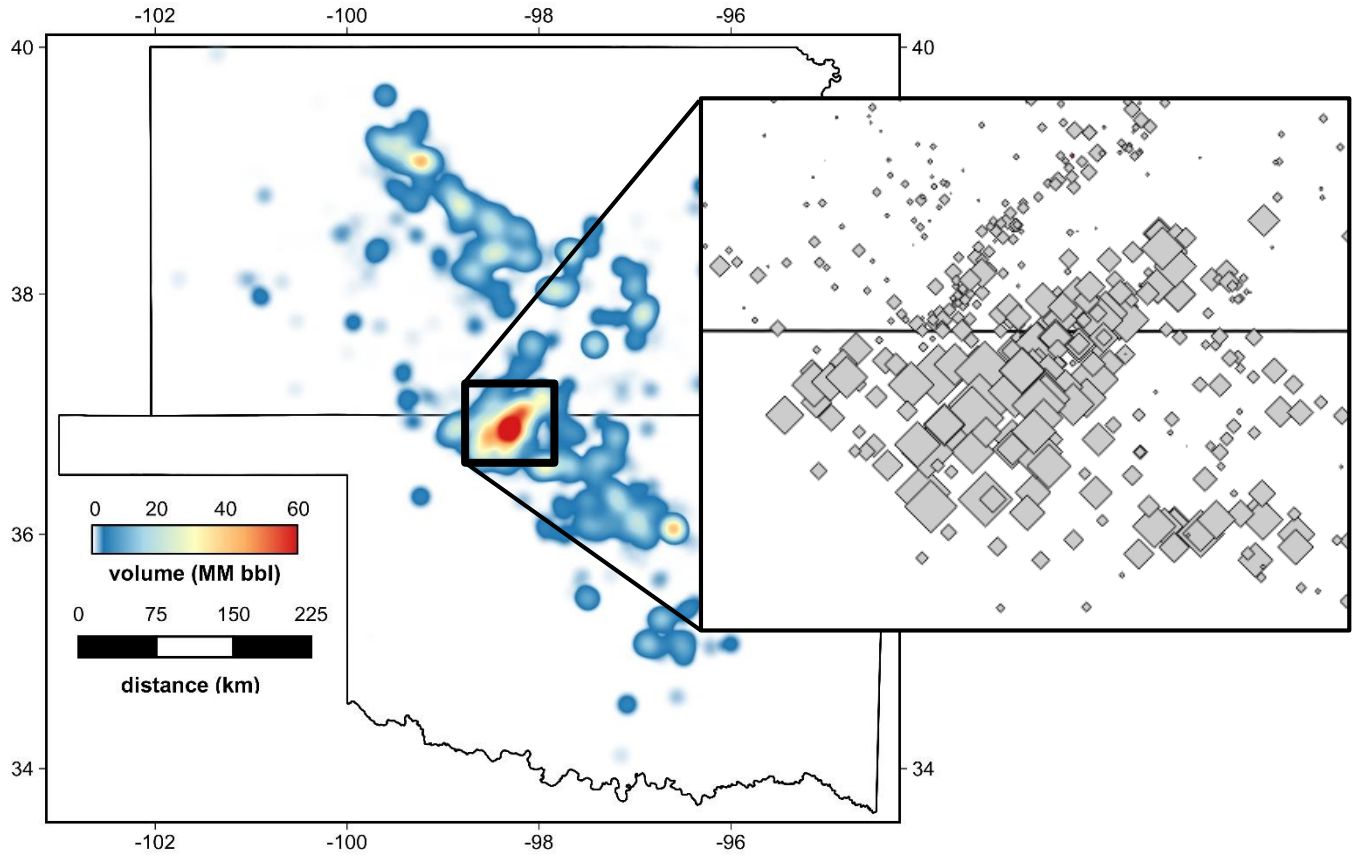


seismicity



- Earthquake consistent with ΔP
- Unprecedented
  - 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
- Poroelastic coupling influences pressure diffusion (Segall, 2015)
  - most studies assume no poroelastic effects
  - uncoupled hydrogeologic models may not be sufficient

Arbuckle Fluid Pressure



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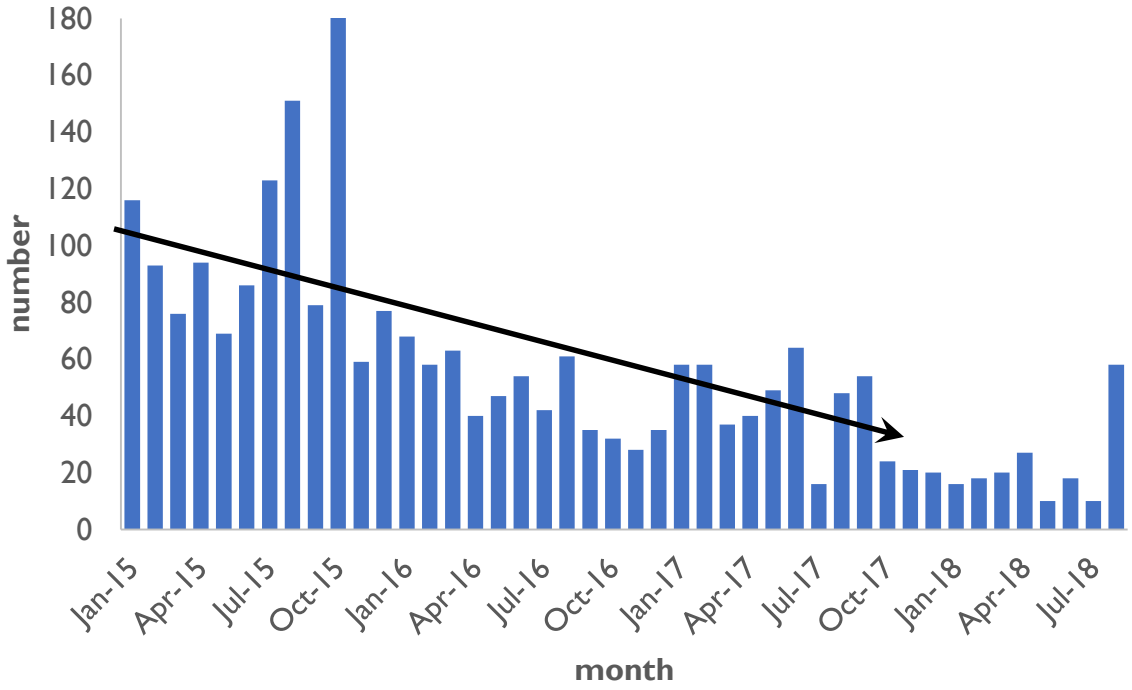
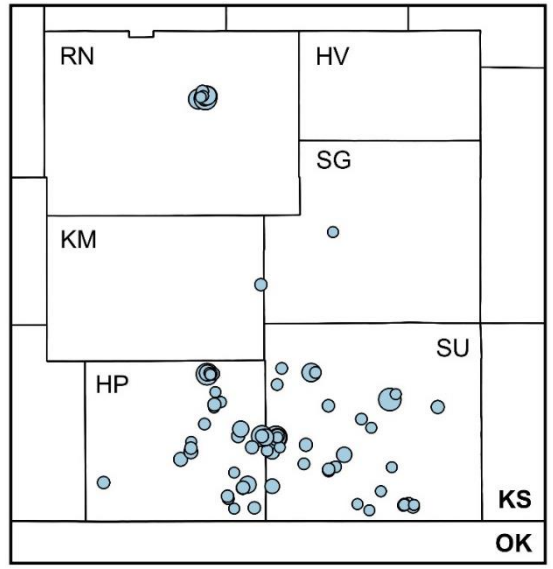
What's happening now?

2018 Seismicity

Earthquakes M ≥ 2

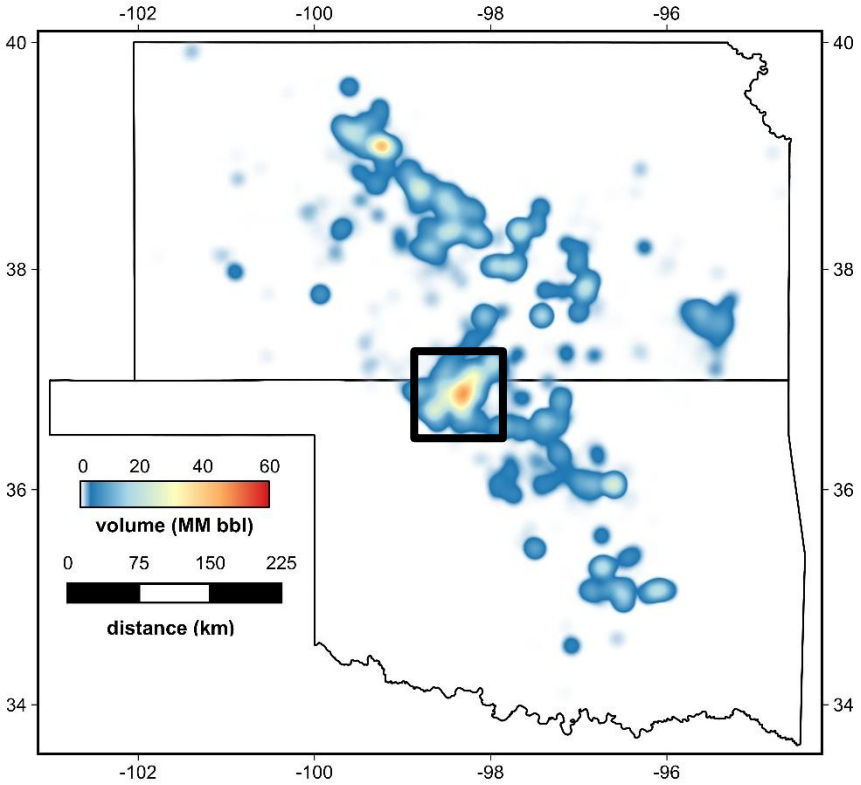


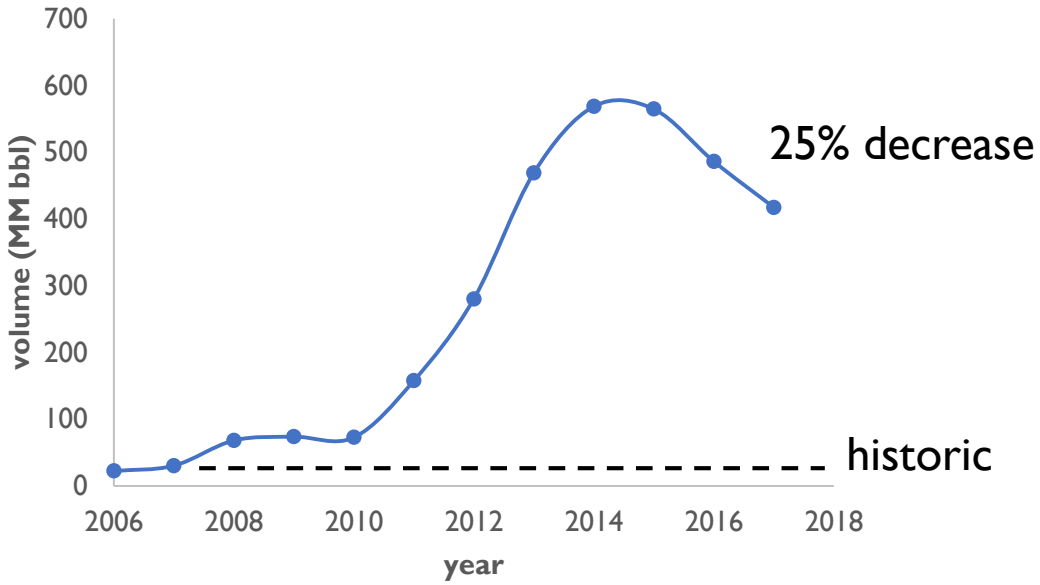
M≥2 Jan-Jun 2018



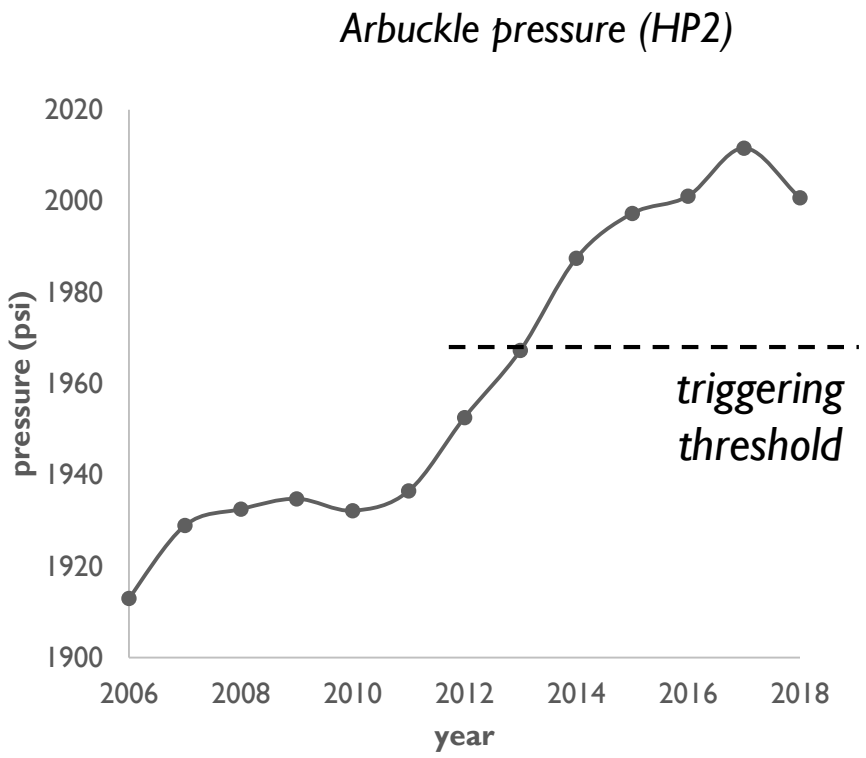
2017 Disposal

Arbuckle disposal volume (2017)





2018 Pressure

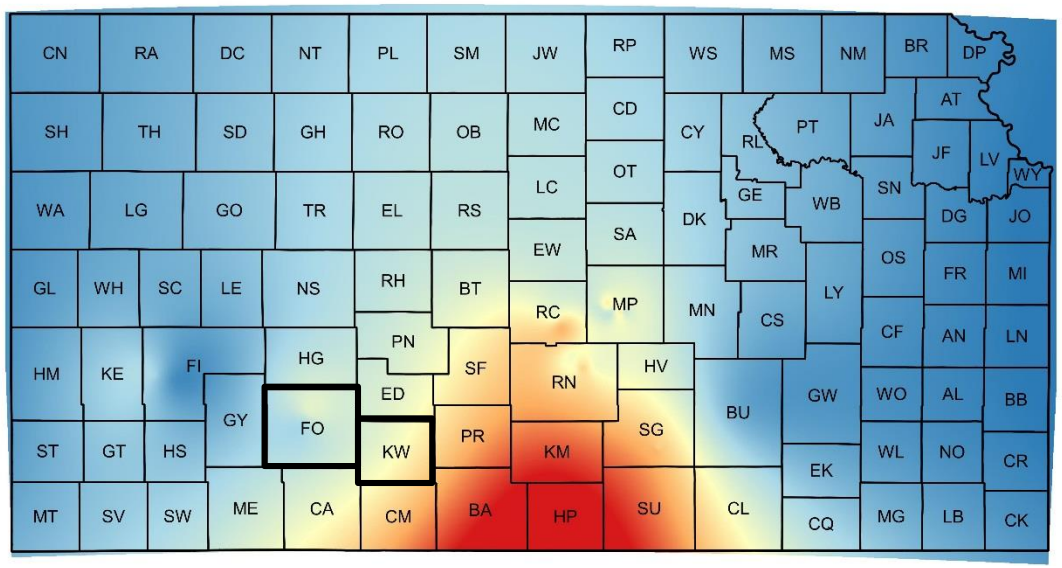


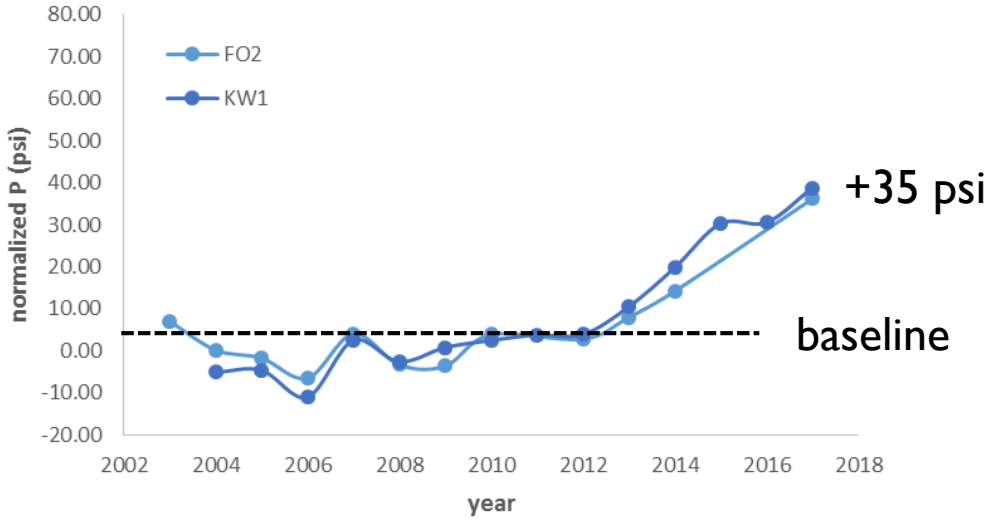
- Regional Arbuckle pressure
  - continued to climb in 2017
  - stabilizing in Harper county
  - unclear elsewhere
- Above triggering threshold
  - faults will be sensitive
  - small fluctuations
  - operations previously tolerated
- Maintain pressure
  - injection volumes remain high
  - pressure could remain elevated

Extent of Pressure Change

is the boundary a result of interpolation, or real?

2017 Arbuckle Pressure

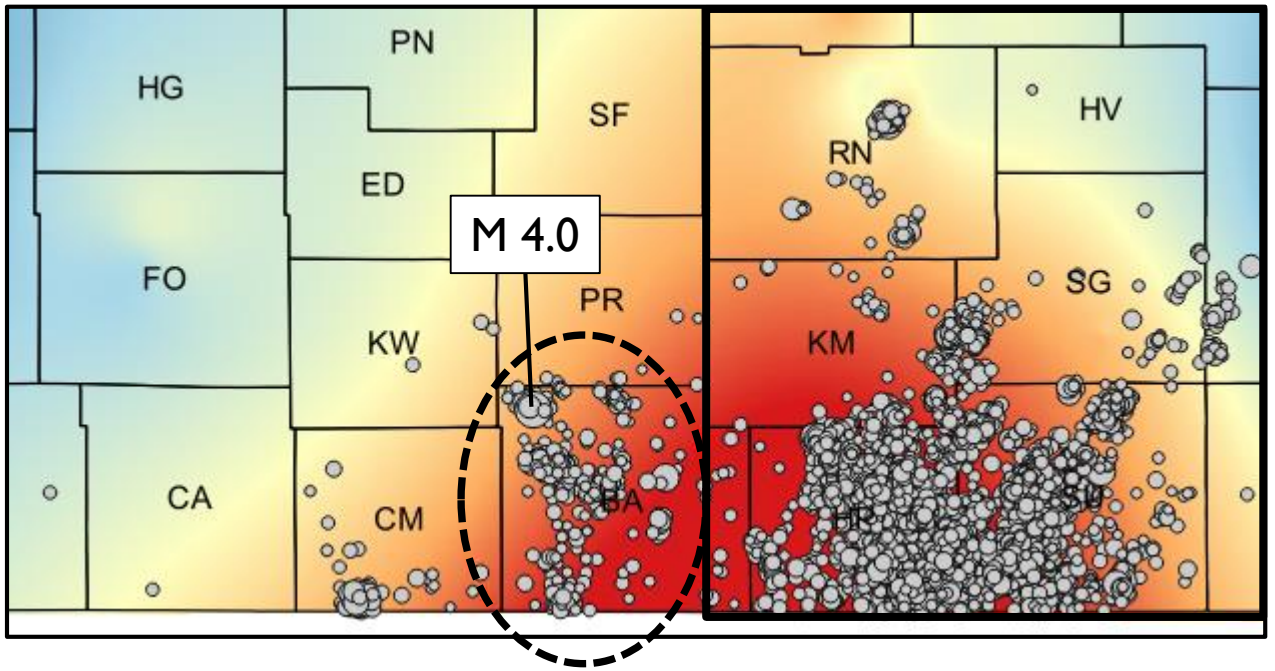




Earthquakes to the West

more than 400 earthquakes

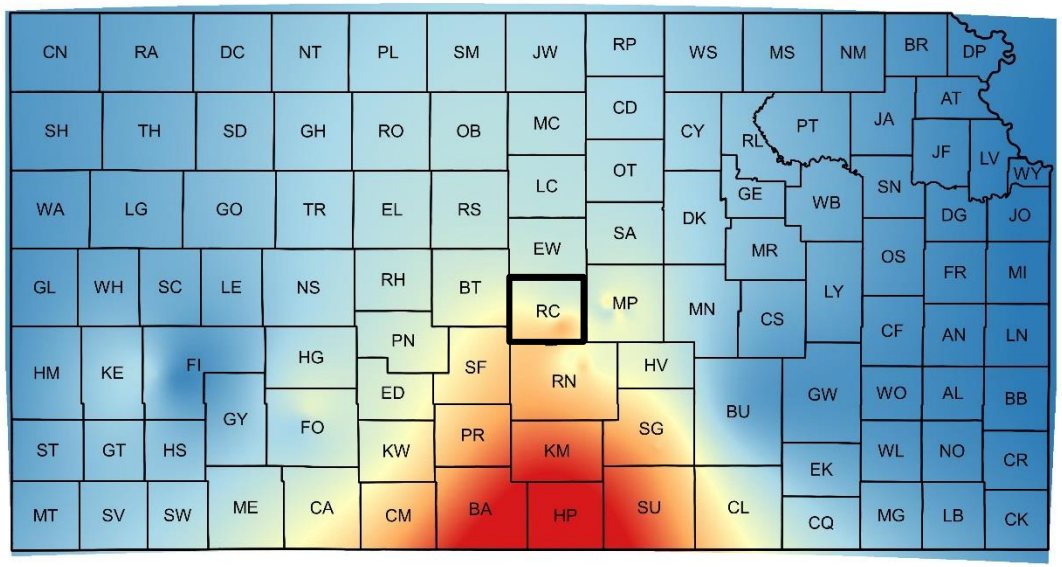
study area



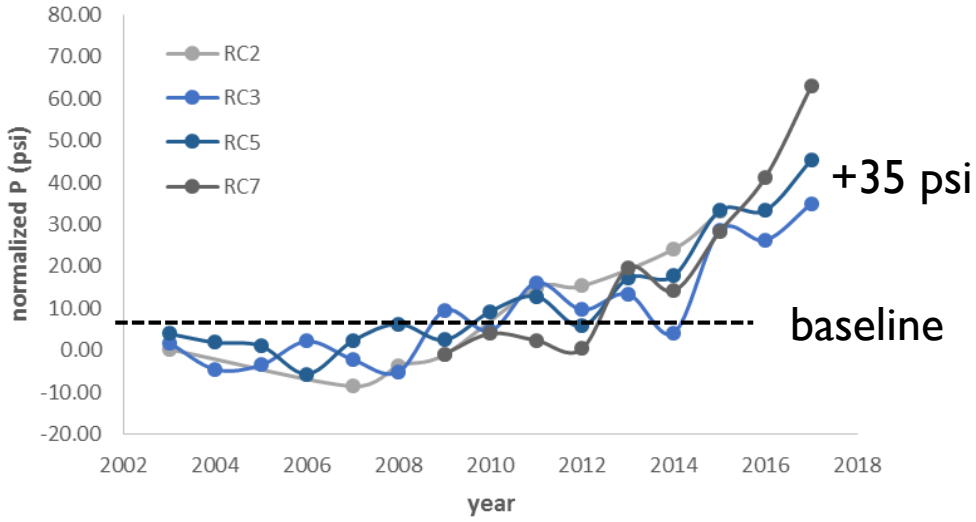
Pratt
Anticline

Extent of Pressure Change

2017 Arbuckle Pressure

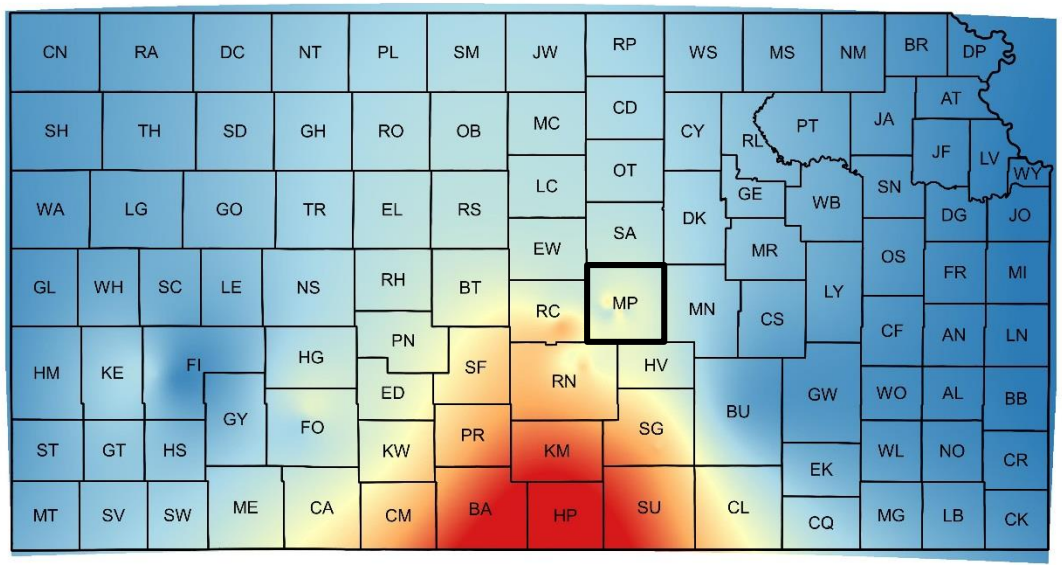


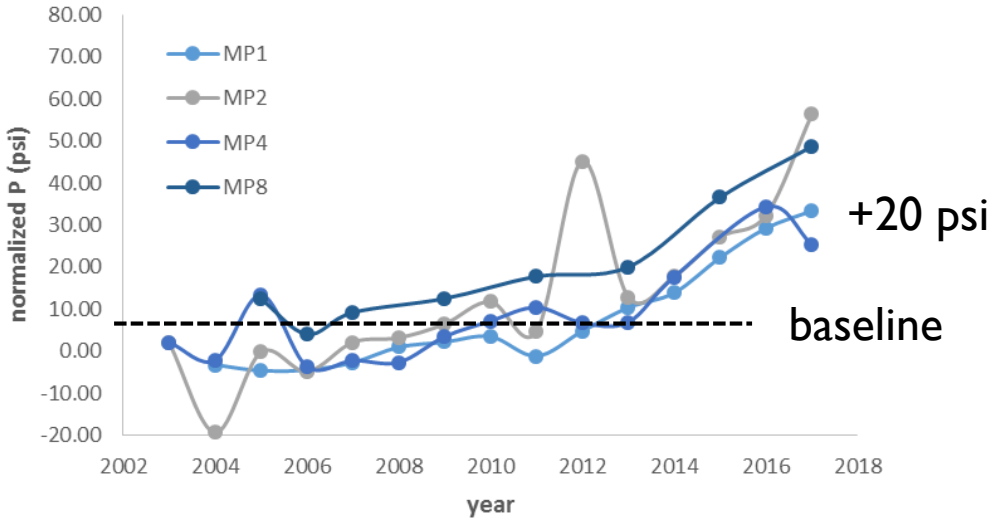
little to no seismicity
monitor for increase/earthquakes



Extent of Pressure Change

2017 Arbuckle Pressure





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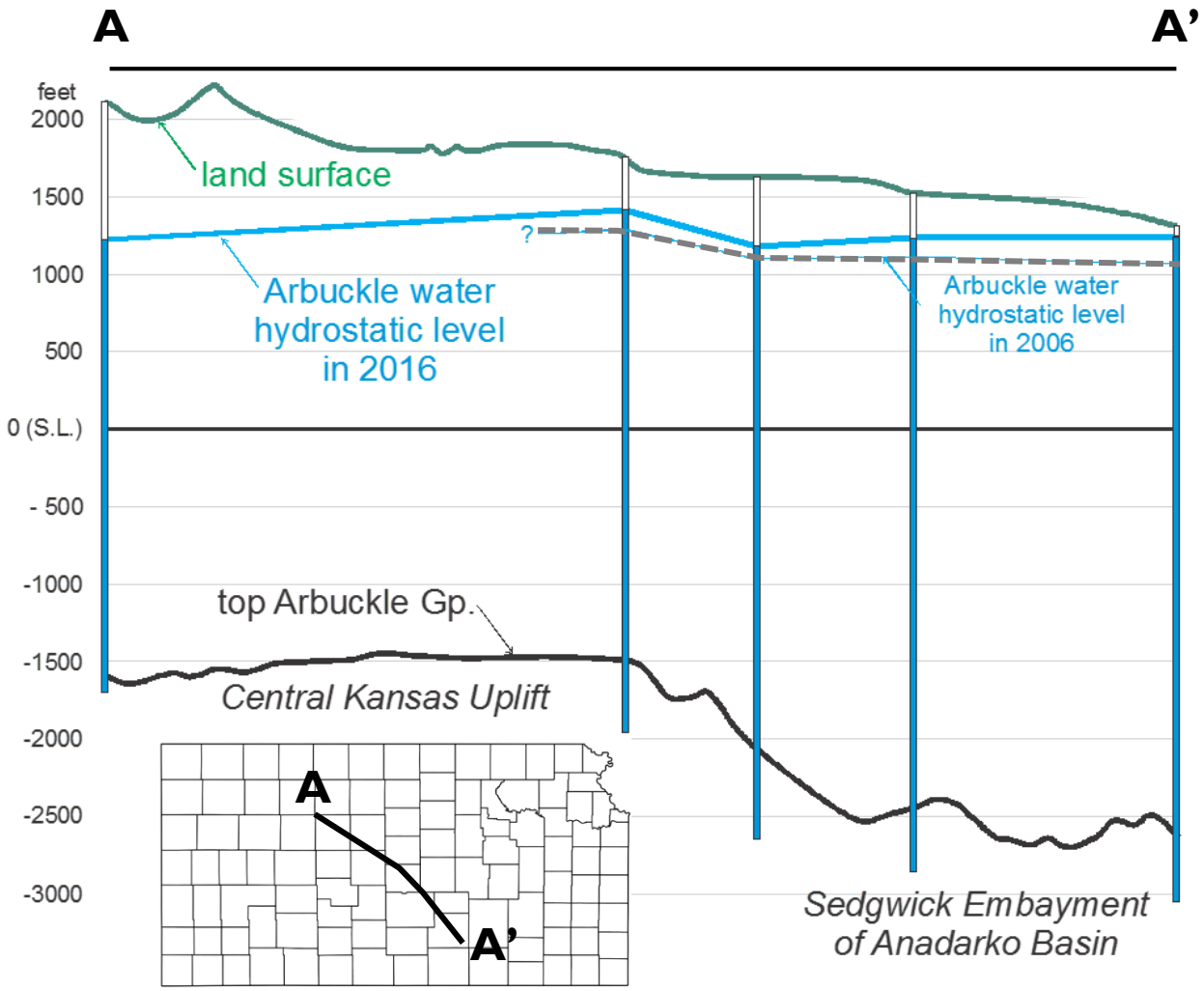
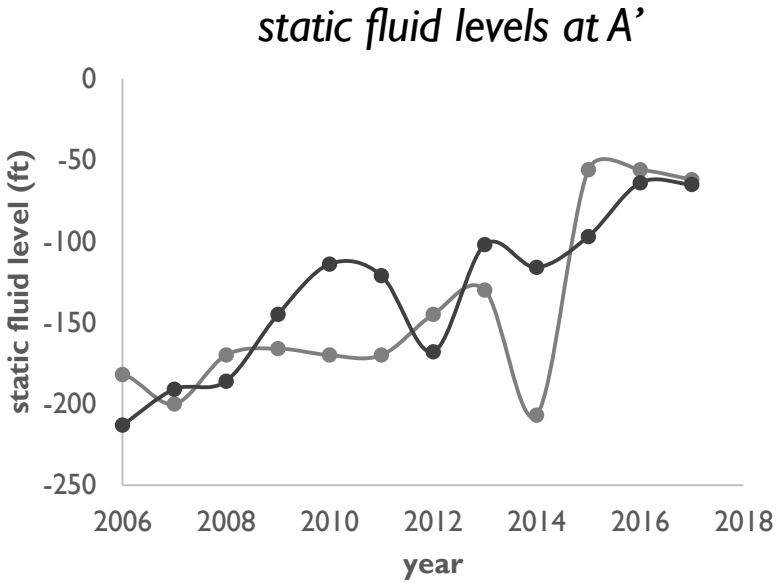
Arbuckle Fluid Levels

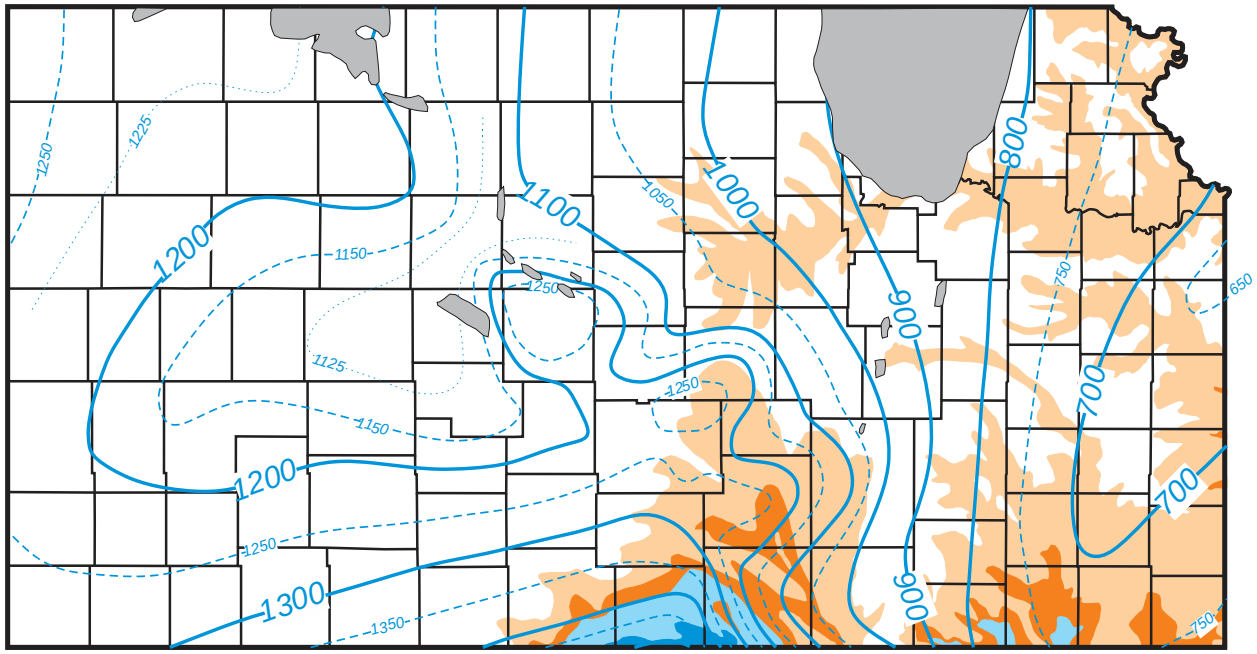




within 50' (<5 years)
lose gravity feed

Arbuckle Fluid Levels

elevation of hydrostatic surface (freshwater)

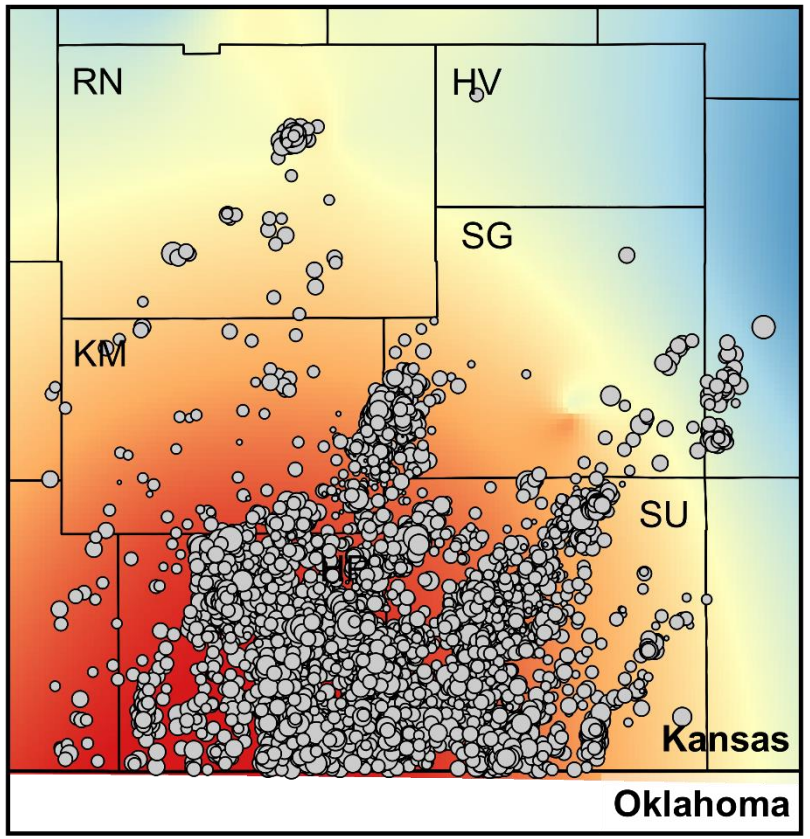


- Dave Newell (KGS)
  - Class I and Class II
  - KS and OK
  - freshwater equivalent
  - insensitive to density
  - regional fluid flow
- Subtract hydrostatic elevation from land surface
- Depth relative to land surface:
  - < 300 ft
  - < 100 ft
  - 0 ft (at surface)
- Cannot injection freshwater under gravity feed alone

Summary

- Increased high-volume SWD
  - regionally elevated pressure
  - migration of seismicity
- Regional pore pressure change
  - farther than previously observed
    - 90 km
    - other studies suggest 20 km limit
    - poroelastic effects
  - value of local monitoring
- Implications
  - triggering threshold
  - rising fluid levels

Arbuckle fluid pressure



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