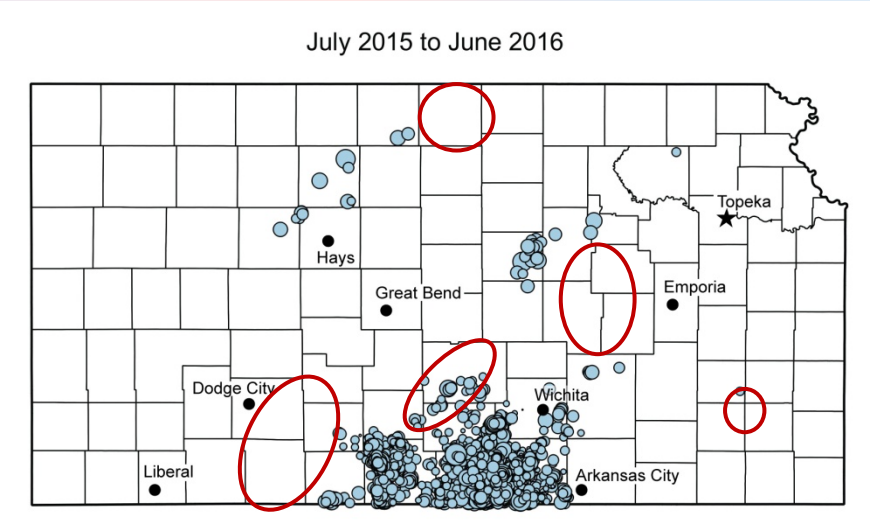
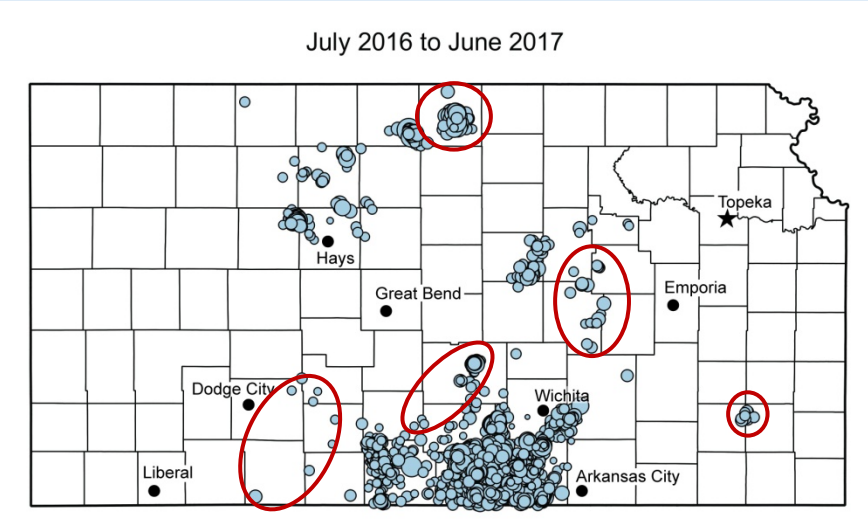
Update on Kansas Seismicity: A Year of Change, What Does it Mean?

A lot more than meets the eye



FY 16

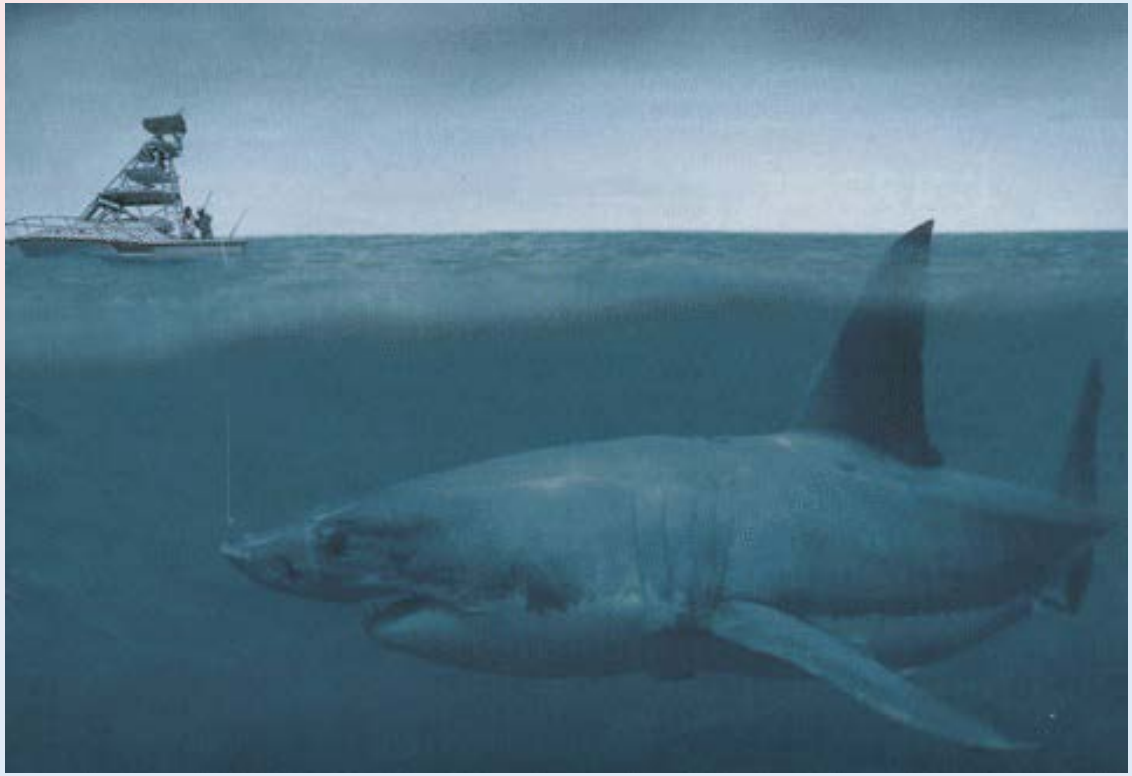


FY 17

Earthquake Studies Contributors at the Kansas Geological Survey:

Rick Miller, Shelby Peterie, Rex Buchanan, Brett Bennett, Julio Gonzales, John Intfen, Joe Anderson, Brett Wedel, Jeremy Scobee

MicroSeismicity:
The Answer Lies Beneath



Limited spatial observations can lead to the wrong answer

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MicroSeismicity:
The Answer Lies Beneath

Insufficient temporal monitoring allows confident misinterpretations

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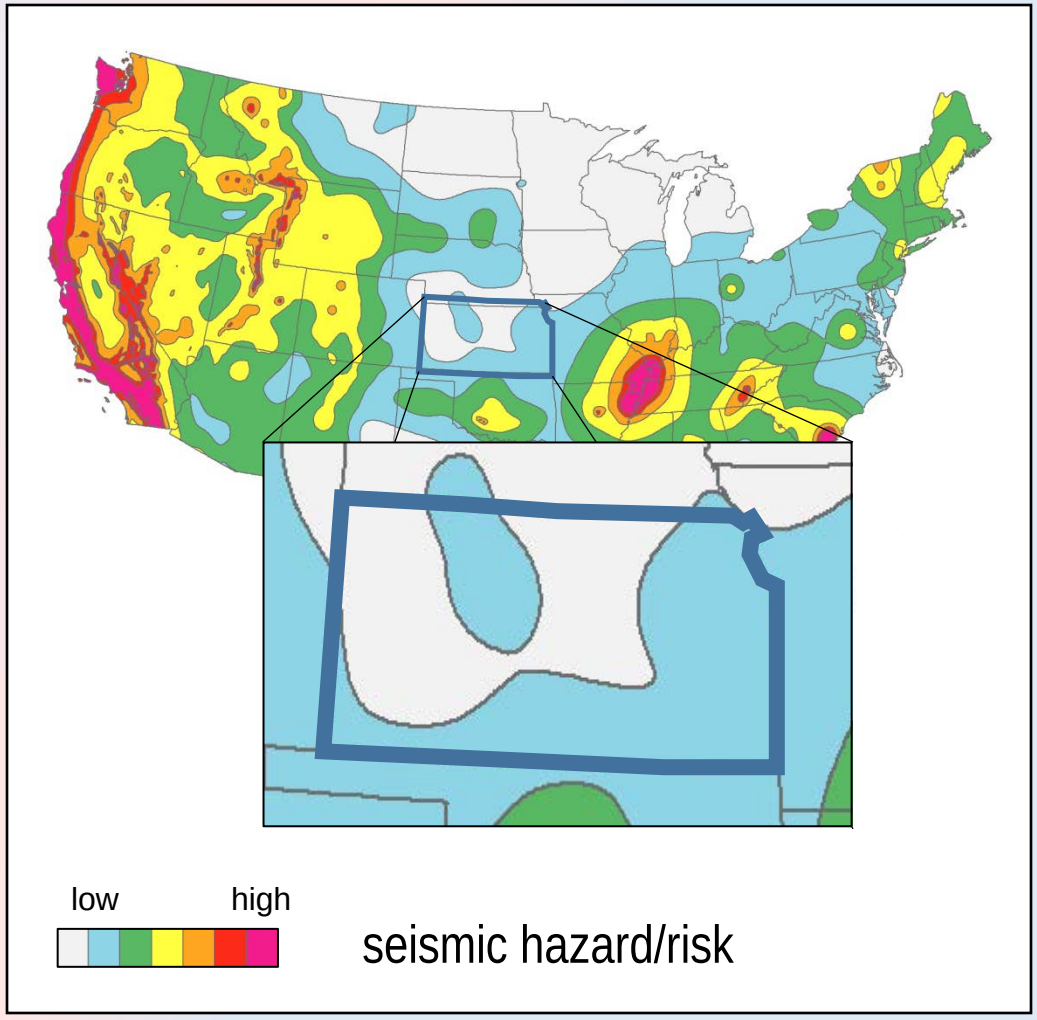
Seismic Risk in Kansas



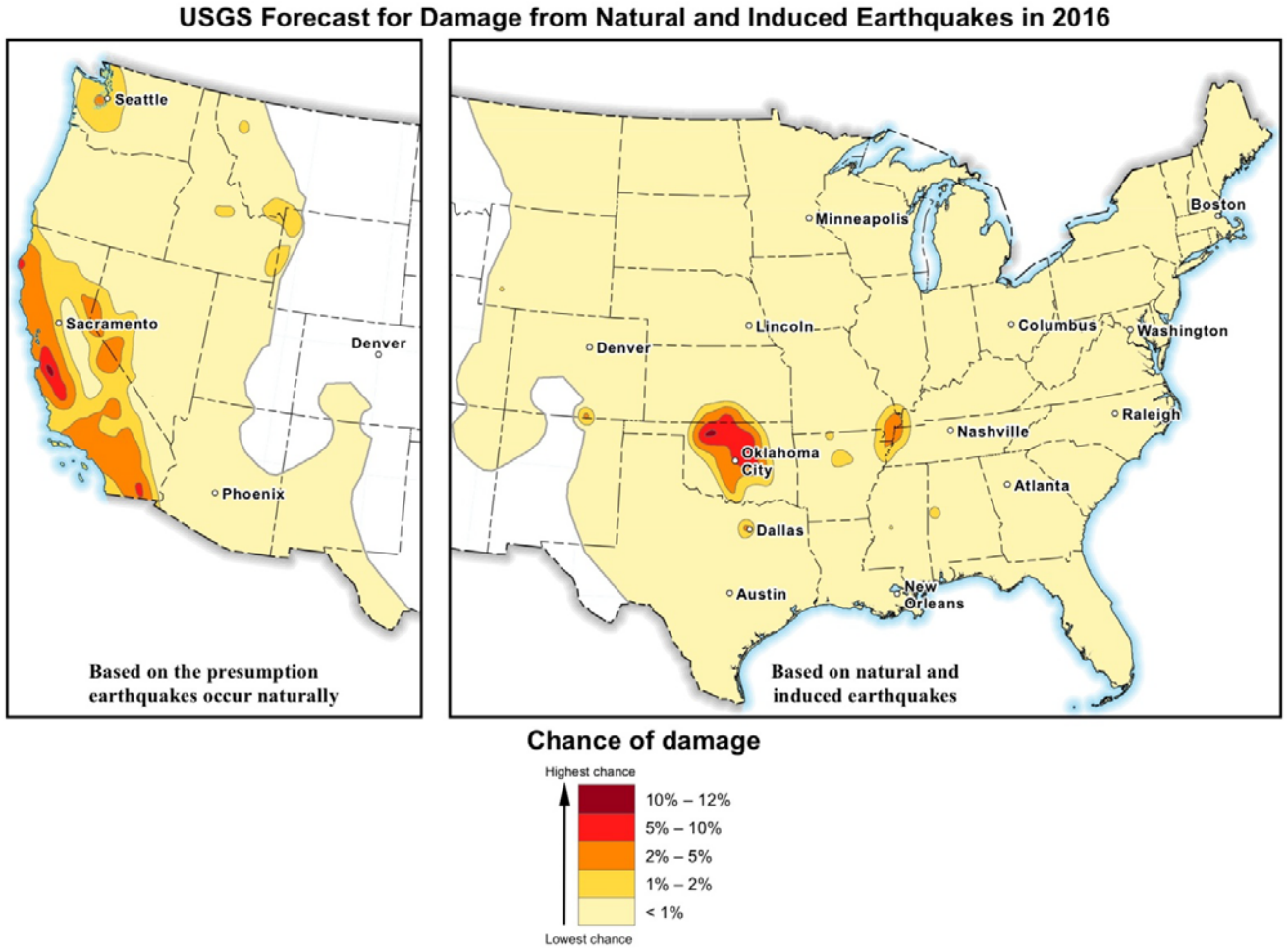
Seismic hazard (USGS 2014)

- natural recursion
- historic regional seismic activity

Kansas is at low risk of a damaging *natural* earthquake

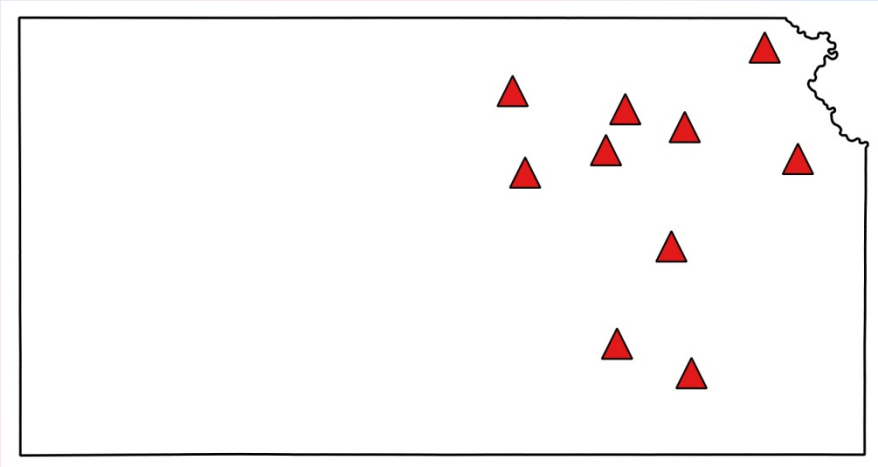
Recent unnatural escalation in seismic activity, based on last 40 years of instrument measurements and several hundred years of felt reporting, leaves little doubt deep fluid injection primary suspect in search for cause.

USGS Earthquake Observations and Forecast



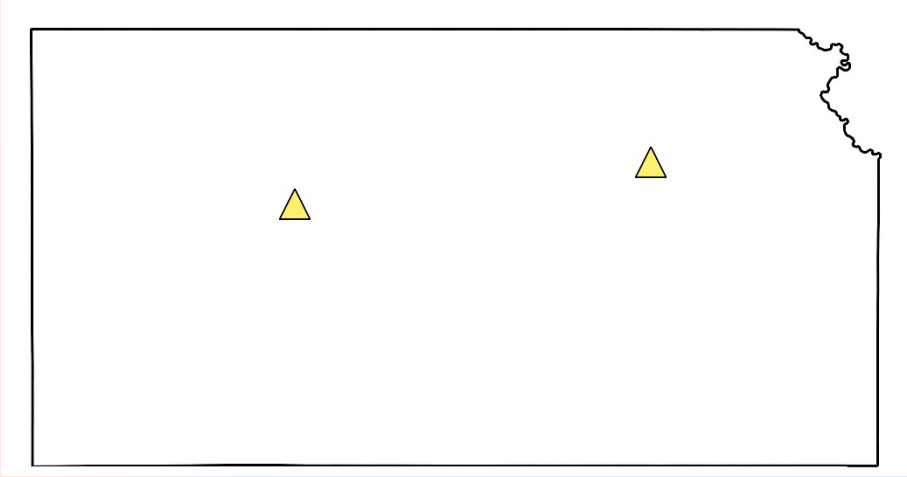
USGS map displaying potential to experience damage from natural or human-induced earthquakes in 2016. Chances range from less than 1 percent to 12 percent.

Regional Networks Prior to 2014



KS: 1977–1989

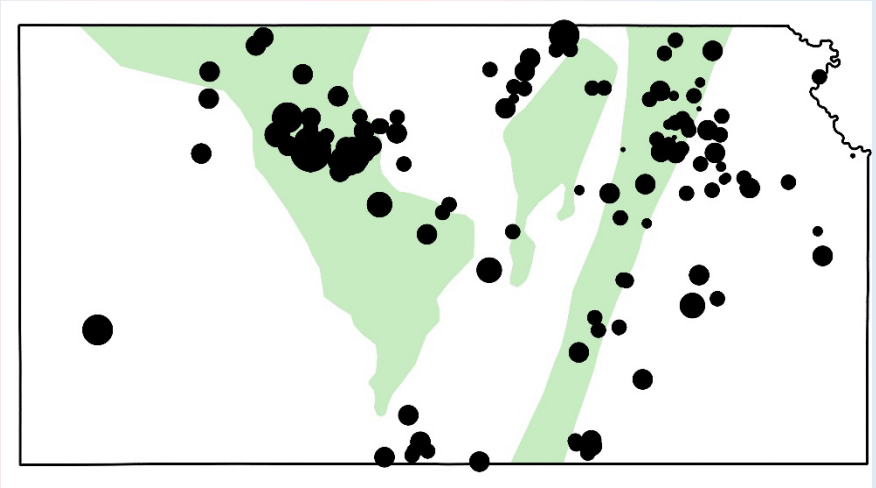
Kansas Regional Network
KGS operated, NRC and USACE funded
Generally sensitive to M 2.0 or > in eastern half & M 2.5 or > across the entire state
Locally sensitive to M <1



NEIC: 1990s–2014

US network
Operated and funded by the USGS
Sparse regional/national network
Generally sensitive to M 3.0 or larger

Earthquakes Recorded by Regional Networks

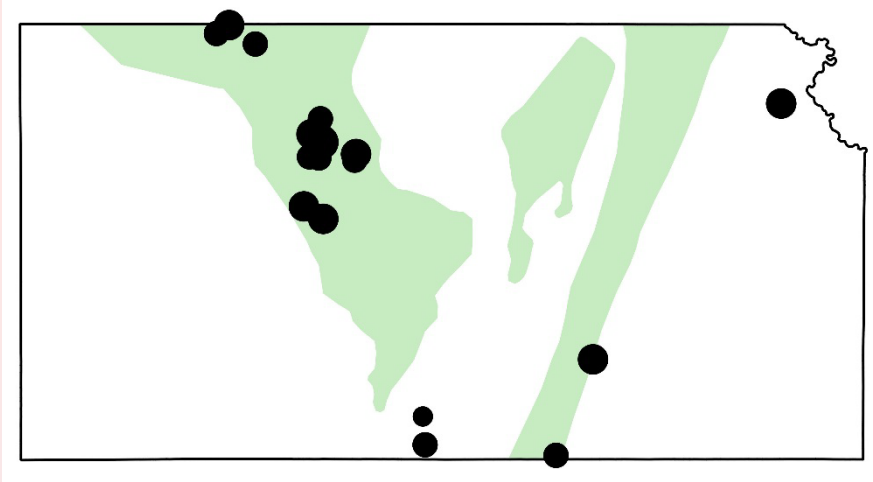


KSNE: 1977–1989 (13 years)

Value of dense network w/ regional focus

Trends in seismicity generally related to known structure

171 earthquakes from M0.5 - M4.0



NEIC: 1990s–2014 (15 years)

Sparse network—location uncertainty

Course sampling of seismicity—felt events

Generally correlates w/ trends of major structures

18 earthquakes from M2.2 - M3.5

Seismicity

Seismicity Rules of Thumb:

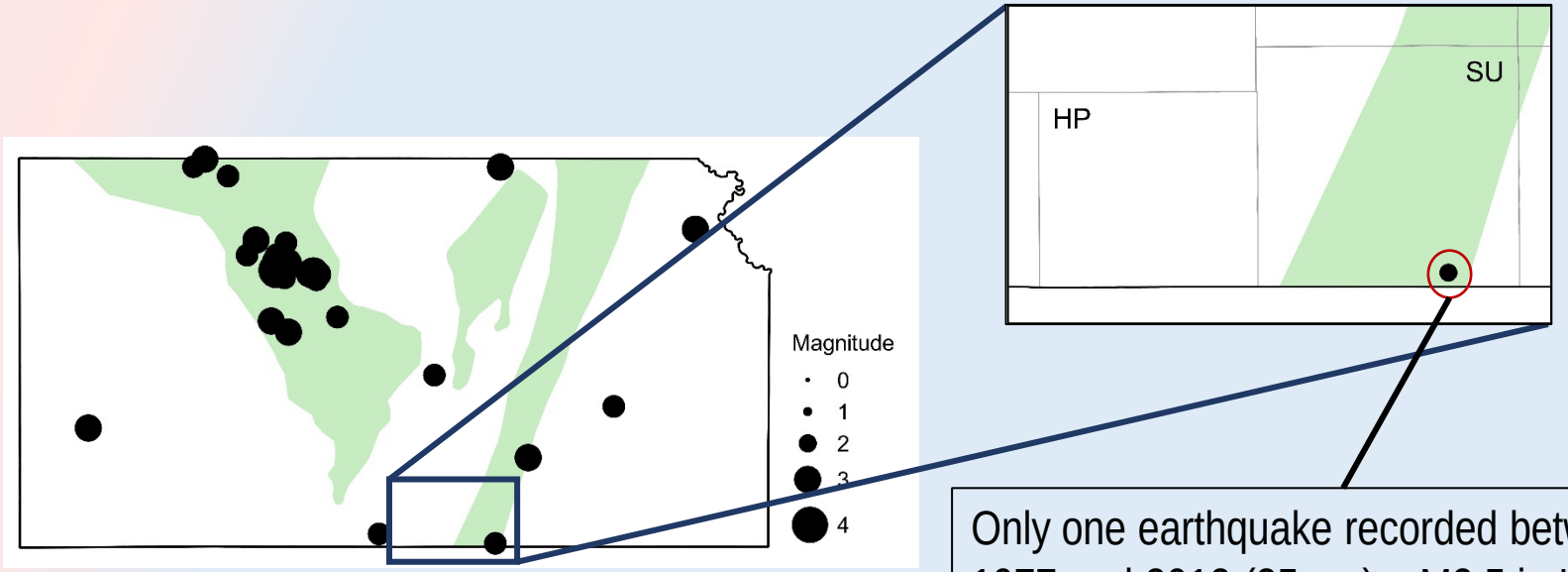
Gutenberg-Richter recursion relationship—10 to 1

Earthquakes can only occur along critically stressed faults

Total energy of earthquake related to length of fault ruptured (maximum earthquake)

Historical, regional seismicity may not be good temporal indicator for induced seismicity

- 1977-2012 earthquake > felt level (M 2.5)



Only one earthquake recorded between 1977 and 2012 (35 yrs), >M2.5 in HP/SU

Seismicity

Seismicity Rules of Thumb:

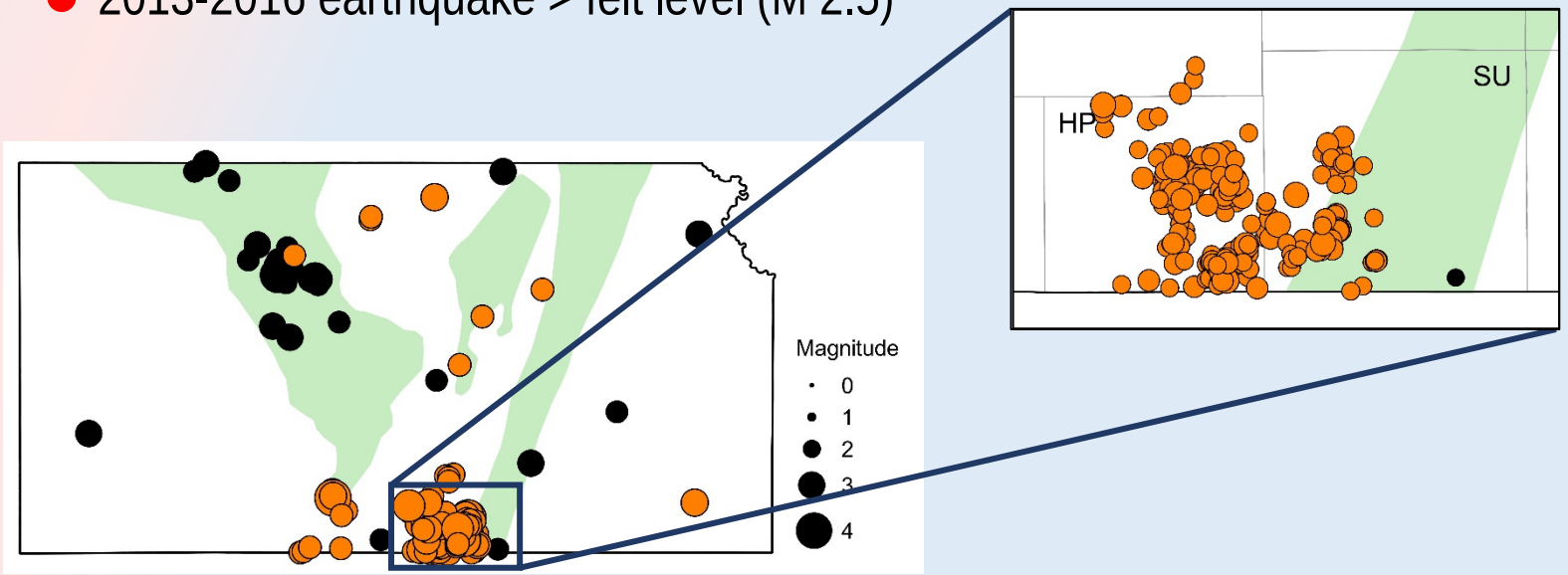
Gutenberg-Richter recursion relationship—10 to 1

Earthquakes can only occur along critically stressed faults

Total energy of earthquake related to length of fault ruptured (maximum earthquake)

Historical, regional seismicity may not be good indicator of potential for induced seismicity

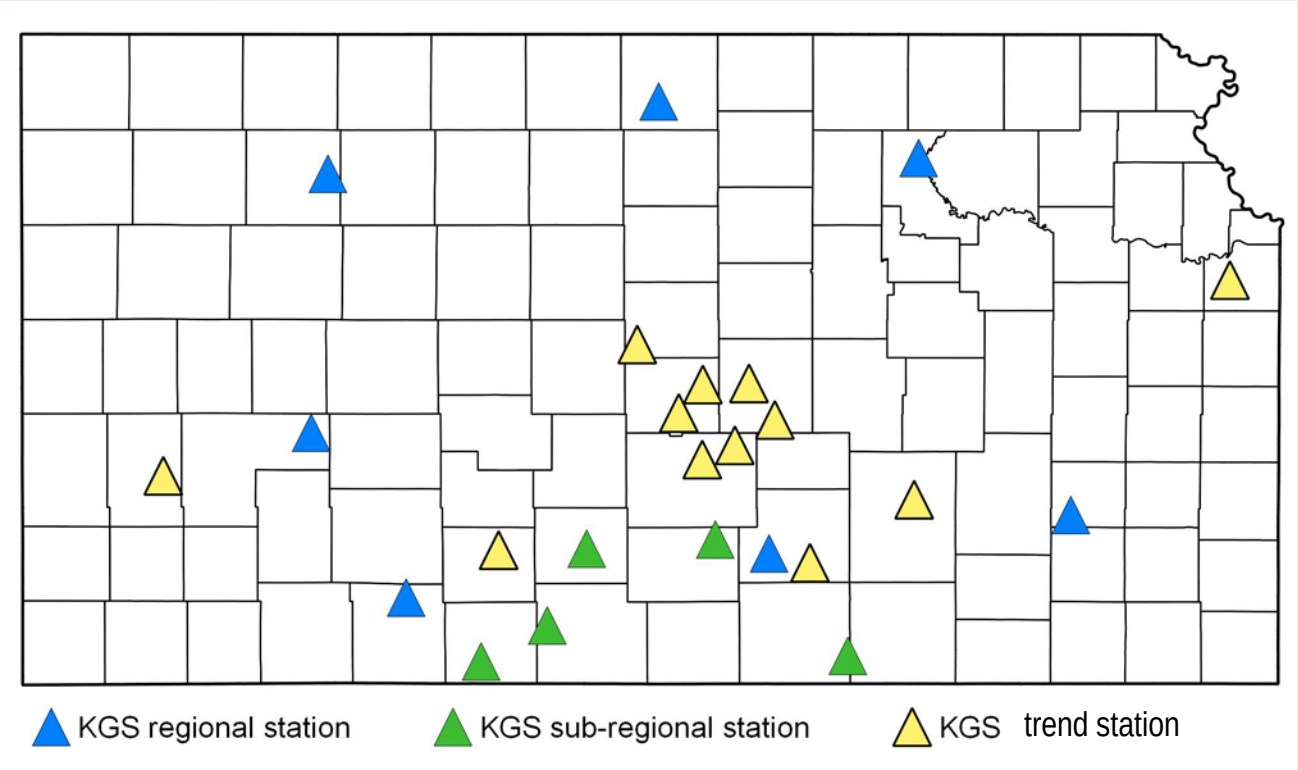
- 1977-2012 earthquake > felt level (M 2.5)
- 2013-2016 earthquake > felt level (M 2.5)



Current Earthquake Networks in Kansas

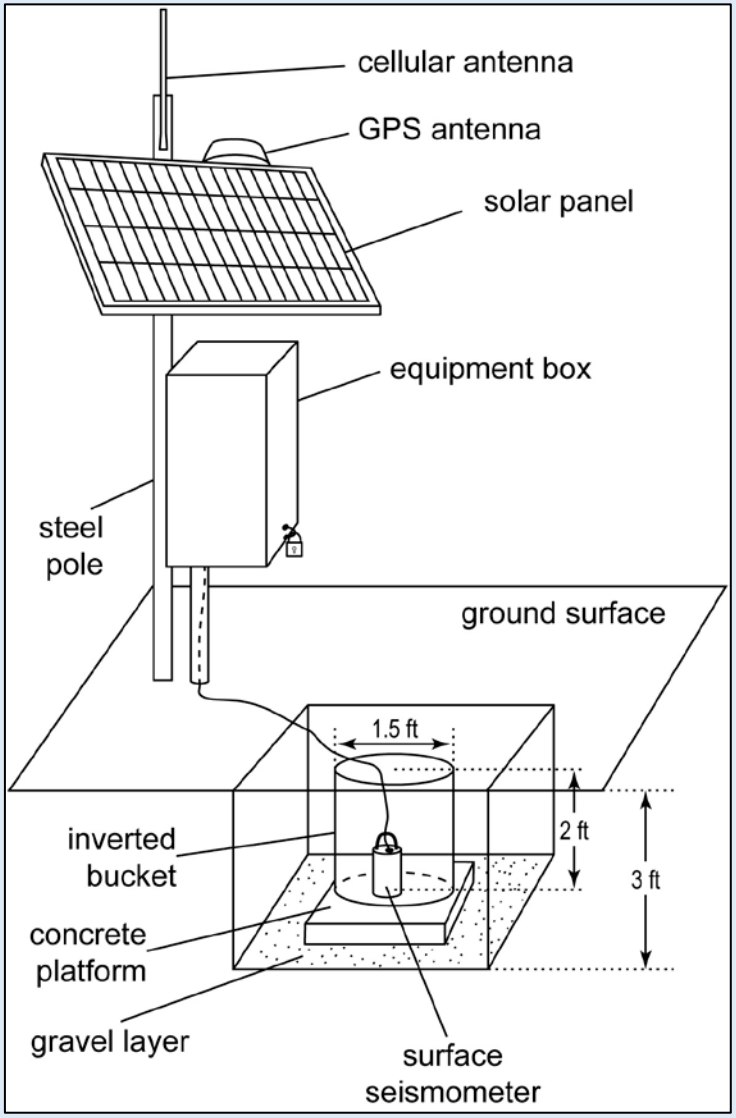
24 stations

- Sub regional—3C surface shallow buried tub enclosure
  - Focused and greatest accuracy and local area sensitivity
- Regional—3C surface and 1C borehole, vault
  - Greatest S/N with borehole for greater reach
- Trend—3C surface, shallow burial w/tub enclosure
  - Focused local ultra sensitivity sub M0.0 within 20 km



Seismic Station Installation

- Seismic sensor
  - Seismometer
  - Digitizer
- Real-time communications
  - cellular modem
  - cellular antenna
  - RTP server
- Power
  - 120 watt 12 V solar panel
  - charge controller
  - two deep-cycle marine batteries



Seismic Station Installation

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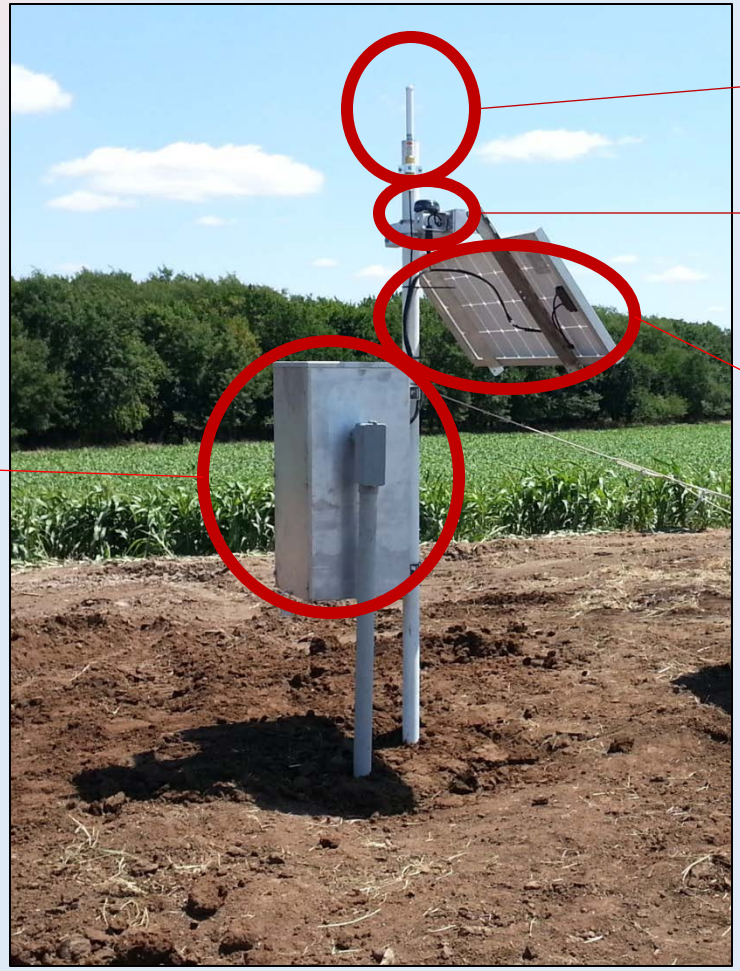
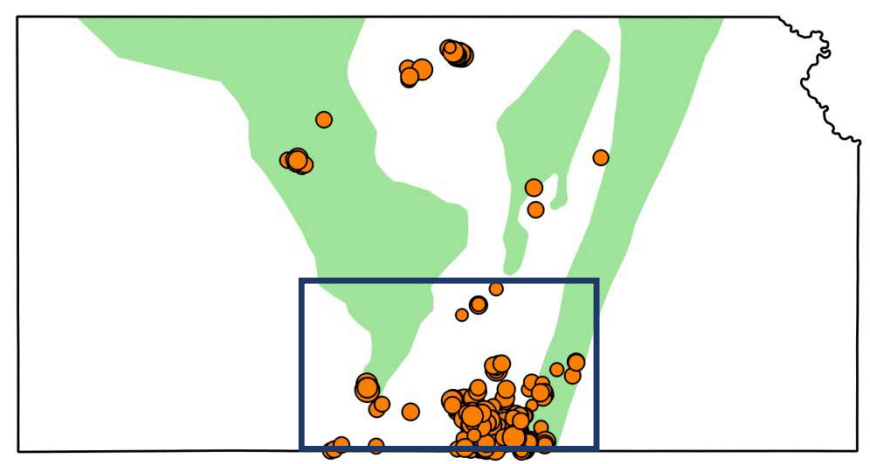
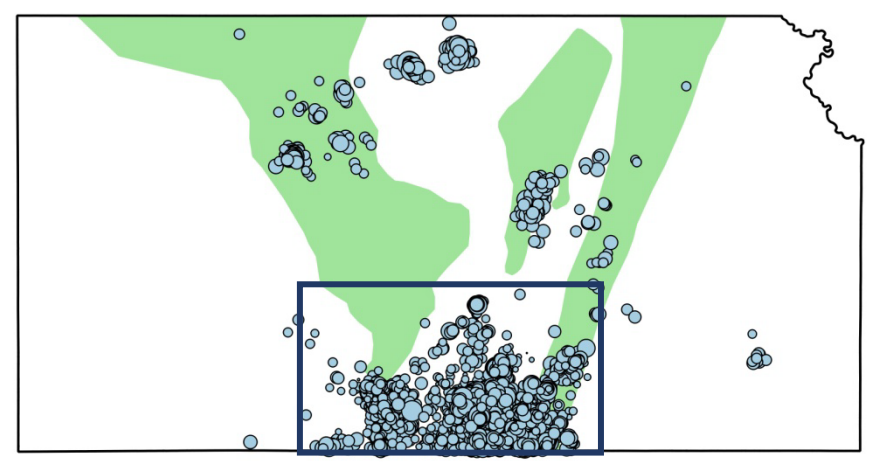


Seismic Station Installation

Network Comparison 1/1/2015-7/1/2017





reported by NEIC

reported by KGS

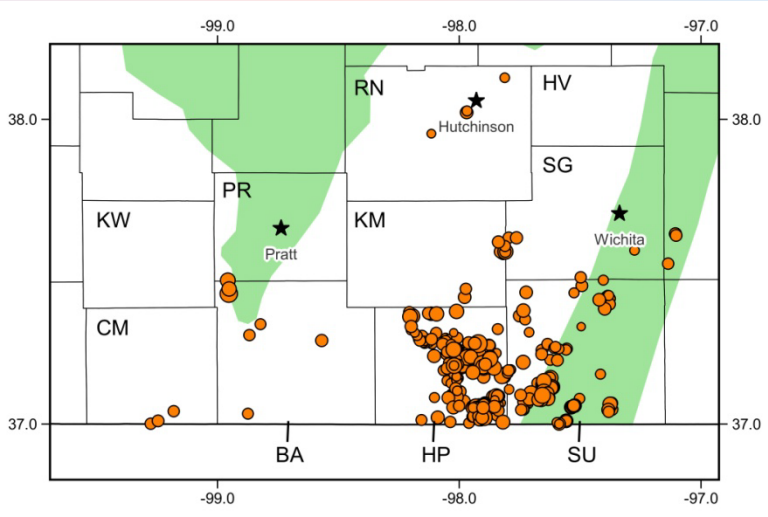
NEIC (regional)

404 earthquakes statewide PDE
M 1.6 to M4.1
Currently 19 stations in KS
2613 special projects catalog (SPC)
M1.5 to M3.5

KGS (Regional & Sub regional)

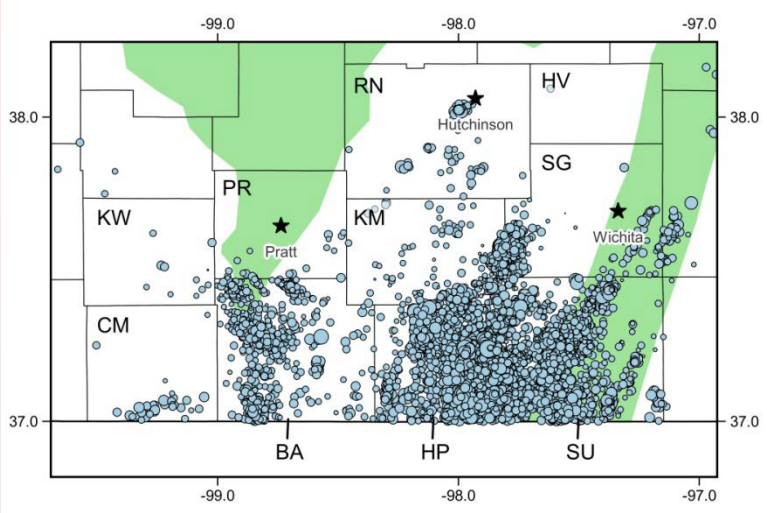
9275 earthquakes statewide
M 0.0 to M4.4
Currently 24 stations in KS

Network Comparison 2015-2017



NEIC (regional)

359 earthquakes in sub region
M 1.6 to M4.1
2613 SPC inside sub region*
M1.5 to M3.5
404 earthquakes statewide
45 events outside sub region



KGS (Regional & Sub regional)

8648 earthquakes in sub region
M 0.0 to M4.4
9275 earthquakes statewide
627 events outside sub region

reported by NEIC

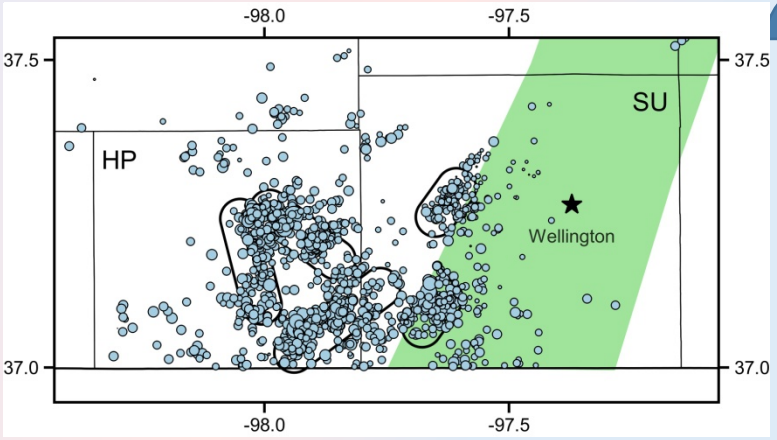
reported by KGS

* Not plotted

Ordered Reduction in Fluid Injection

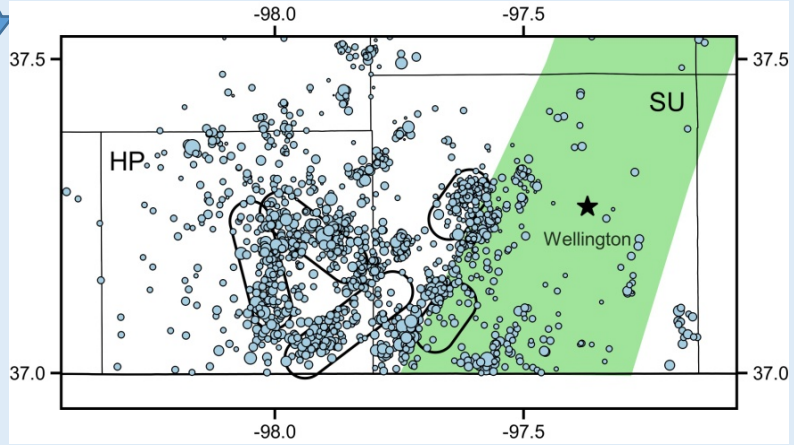
In 2015, the KCC ordered phased reduction in Arbuckle injection within 5 high seismicity zones

Vast potential of microseismic activity to understand and delineate sensitive structures



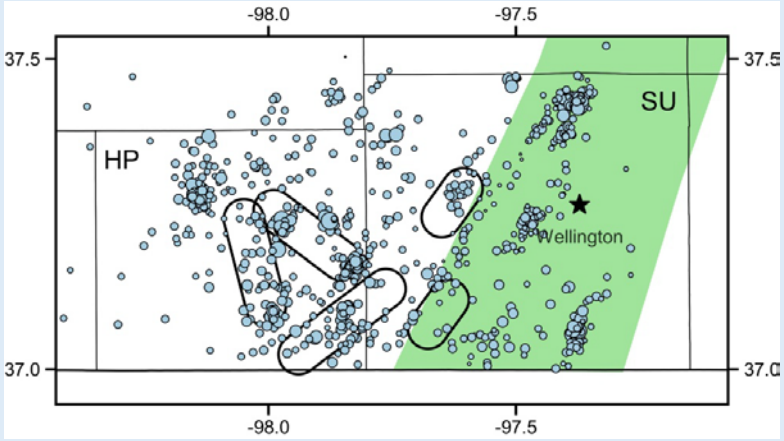
January–June 2015

Order fully in place



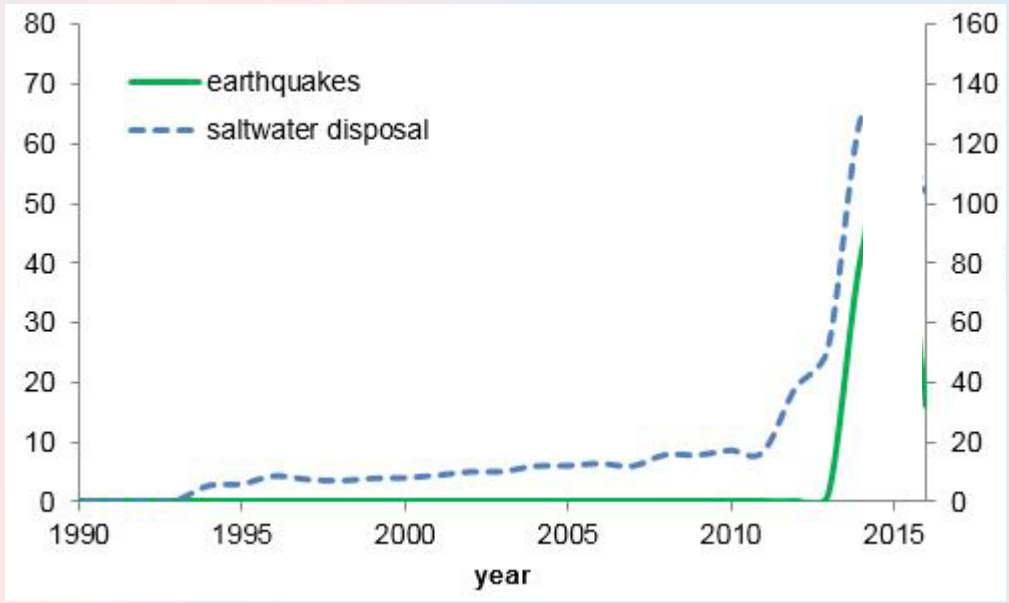
January–June 2016

January–June 2017



- reported by NEIC
- reported by KGS

Harper and Sumner Counties

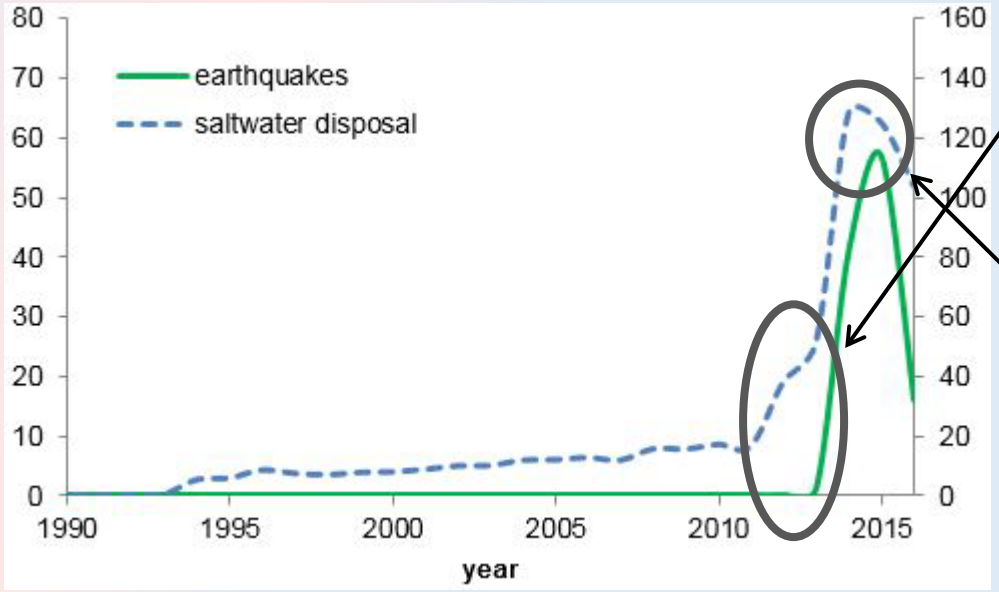


1993-2016

50% reduction in M3 and > earthquakes after EO 2013 and 2014 was issued

Order of magnitude increase in deposed volumes 2011-2014 into Arbuckle

Harper and Sumner Counties



~2 year lag between increased SWD in Arbuckle and increase in felt earthquakes

~1 year lag between decreased SWD in Arbuckle and decrease in felt earthquakes

1993-2016

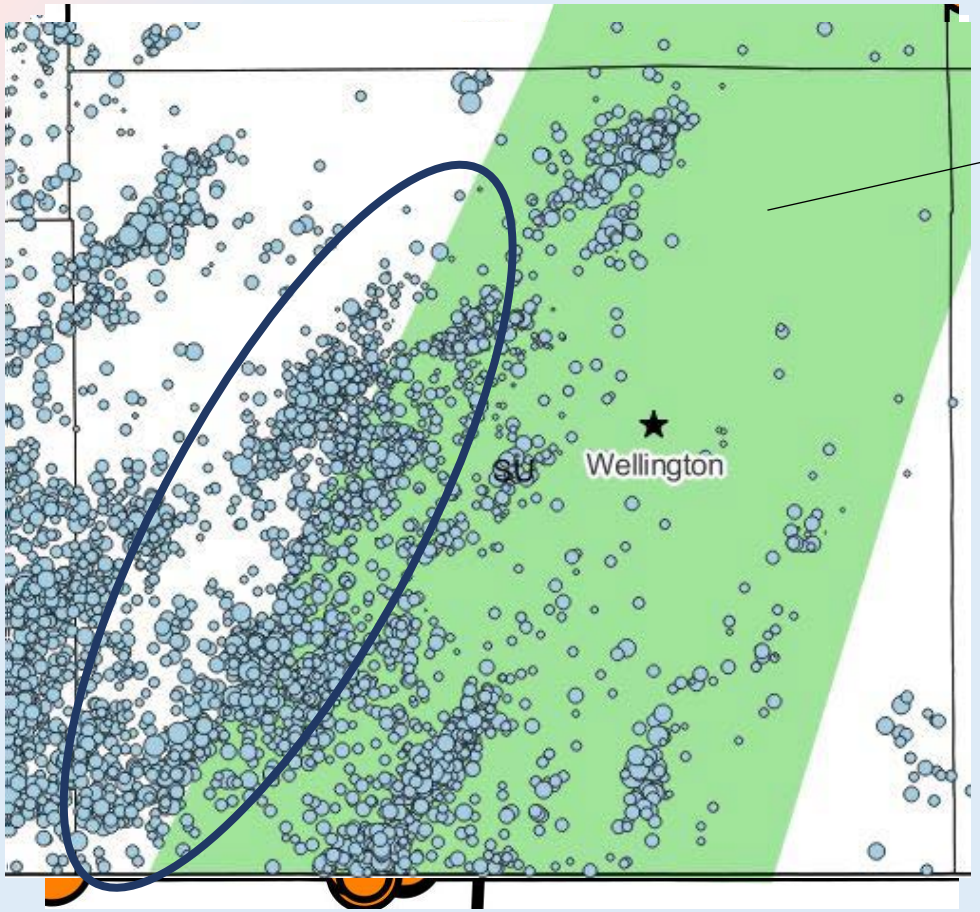
Trends in Seismicity

Looks reasonable—

- Rate of felt earthquakes increased consistent with dramatic increased rate of injection. **two year lag**
- Rate of felt earthquakes dropped with reduction in injection volume in seismically sensitive areas. **about one year lag, area wide in part due to production drops**
- Rate of felt earthquakes constant in spite of dramatic increase in rate of injection in North Dakota in Bakken Trend—this is a clue.
- Areas with increased potential for felt earthquake
  - any microearthquake can be precursor to felt earthquakes
  - clustering of microearthquakes both temporally and spatially
  - earthquakes trends can take centuries to develop and can be dormant for centuries

Trends Along Known Structures

2016 - 2017

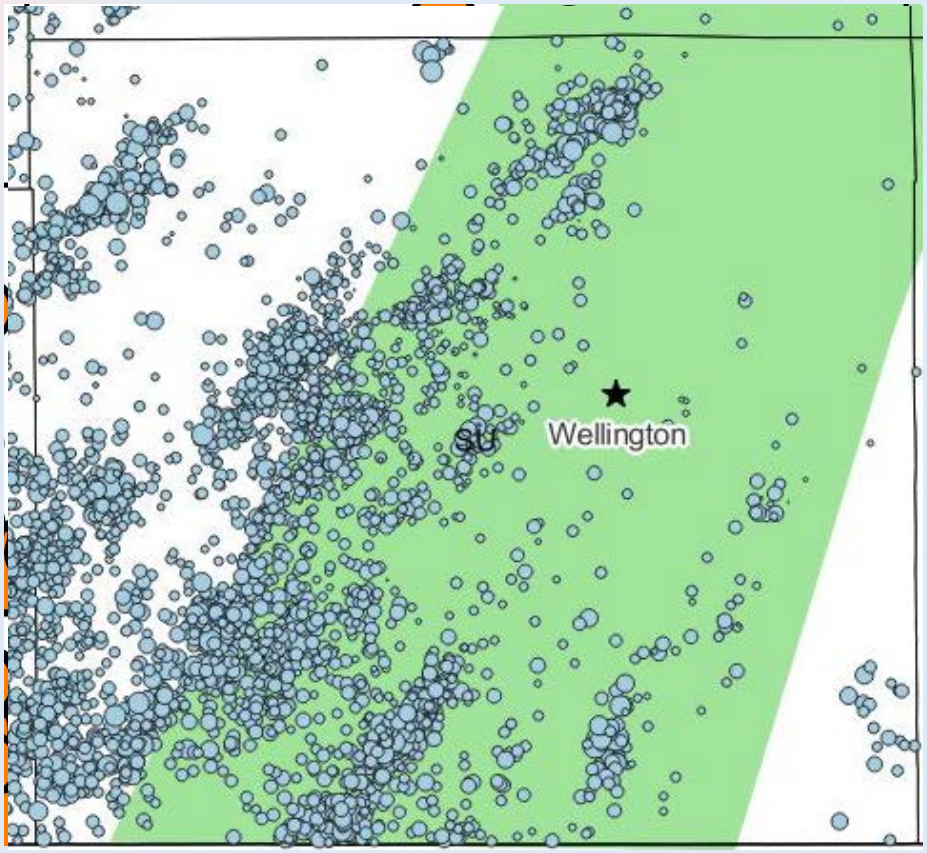


Nemaha Ridge

Microseismic Trends Along Known Structures

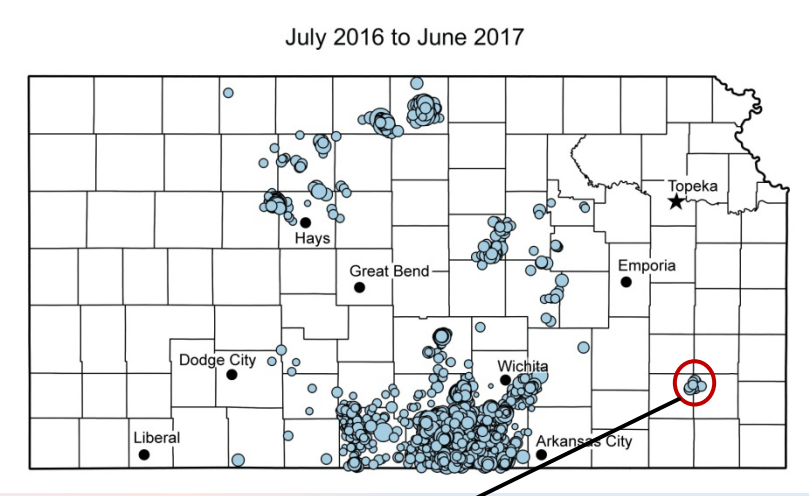
Advantages of a dense network and sub-felt focus

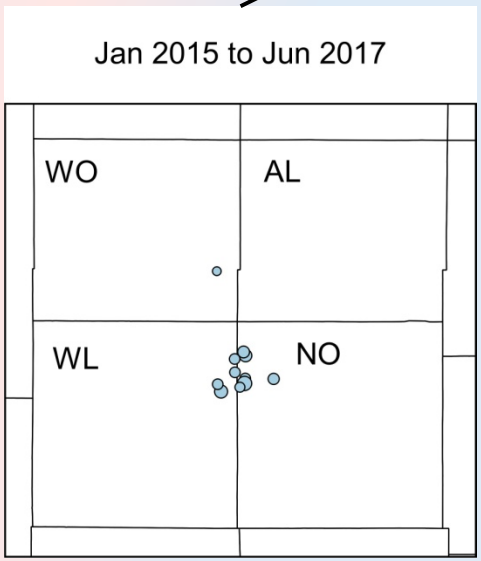
2016 - 2017



Trends Along Structures: Some Known, Some Not

Earthquakes can only occur on faults w/displacement and aligned w/regional stress field





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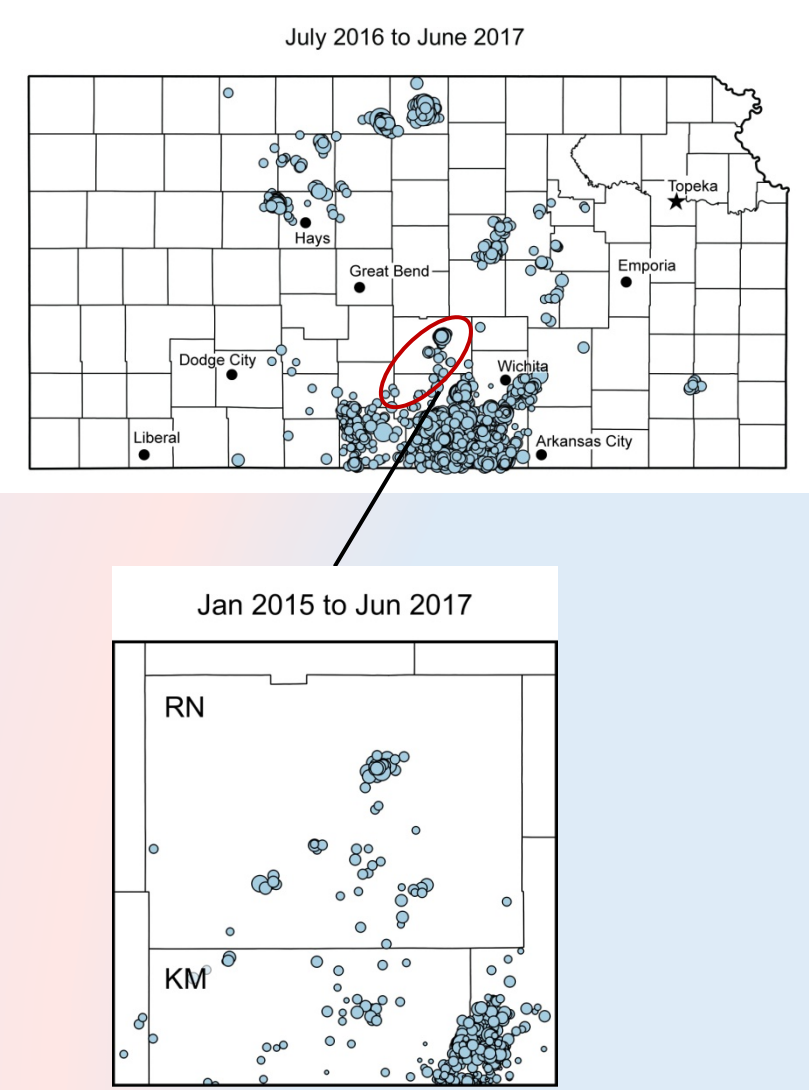

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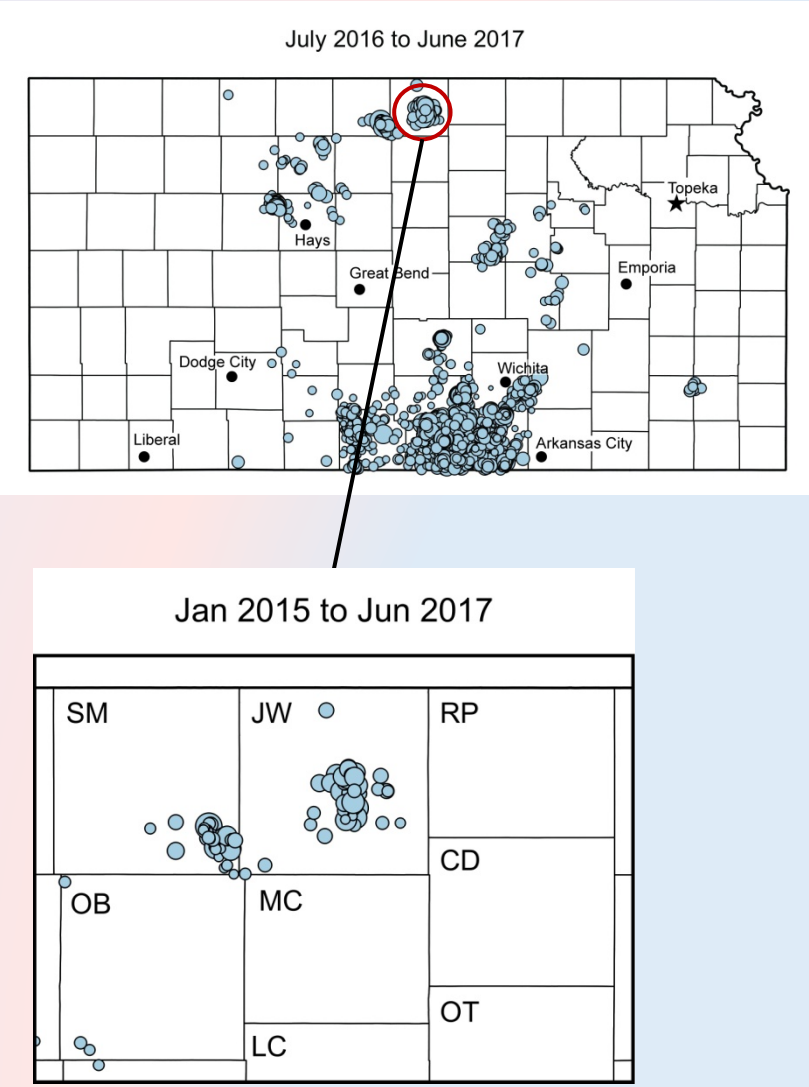

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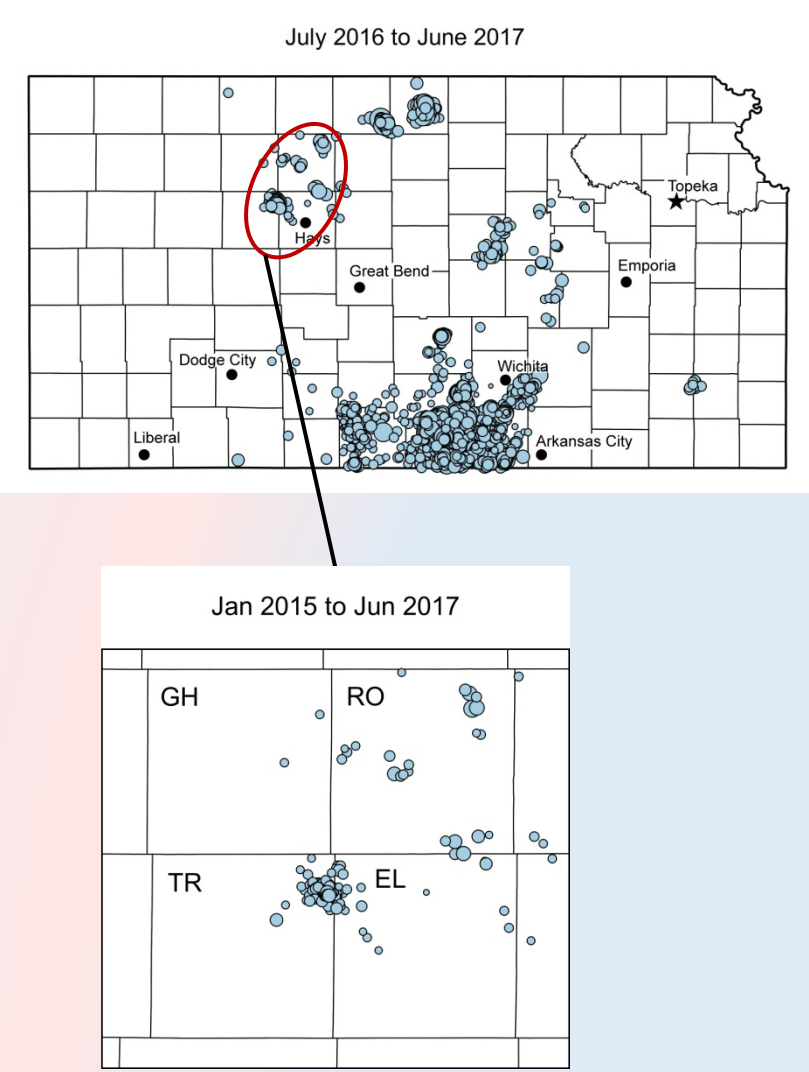

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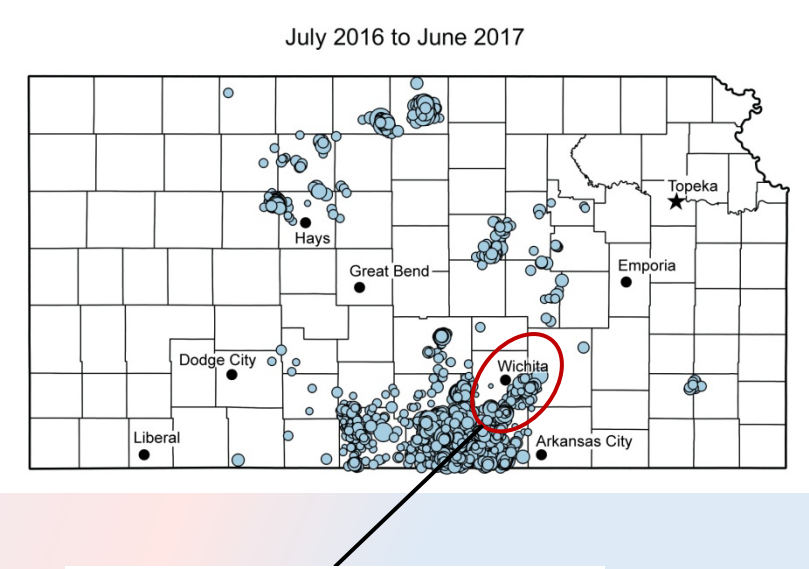
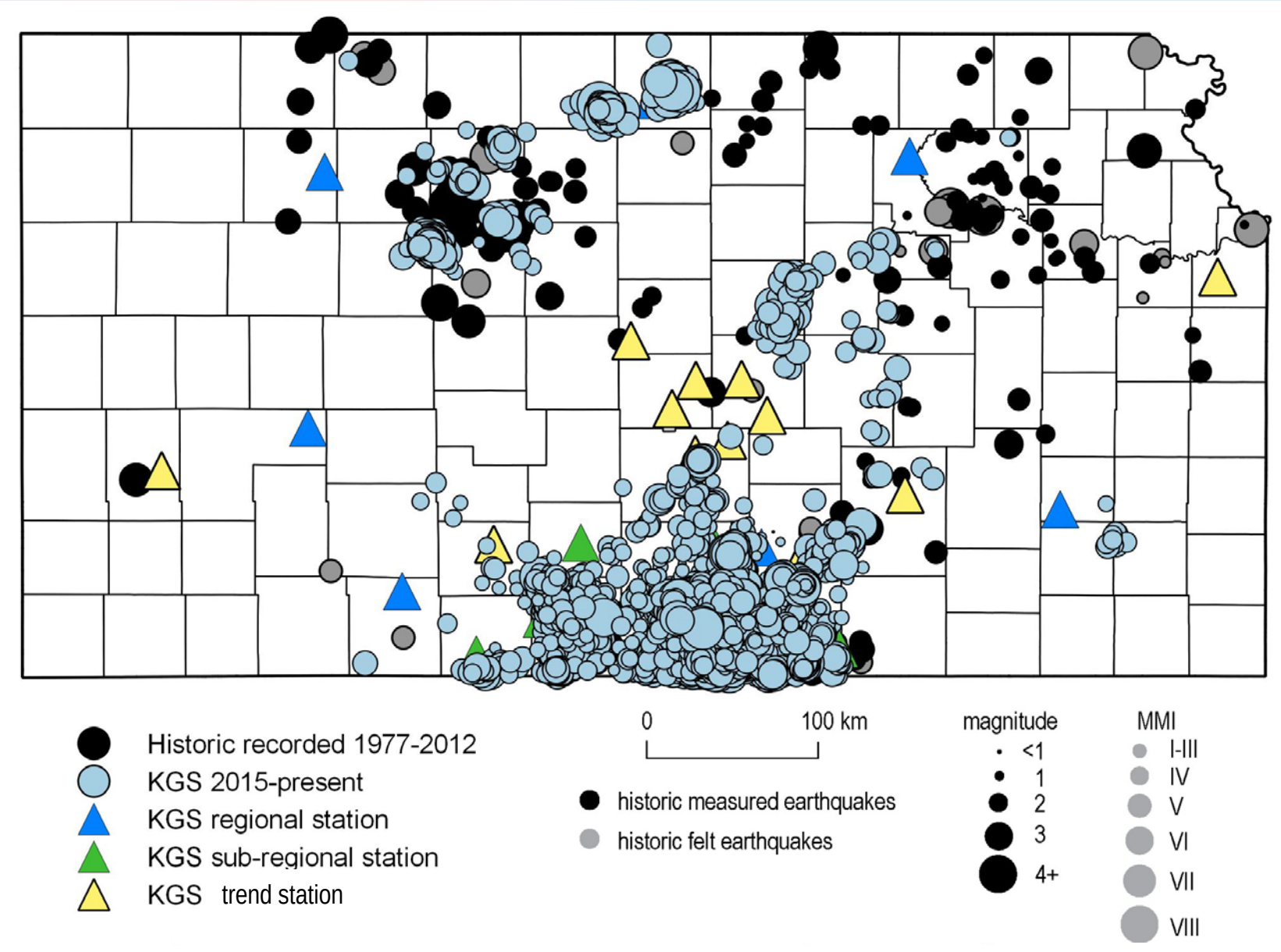


Understanding Seismicity at Local & Regional Scales

- Earthquake prone fault structures in Kansas are present around the state.
- Historical and current earthquake patterns (temporal and spatial) allow:
  - postulate earthquake trigger (induced or natural), rarely is 100% confident
  - identify changes in seismcity,
  - correlate anthropogenic influences to seismicity trends
  - identify seismically sensitive zones
  - recurrence relationship (earthquake magnitude and rate)
- Sensitivity changes related to fluid injection practices
  - avoid, critically-stressed basement
  - note correlations in changes in seismicity with changes in fluid injection
  - microseismic events are excellent indicators of potential for felt earthquakes
- Monitoring options (KGS is utilizing)
  - local networks interfaced to regional network
  - stations close to injectors targeting sub M 0.5 on active faults

Monitoring to Understand Trends & Triggers



Monitoring Challenges

Earthquakes are not a source of revenue or proprietary resource—no money in it
Optimization w/o duplication: State wide network, subnets, trend nets, and local expertise
Insure transparent, science-driven advances to understand seismicity and its catalysts
Quantify and evaluate microseismic events and potential relationship to local influences
Focus on trends and develop predictive models
Open communication with industry/community about advantages beyond revenue stream,
use data to establish “reasonable oversight”

Knowledge is Power,
Understanding Surroundings,
Allows Linking Cause and Effect