MEWBOURNE COLLEGE OF EARTH AND ENERGY
SCHOOL OF GEOSCIENCES
The UNIVERSITY of OKLAHOMA

Induced seismicity in the mid-continent of the United States

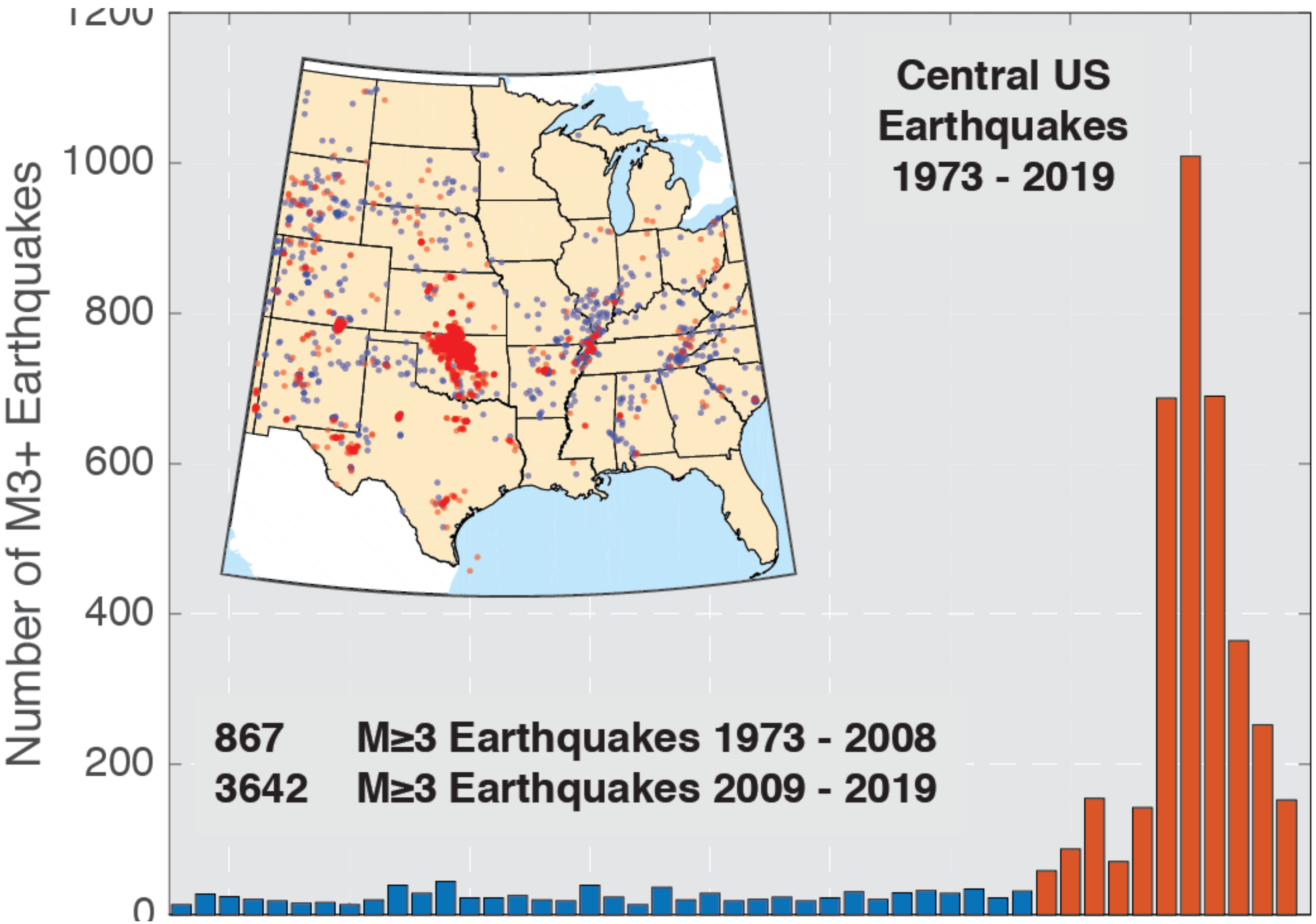
- with a focus on Oklahoma

Xiaowei Chen

Outline

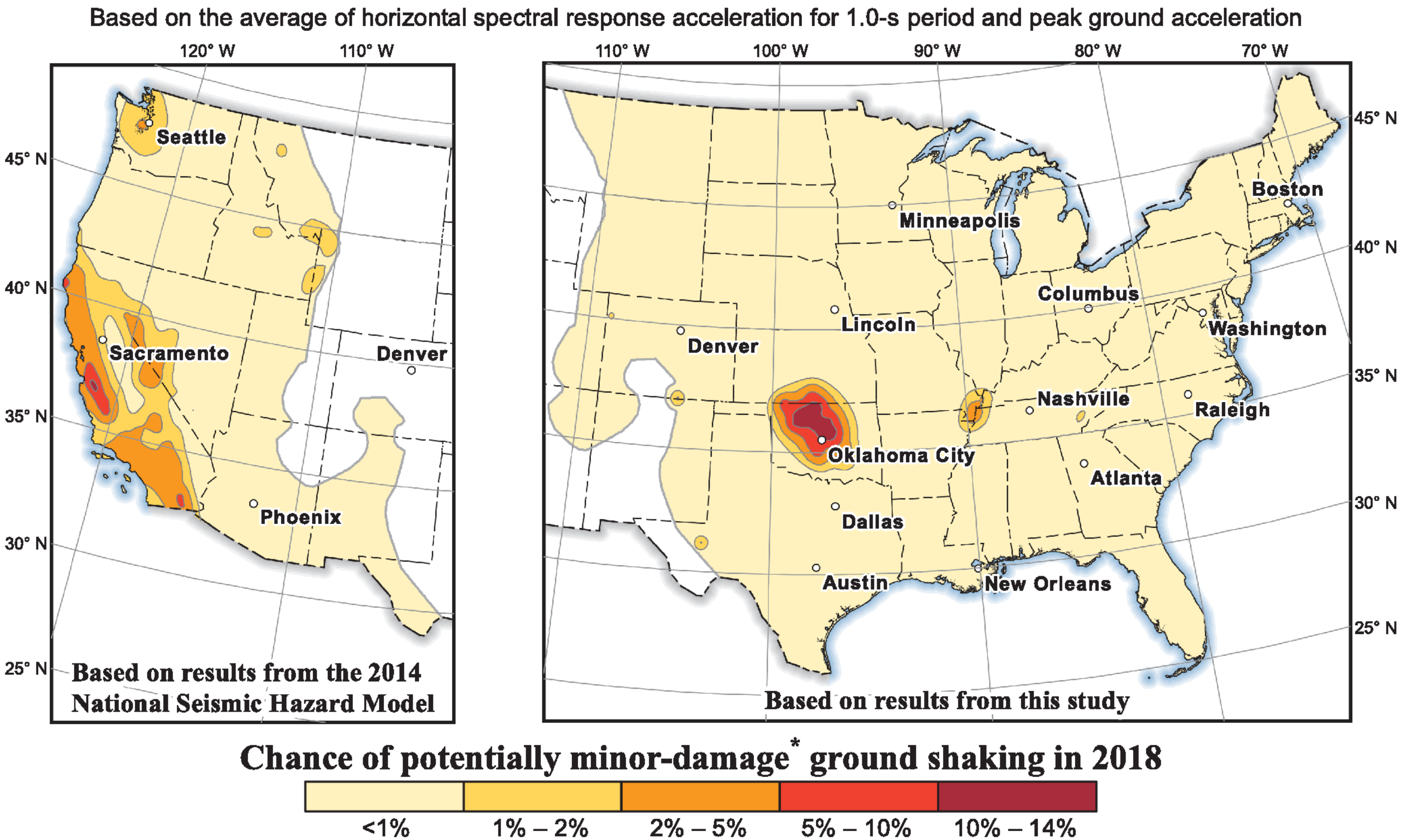
- Overview of induced seismicity in the mid-continent in the US
- Oklahoma earthquakes and tectonics/geology.
- Oklahoma faults and stress field.
- Wastewater injection, fault activations, earthquake source process.
    - Case study from Oklahoma
- Hydraulic fracturing induced earthquakes in Oklahoma.

Induced earthquakes in Central & Eastern US started to increase around 2009, peaked in 2014 & 2015, gradually decline after 2016, but still above background seismicity level



USGS, 2019

Oklahoma projected 2018 ground motion hazard is high compared to the rest of central US when incorporating induced seismicity

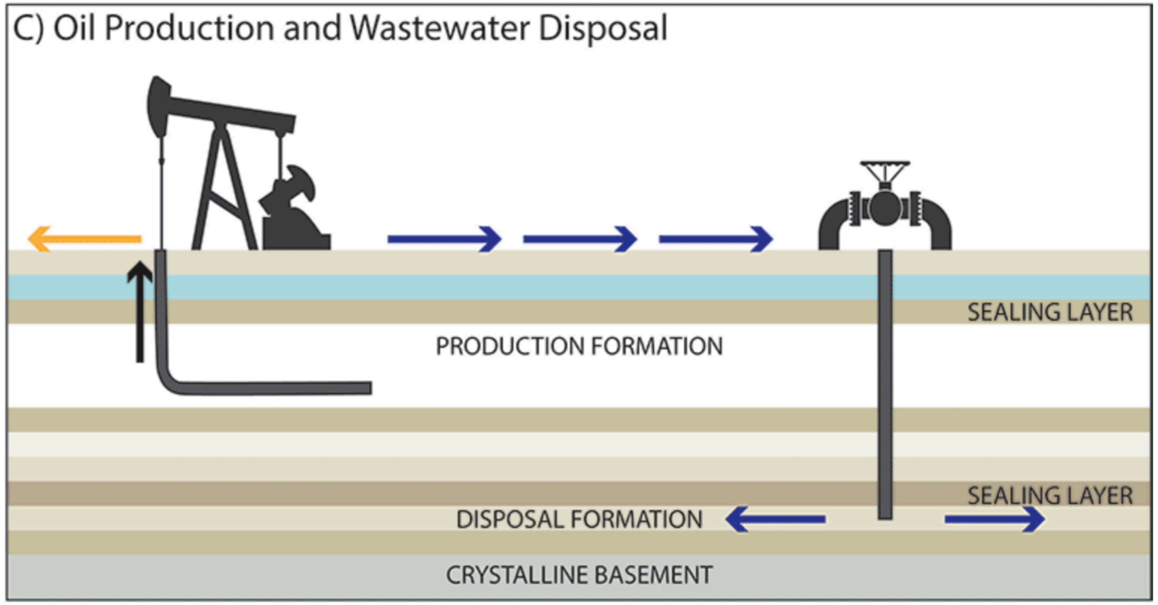


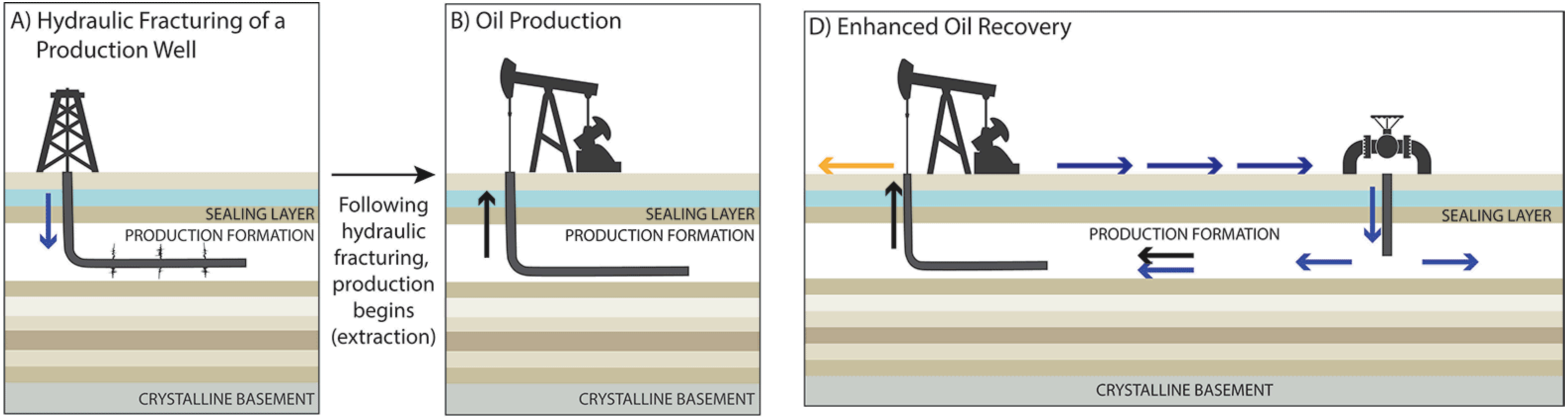
* equivalent to modified Mercalli intensity VI, which is defined as: "Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight."

Peterson et al., 2018

Common procedures lead to induced seismicity.
In mid-continent of US:

(1) Small percentage from hydraulic fracturing;
(2) Small percentage from enhanced oil recovery (sometimes referred to as water flooding;
(3) Large percentage (dominantly) from wastewater disposal.



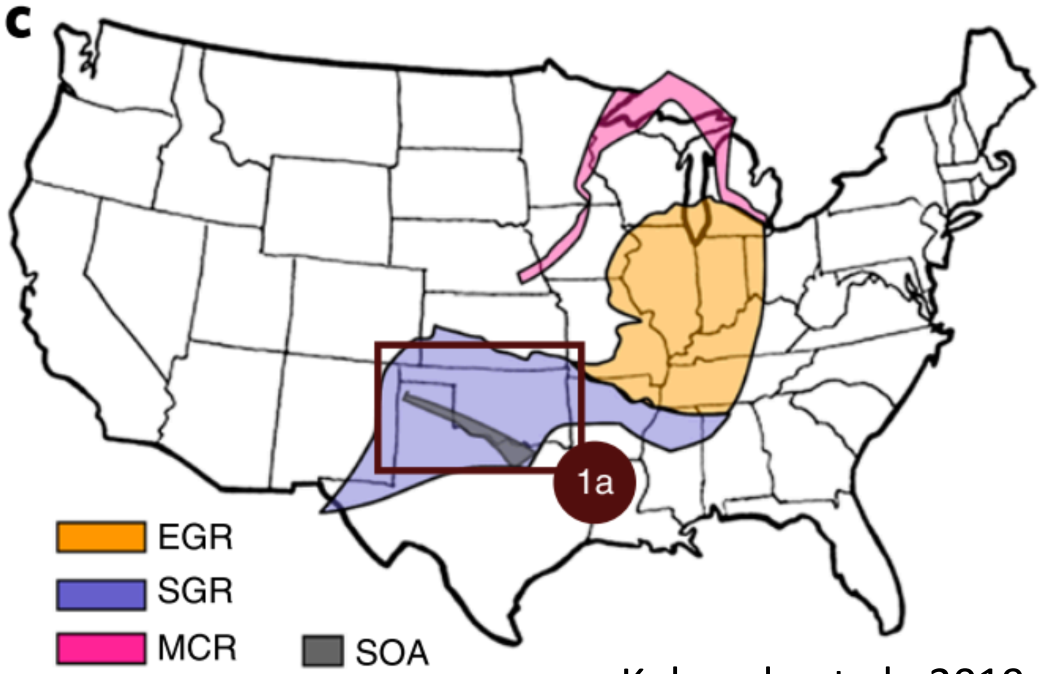


Rubinstein and Mahani, 2015

Oklahoma Induced Earthquakes

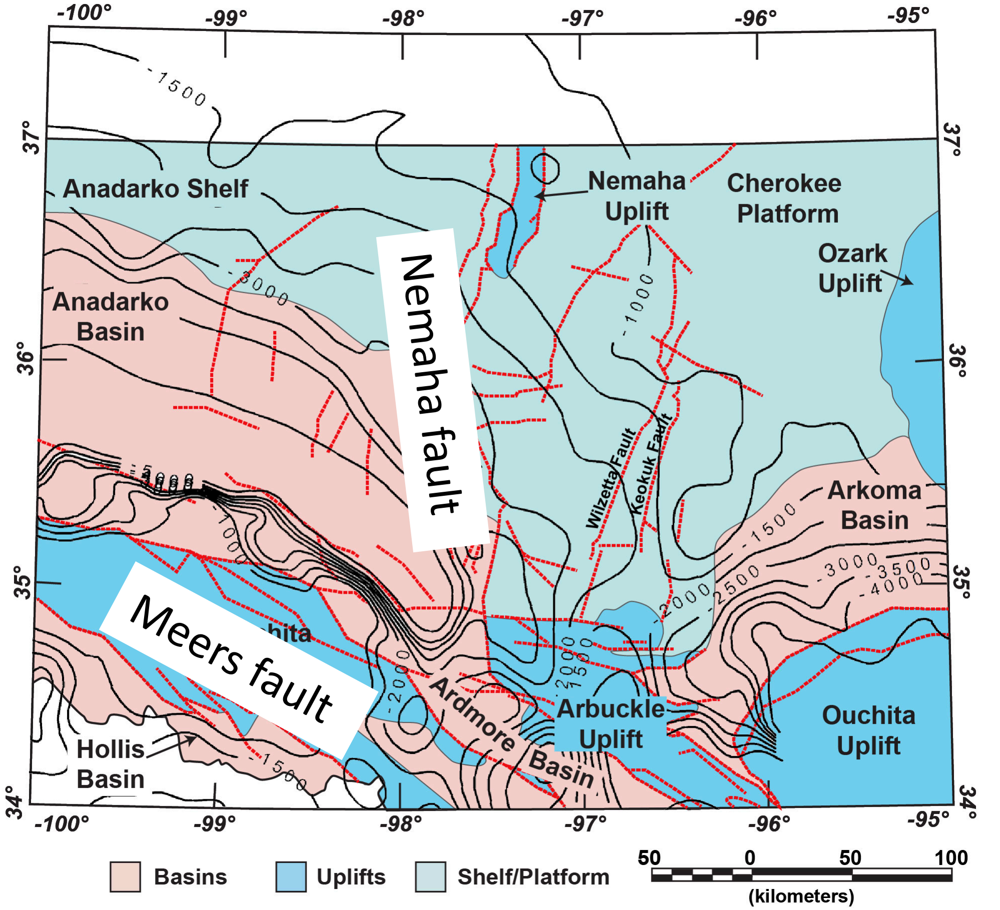
- Questions #1: What is the relationship between earthquake occurrence and tectonics/geology?
- Question #2: What is the background stress field in Oklahoma, and how optimally oriented are Oklahoma faults?
- Question #3: How does waste injection affect fault activation and source processes?
- Question #4: How does hydraulic fracturing affect earthquake occurrence?

Oklahoma Tectonic Background



Kolawole et al., 2019

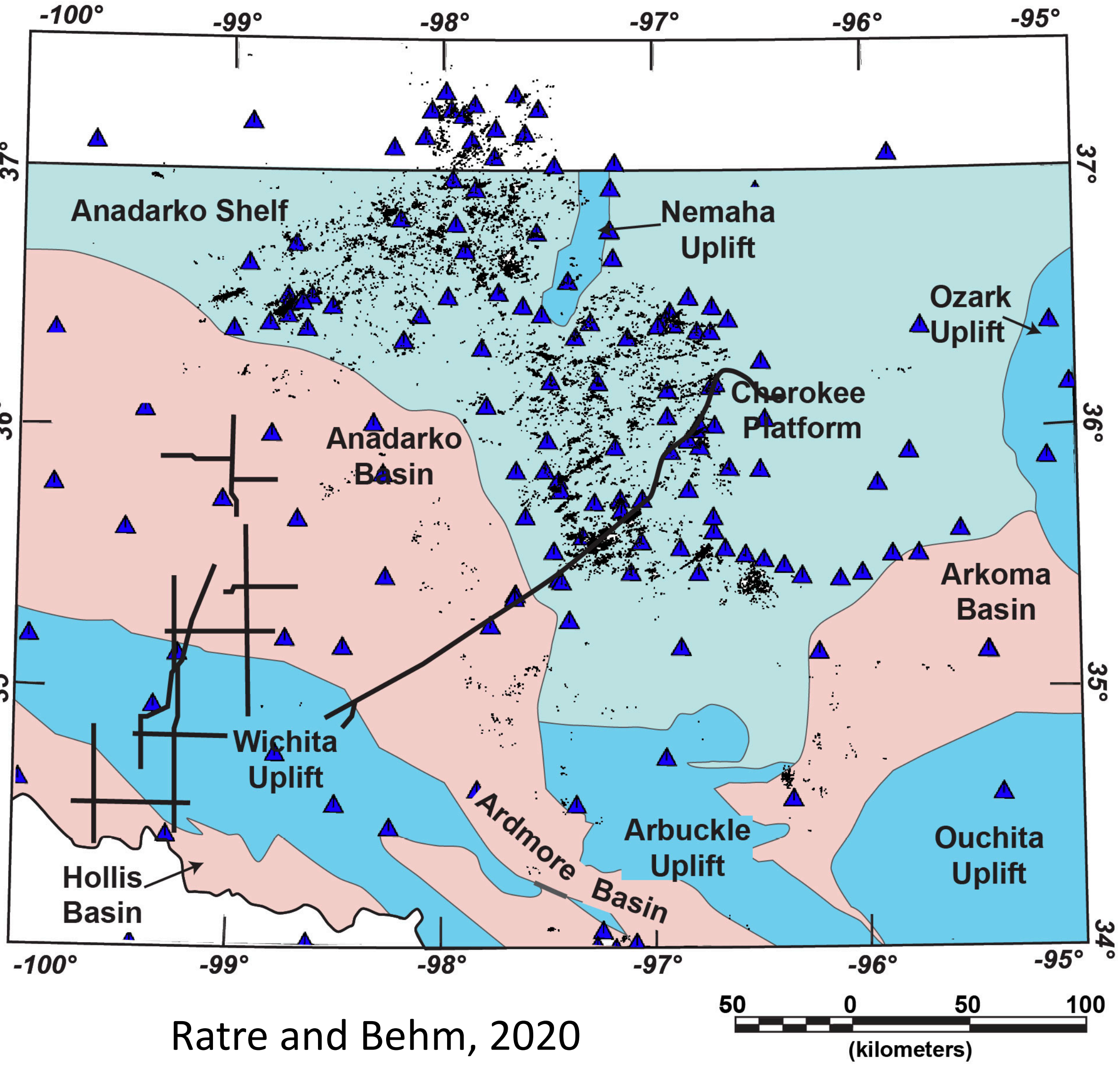
- EGR, Eastern Granite–Rhyolite Province
- SGR, Southern Granite–Rhyolite Province
- MCR, Midcontinent Rift
- SOA, Southern Oklahoma Aulacogen (Cambrian) – a failed rift arm



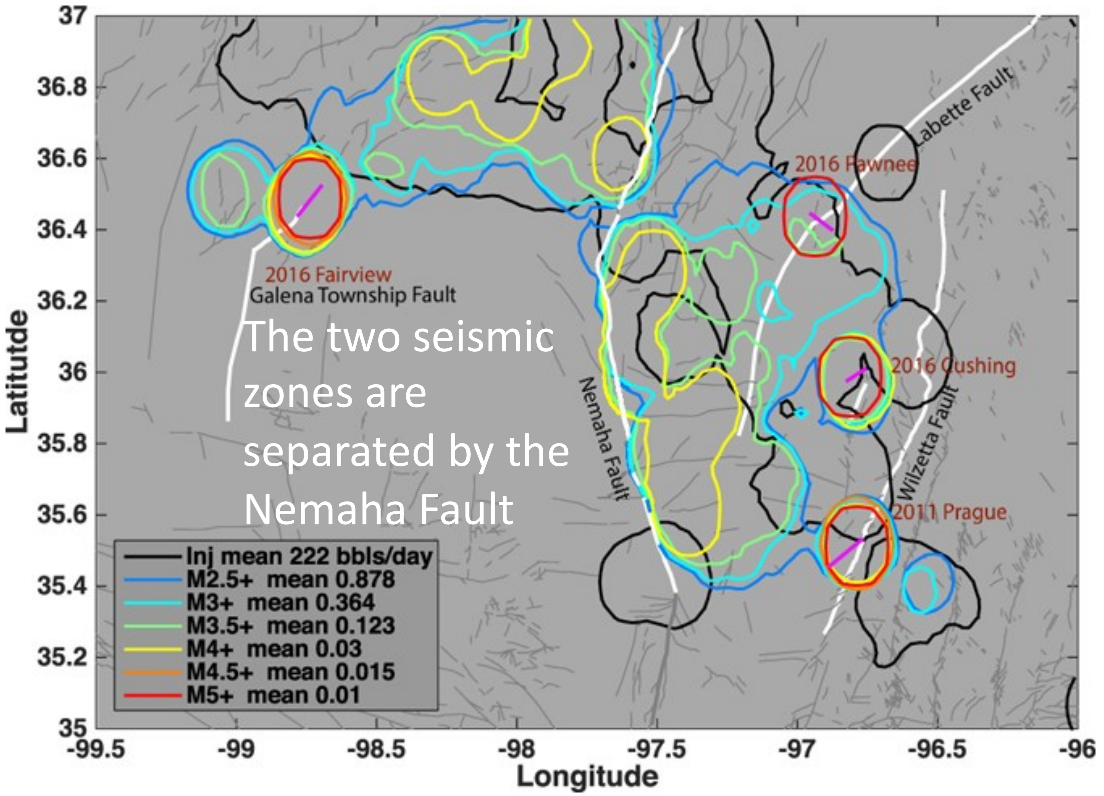
Ratre and Behm, 2020

- Major faults:
  - NS-trend: Nemaha fault
  - NW-SE trend: Meers fault, M7 earthquake ~ 1100 years

Where are the earthquakes?



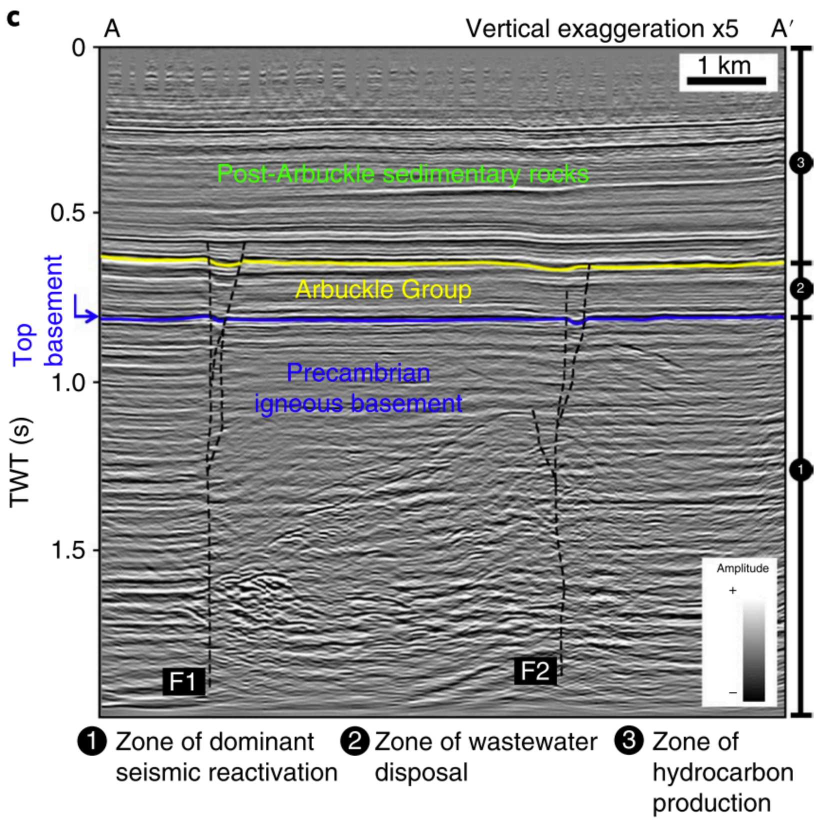
Ratre and Behm, 2020

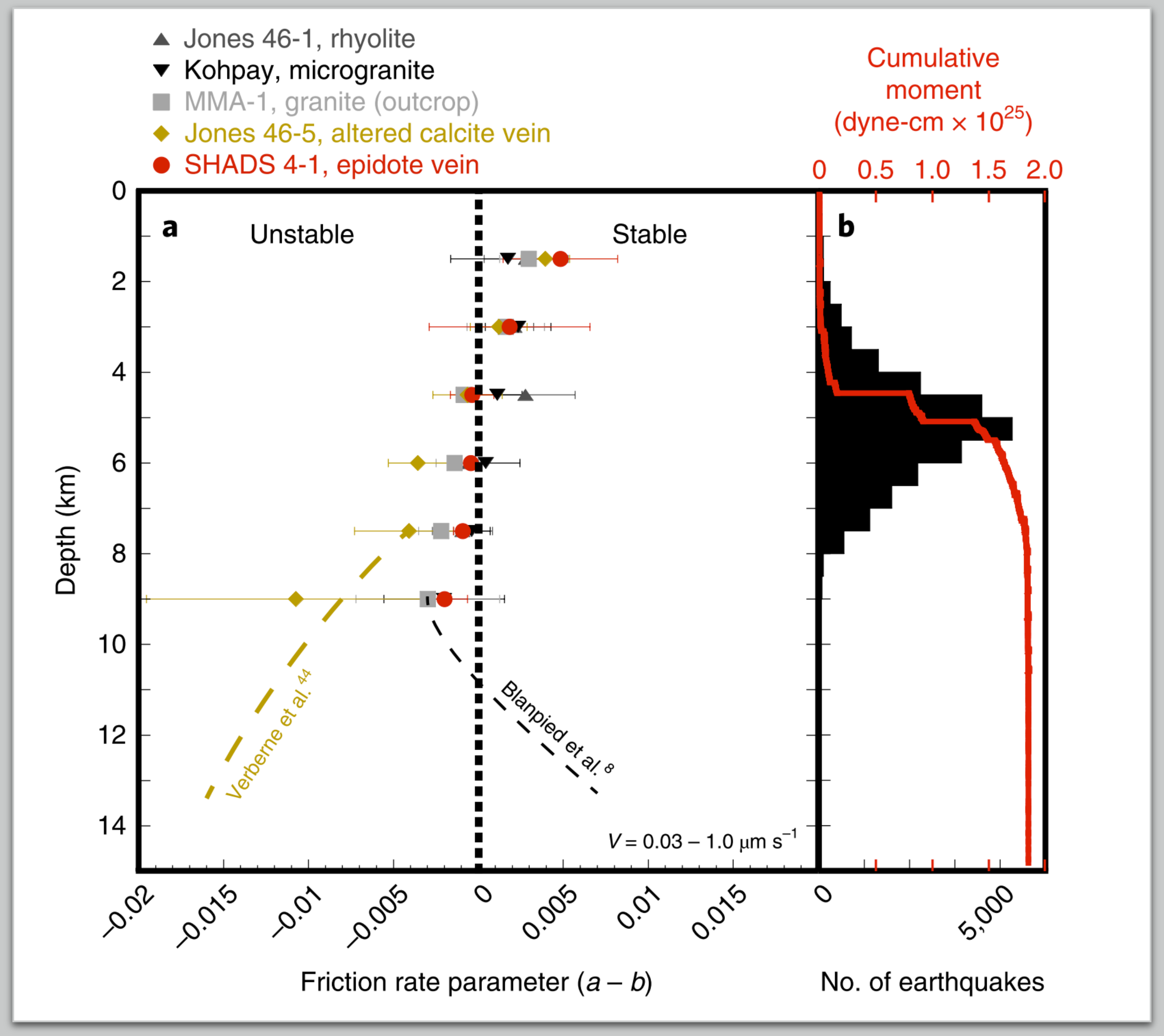


Chen et al., 2017

- Wastewater disposal induced earthquakes are mostly in the Anadarko Shelf and Cherokee Platform (shallow basement depth)
- Hydraulic fracturing induced earthquakes are mostly in the Anadarko Basin and Arkoma Basin (deeper basement depth)
- All the M≥5 earthquake occurred along splay faults from major fault systems. None of the faults that hosted M≥5 earthquakes were previously mapped.

1. Oklahoma's basement rocks become seismically unstable at conditions relevant to the dominant hypocentral depths of the recent earthquakes.
2. Oklahoma seismogenic basement faults penetrate the overlying sedimentary sequences, representing pathways for wastewater migration

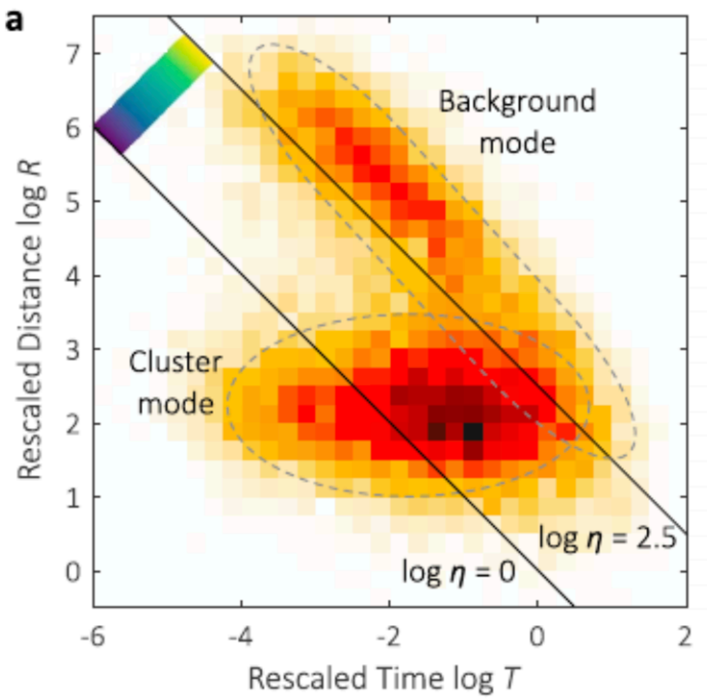




Kolawole et al., 2019

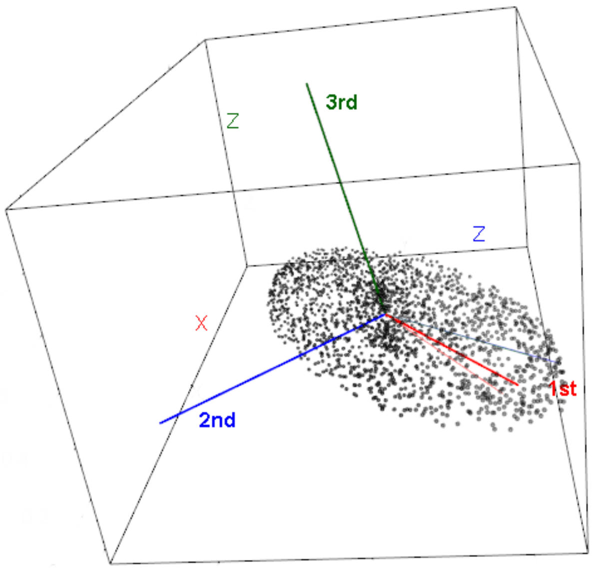
Mapping seismogenic faults from earthquakes

- **Data**: combined relocations from Chen [2016] and Schoenball and Ellsworth [2017a]
- **Methods:**
  - Fault mapping: hierarchical clustering
  - Fault characterization principal component analysis (PCA) (Vidale and Shearer, 2006)



Schoenball and Ellsworth, 2017b

PCA applied to an ellipsoidically shaped point cloud

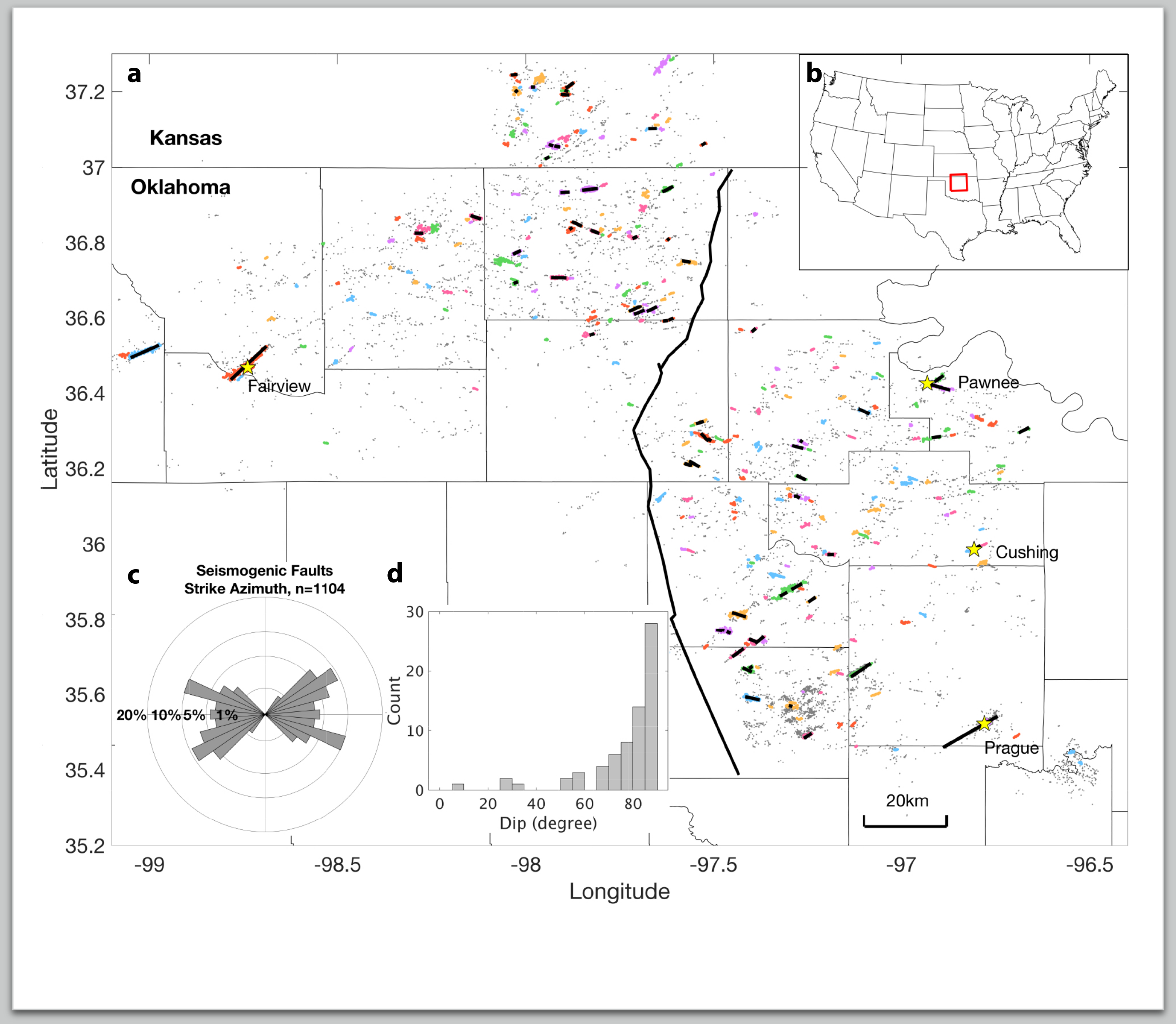


Qin et al., 2019

Seismogenic fault orientations

◉ Observations:

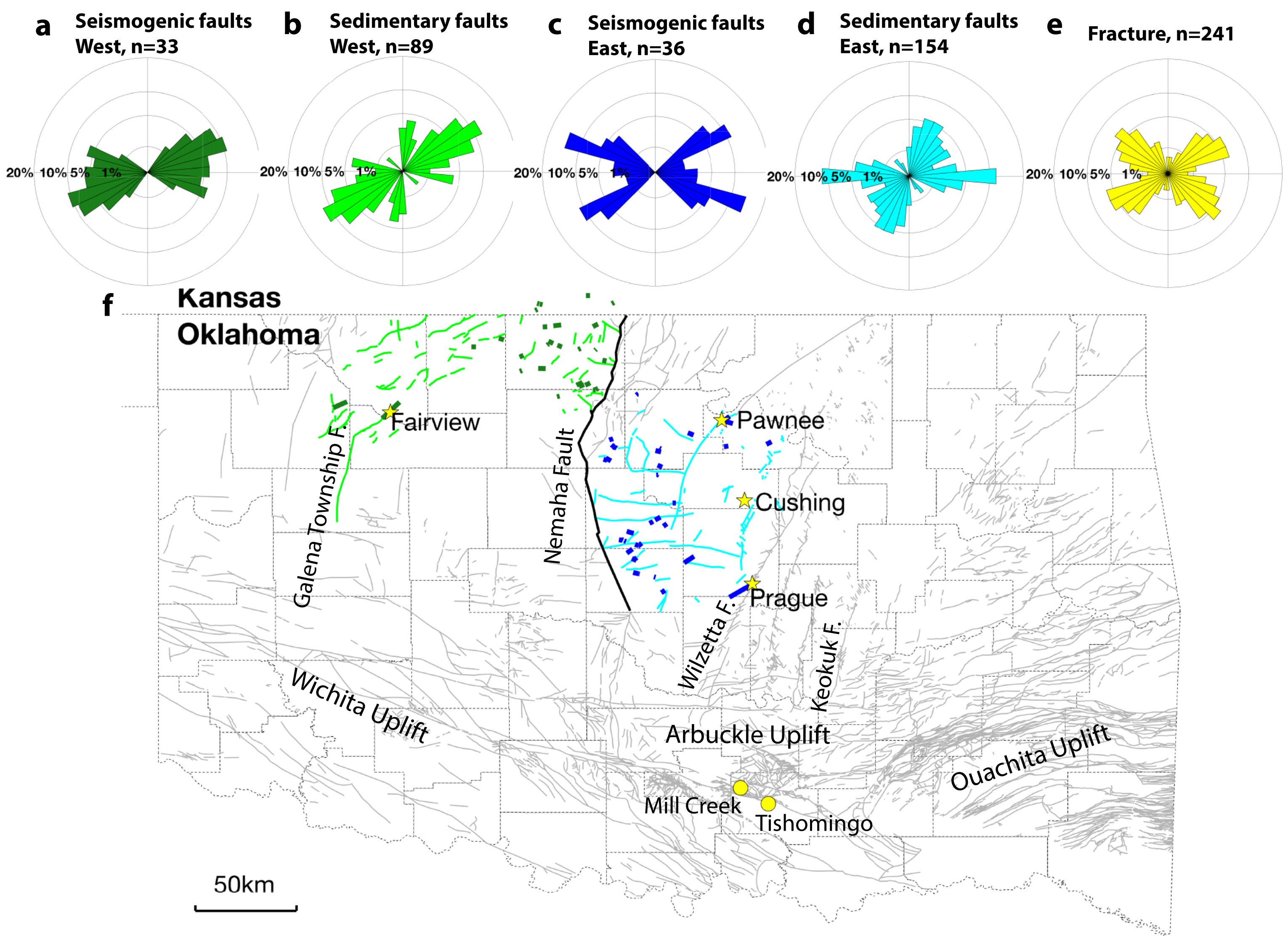
- Fault strike: mainly in the ranges of [55 75°] and [105 125°], conjugate patterns relative to σ_{Hmax} orientation of N85°E.
- Fault dip: over 80% of seismogenic faults are steeply dipping (dip>70°).



Qin et al., 2019

Seismogenic and Sedimentary (from fault database) Faults

- West: NE for both types of faults (dominance of NE basement rooted splays)
- East: NE and NW trends are reactivated; the sedimentary faults (NNE to NE, EW) possibly associated with the large basement-rooted NNE faults.
- Exposed basement fracture: similar conjugate pattern
- ◉ common tectonic control of seismogenic and geology faults



Qin et al., 2019

Oklahoma Induced Earthquakes

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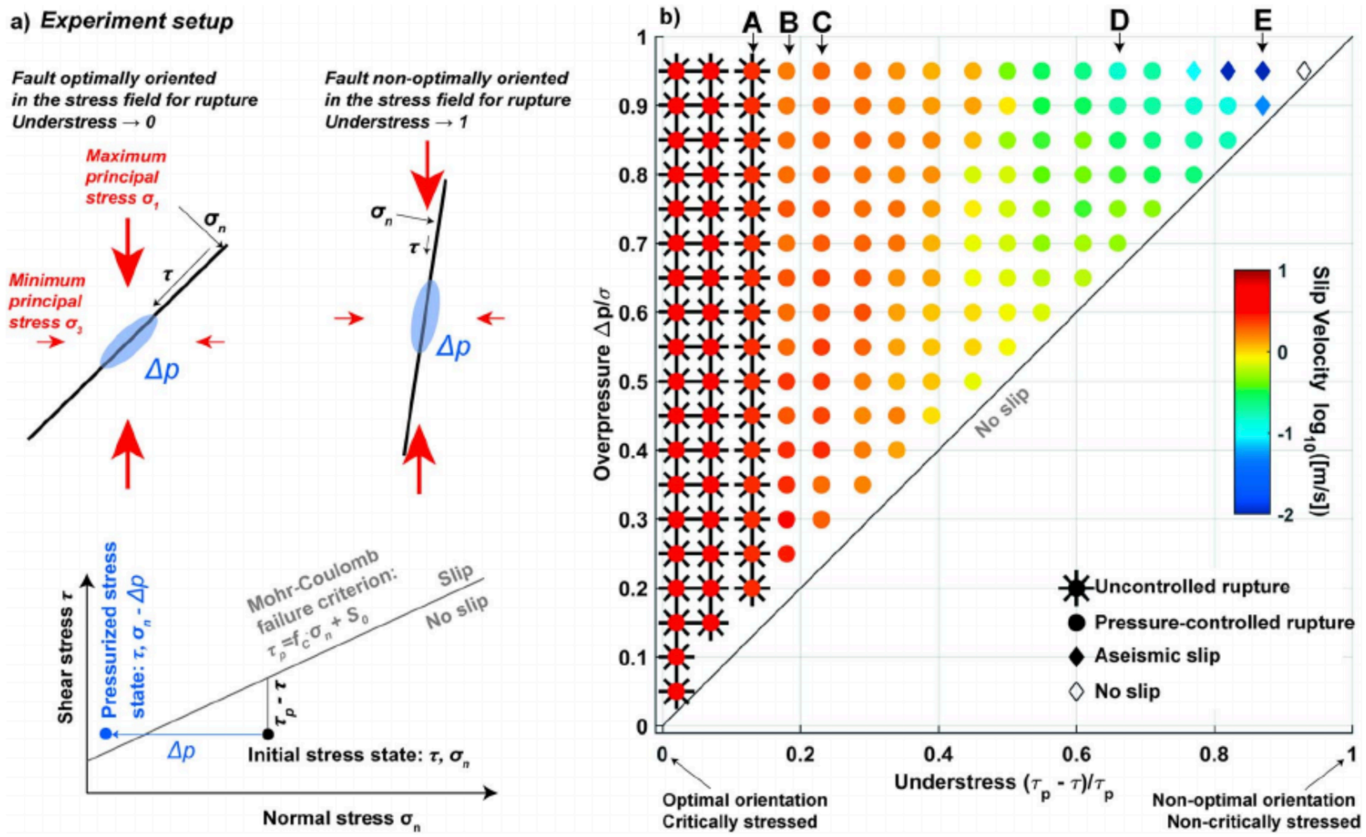
Stress field and fault orientation influence fault activation



(Figure from Gischig, 2015)

- The experiment objective:

Rupture behaviors for optimally and non-optimally oriented faults

- Definition of understress:

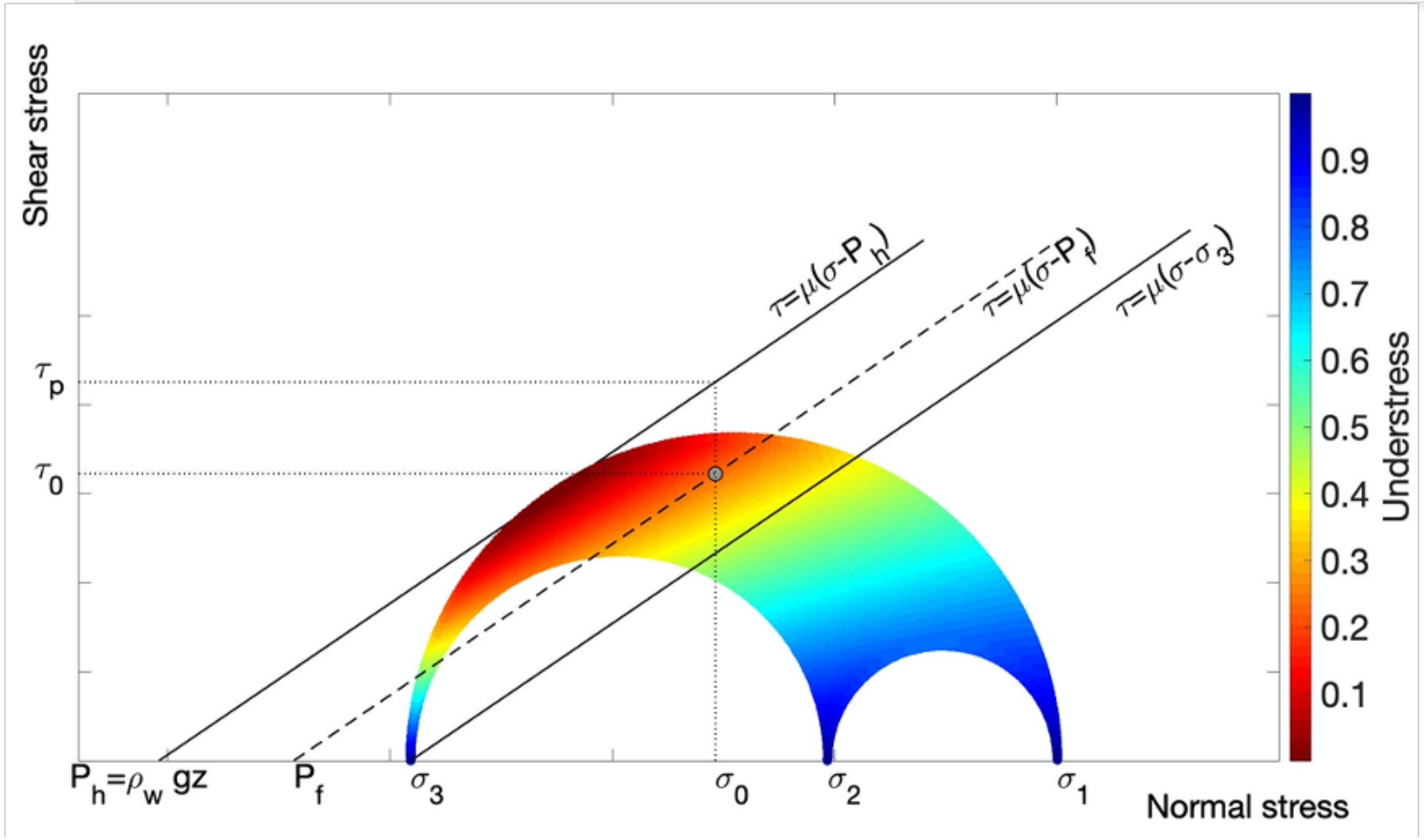
Understress near 0 means optimally oriented, and understress of 1 means non-optimally oriented.

$$understress = \frac{\tau_p - \tau_0}{\tau_p}$$

- Fault rupture behaviors:

Pressure-controlled rupture for <u>non-optimally oriented faults</u> **VS** uncontrolled rupture for <u>optimally oriented faults</u>

Mapping Oklahoma stress field and fault stress state



- Invert stress field using 2047 focal mechanism solutions using MSATSI (Martinez-Garzon et al., 2014).
- Mapping fluid pore pressure Focal Mechanism Tomography (FMT) (Terakawa et al., 2010).
- Calculate **understress** for each fault:

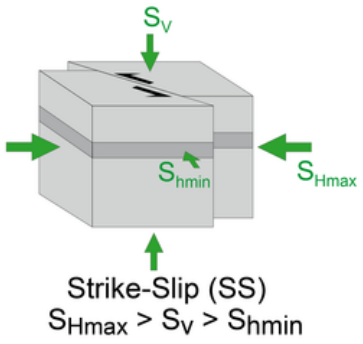
Understress near 0 means optimally oriented, and understress of 1 means non-optimally oriented.

$$understress = \frac{\tau_p - \tau_0}{\tau_p}$$

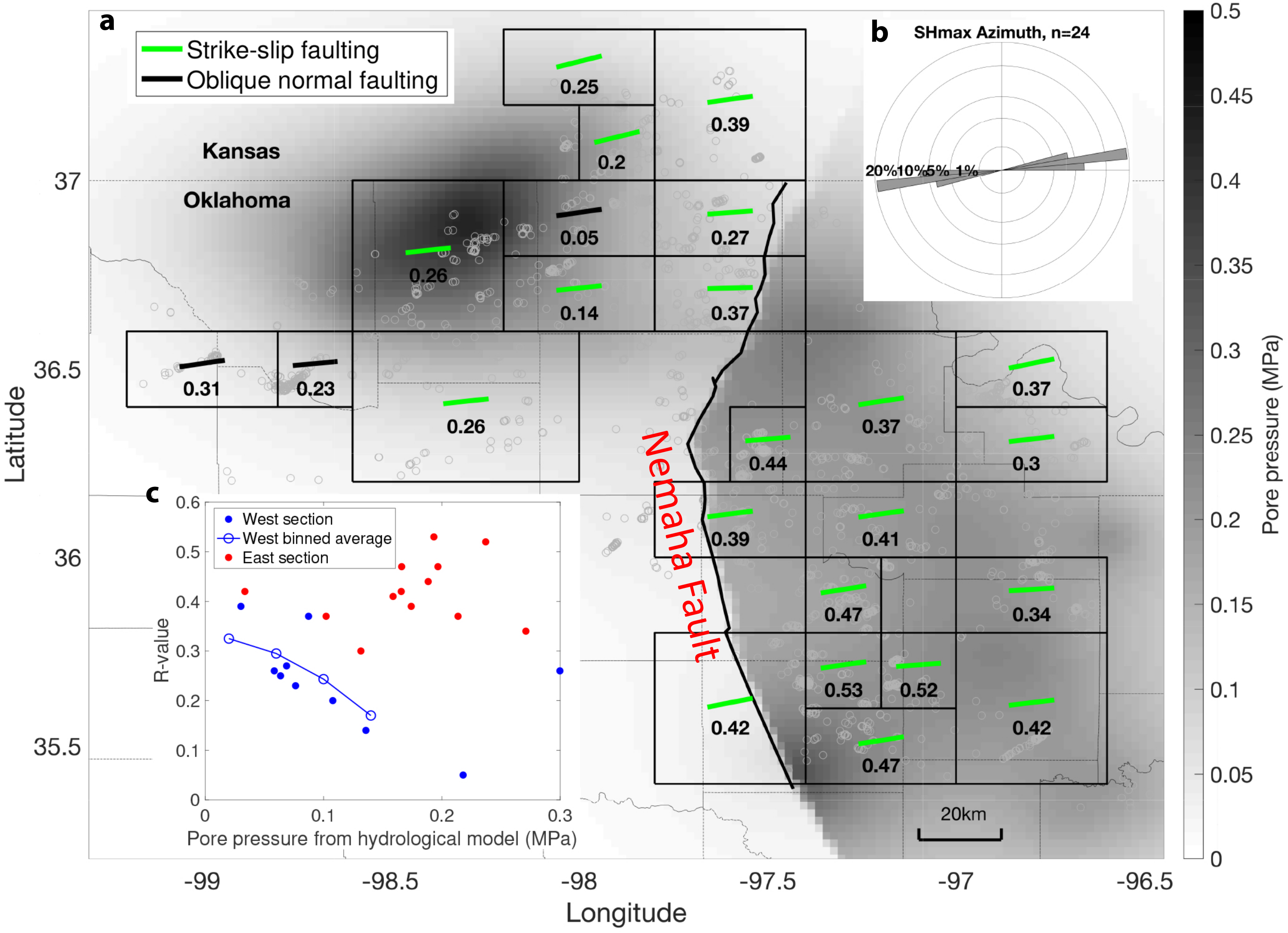
Qin et al., 2019

Stress field result

- Central OK: strike-slip faulting;
- North and northwest OK: oblique normal faulting
- Dominant σ_{Hmax} 80°--90°
- West of Nemaha: negative correlation between R value and pore pressure, possibly explained by poroelastic effects (pore pressure change causes changes on the elastic stress field)



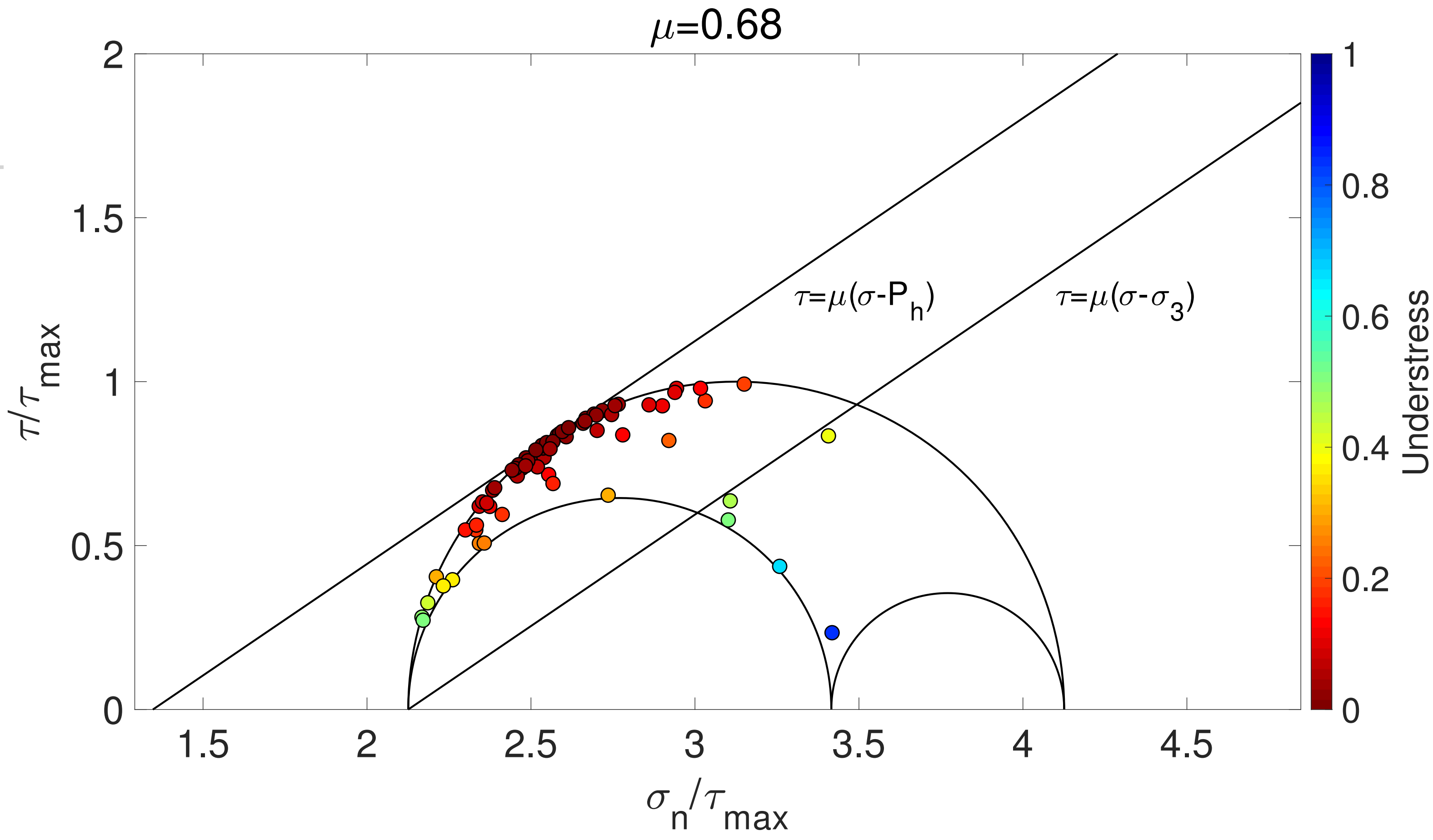
$$R = \frac{S_H - S_v}{S_H - S_h}$$



Qin et al., 2019

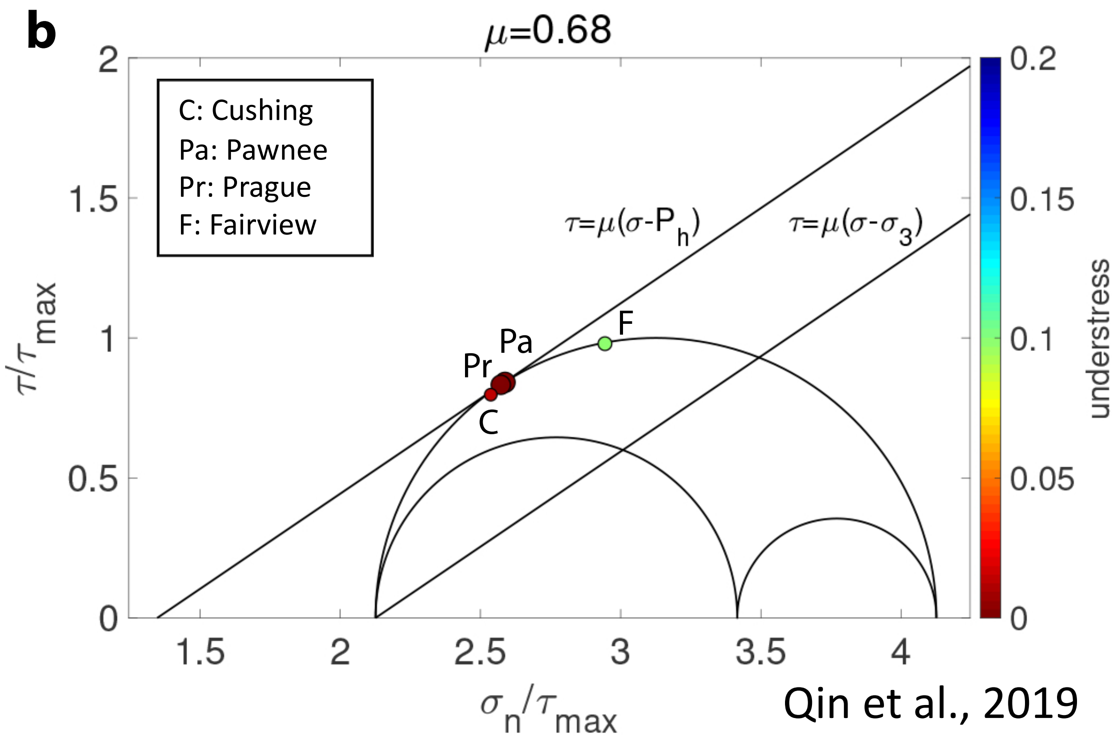
Fault Stress state

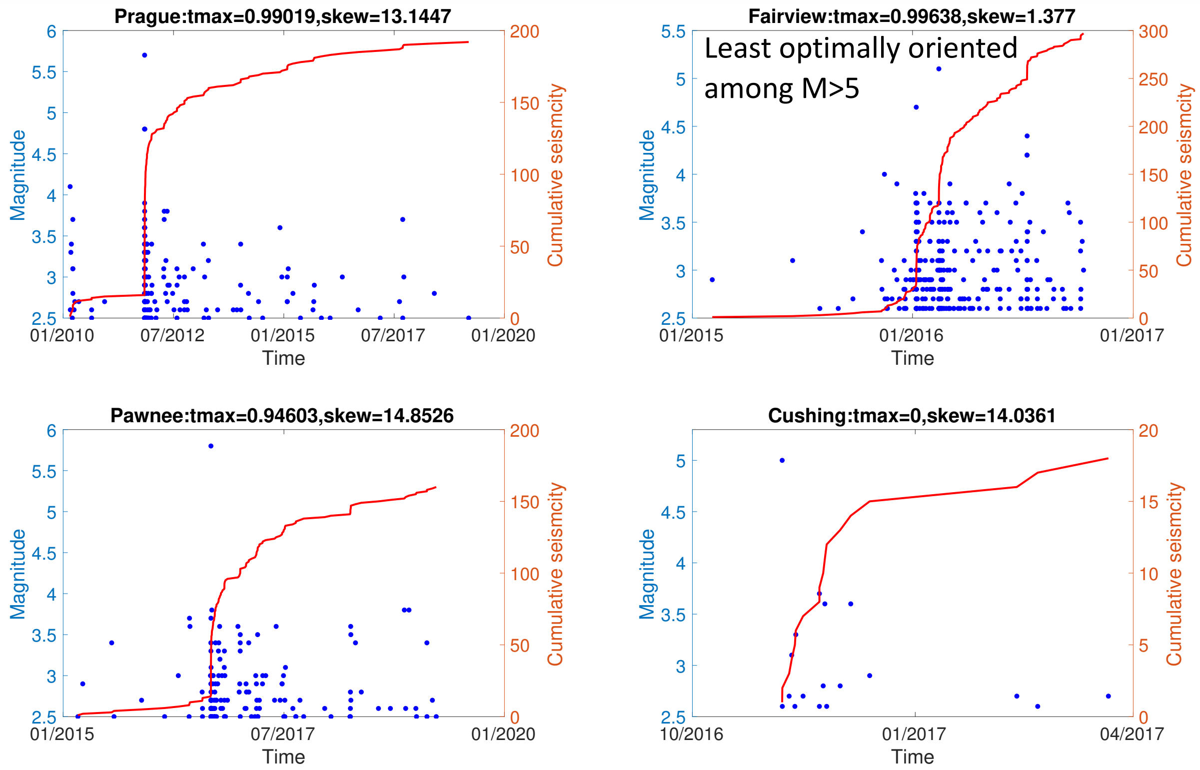
- 78% faults are critically stressed with understress smaller than 0.2.
- Non-optimally oriented faults being reactivated, due to locally high pore pressure or other factors, e.g., earthquakes interactions.



Qin et al., 2019

Different temporal evolutions of M≥5 earthquake sequences may be influenced by different stress state





- The faults in Prague, Pawnee, and Cushing were critically stressed (understress<0.02). Predominantly mainshock-aftershock sequences
- The fault in Fairview: the least optimally oriented (understress 0.1), the mainshock (understress 0.2). A swarm-type sequence

Summary of stress field and geology

- Oklahoma seismogenic faults have the same tectonic origin with sedimentary faults, and fault connectivity with sedimentary layer provide possible fluid pathway.
- Although the majority of the seismogenic faults (NE and NW trending) are optimally oriented relative to the local stress field, some non-optimally oriented faults are identified.
- Fault stress state and orientation may influence temporal earthquake sequence evolution (e.g., Fairview versus other M5 sequences).

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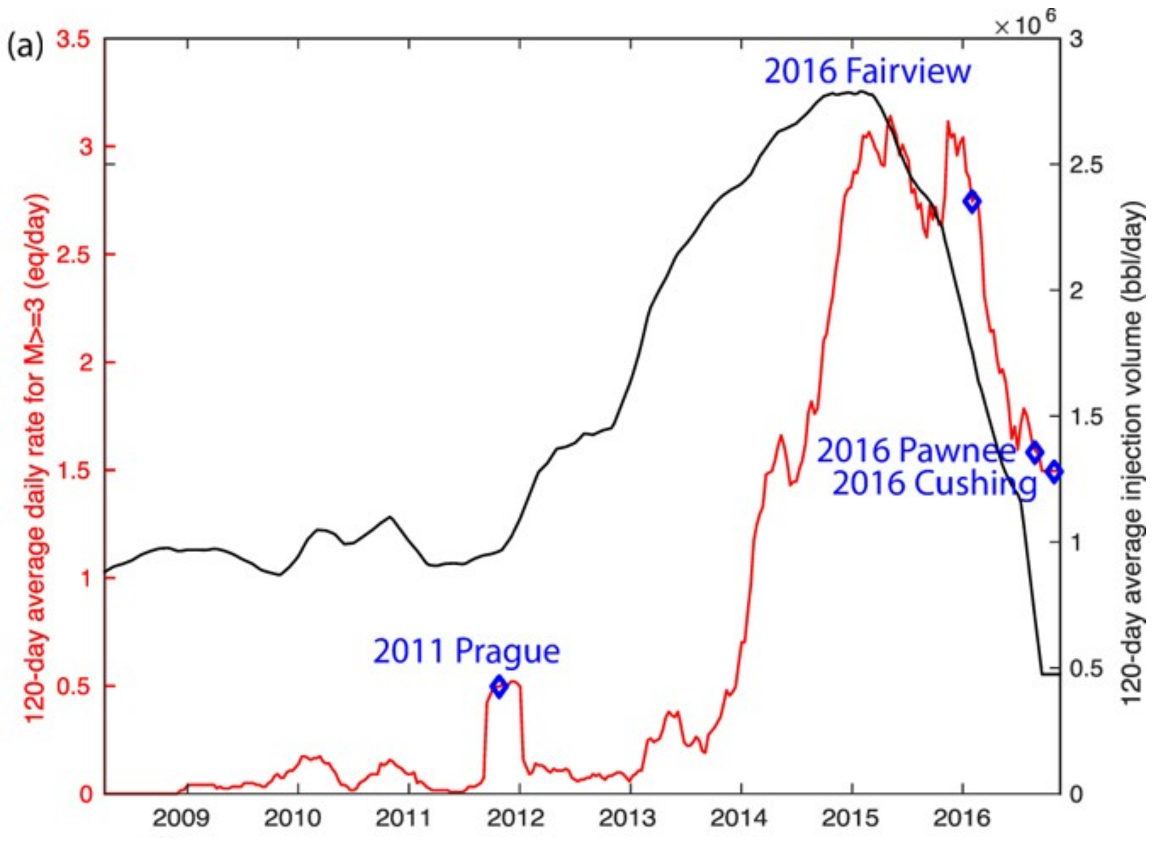
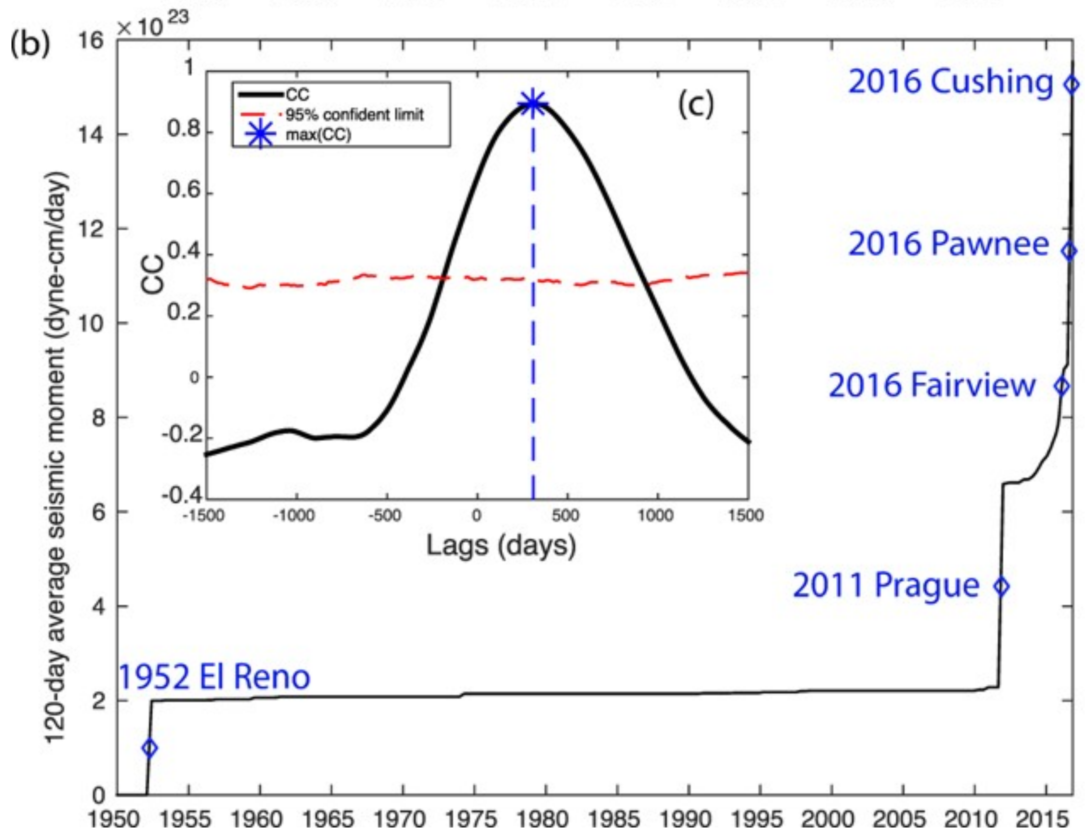
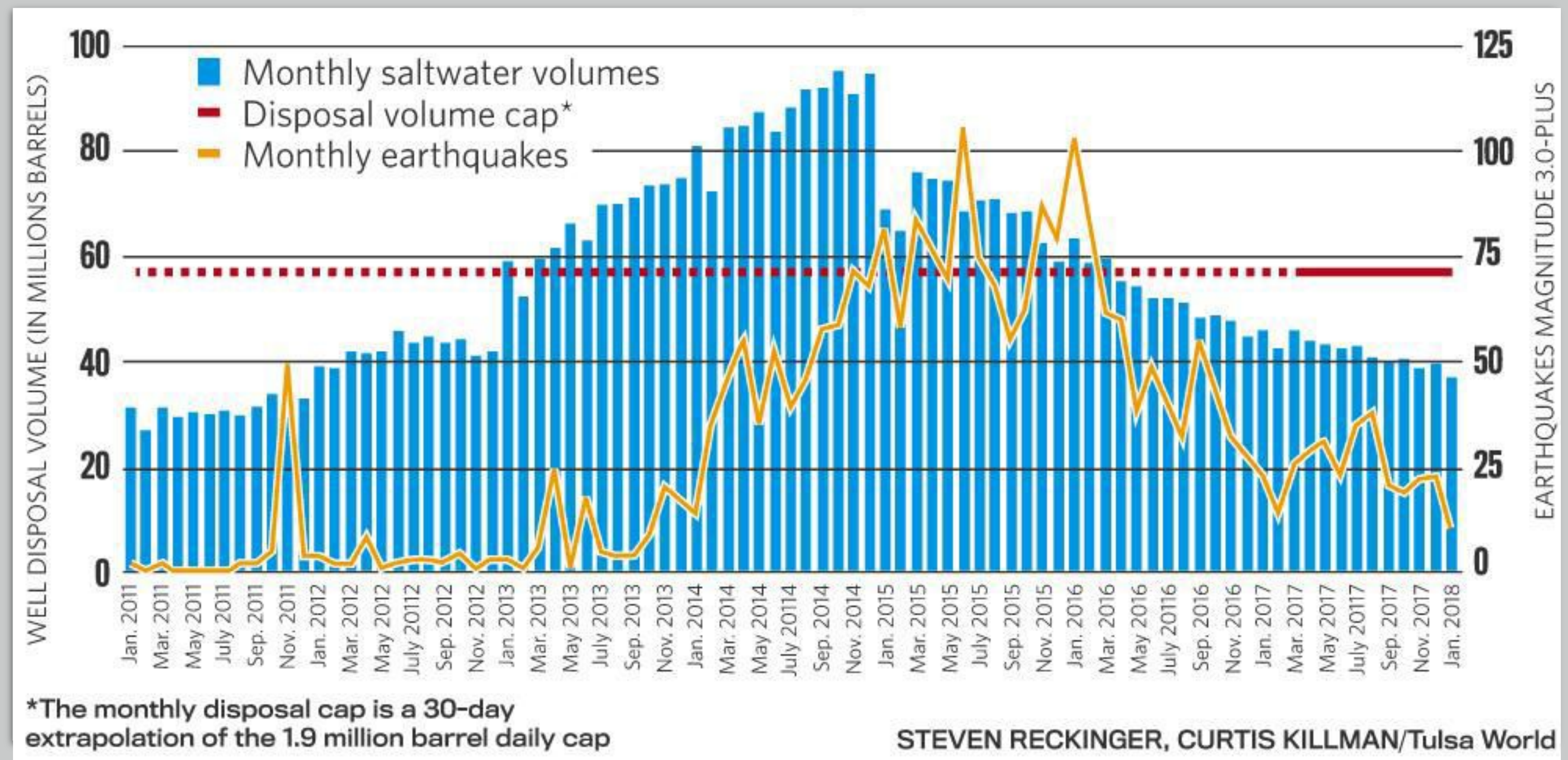
- Question #3: How does waste injection affect fault activation and source processes?
  - Statewide analysis & Individual cluster analysis
- Question #4: How does hydraulic fracturing affect earthquake occurrence?

Strong correlation between earthquake rate and wastewater injection





Chen et al., 2017

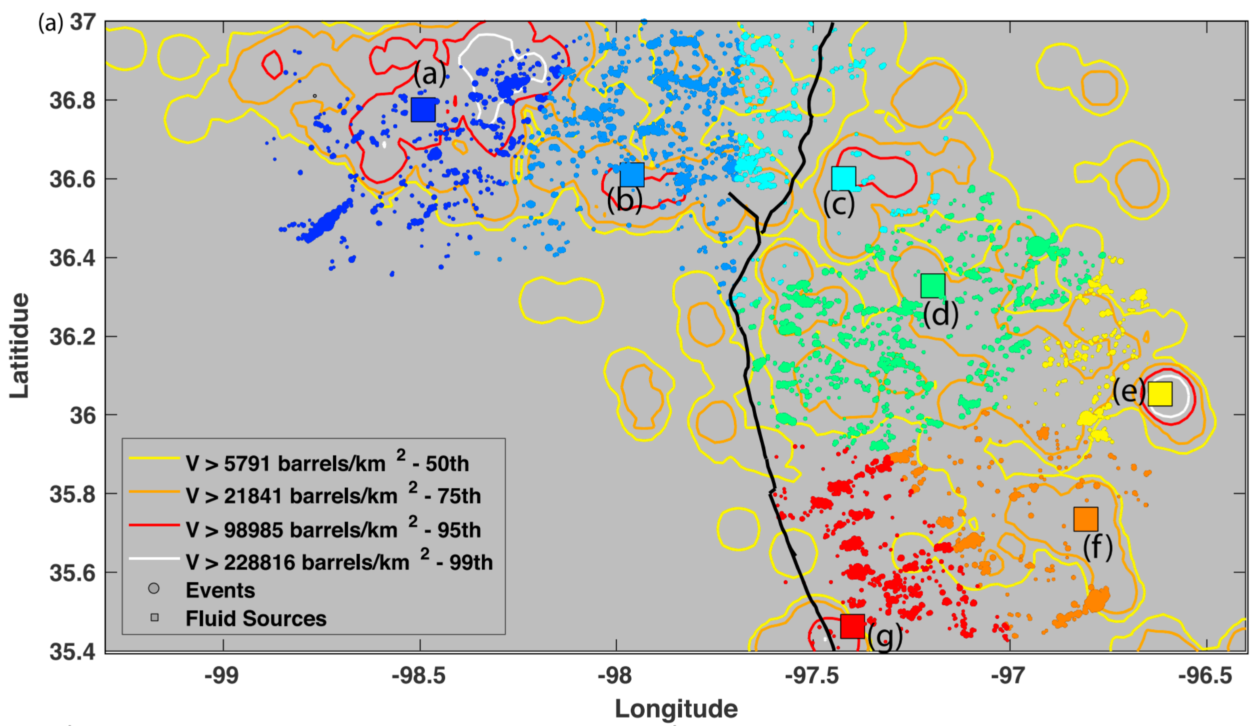


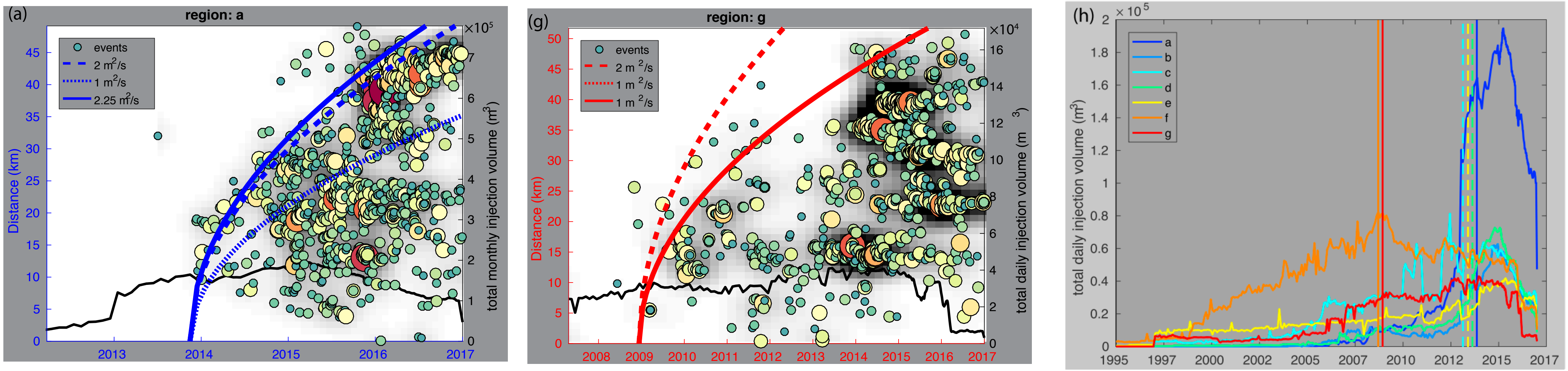
Decline in injection volume drives the decline in seismicity

Most of the wastewater comes from co-produced water from oil and gas wells. The median water:oil and water:gas ratios were 7.4 and 9.8 for wells in western Oklahoma (Murray, 2014).

Wastewater disposal can affect seismicity up to 50 km away with diffusivities around 1.5 m^2/s

- Automatic diffusion curve fitting found <u>the starting time of diffusive migration</u> Matches <u>the changes in injection rate</u> (sharp increase in western OK, and peak injection in eastern OK).



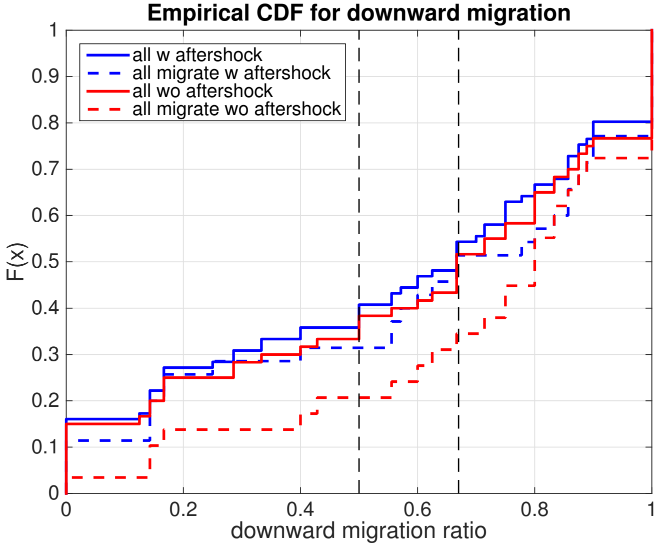


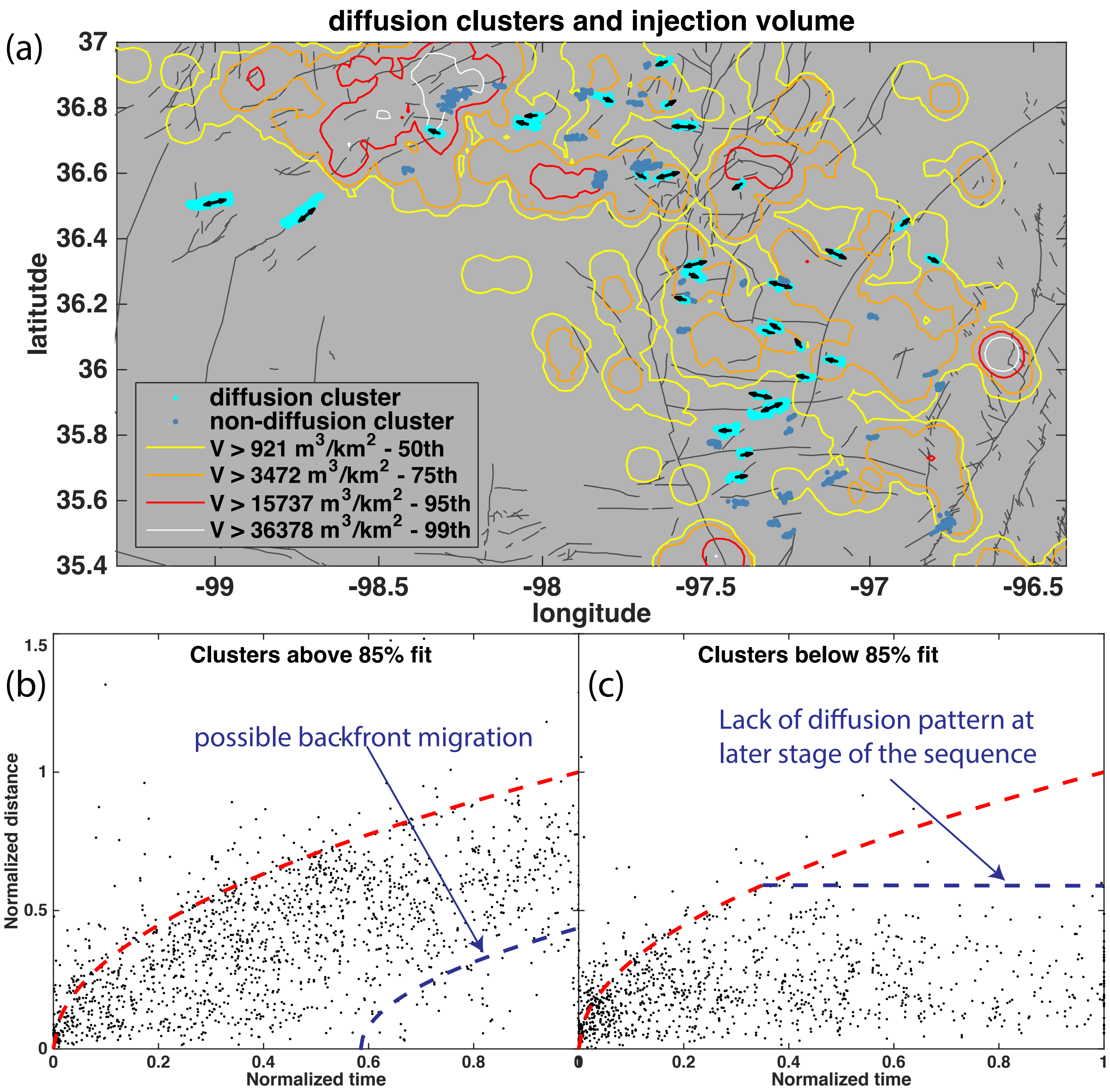
Haffener et al., 2018

Diffusive migration within individual clusters has diffusivities around 0.03 m^2/s

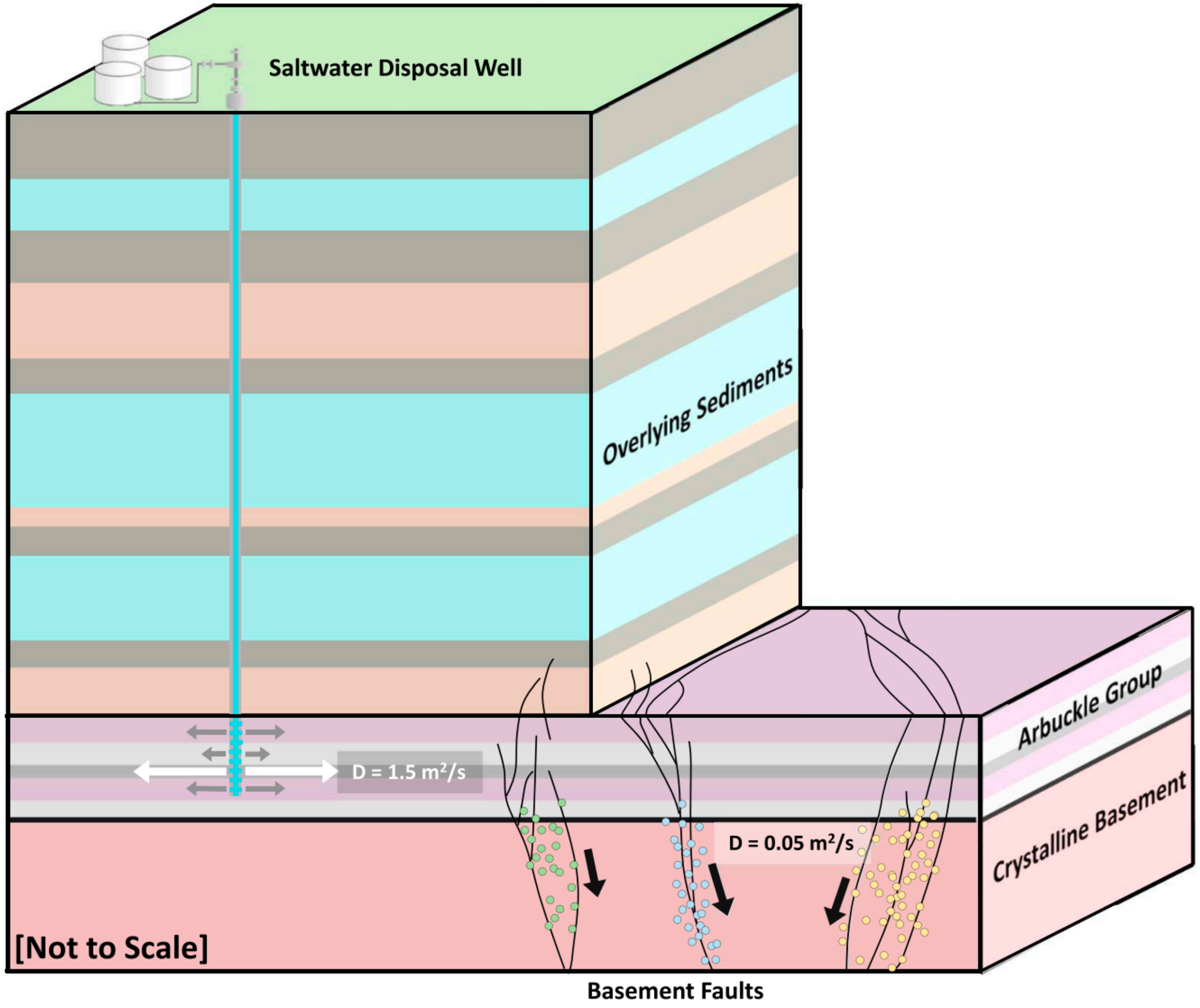
- About 60% of clusters show statistically significant migration, the percentage is similar to southern California.
- The diffusivity of basement clusters are much lower than large-scale pattern, and are similar to other crustal swarms in tectonic earthquakes.
- There is no clear directional migration pattern from injection zones.

Over half of the clusters show downward migration direction.





Haffener et al., 2018



Haffener et al., 2018

Summary of wastewater disposal triggering from statewide analysis

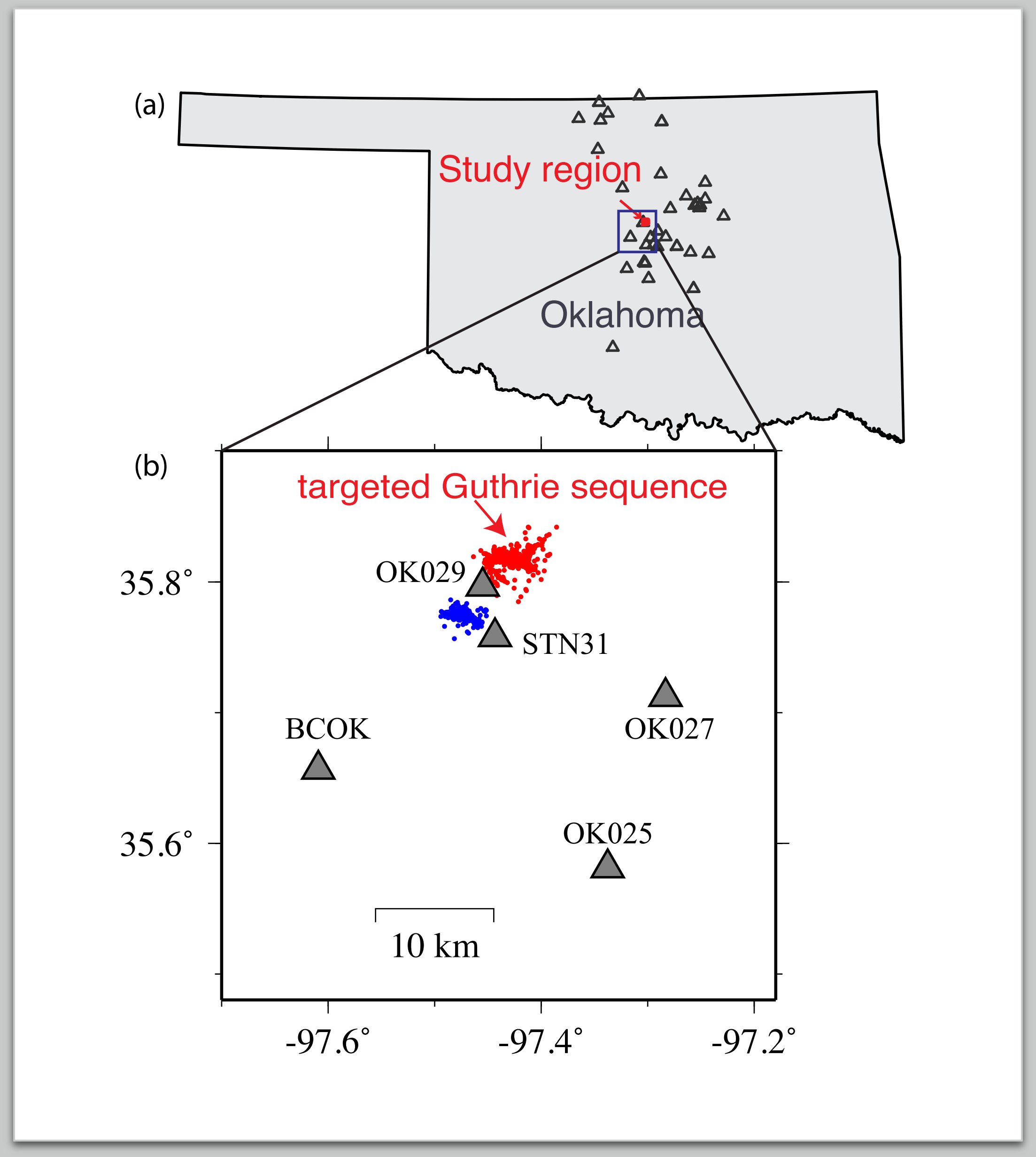
(1) Long-range triggering is facilitated by high diffusivity within the Arbuckle layer.

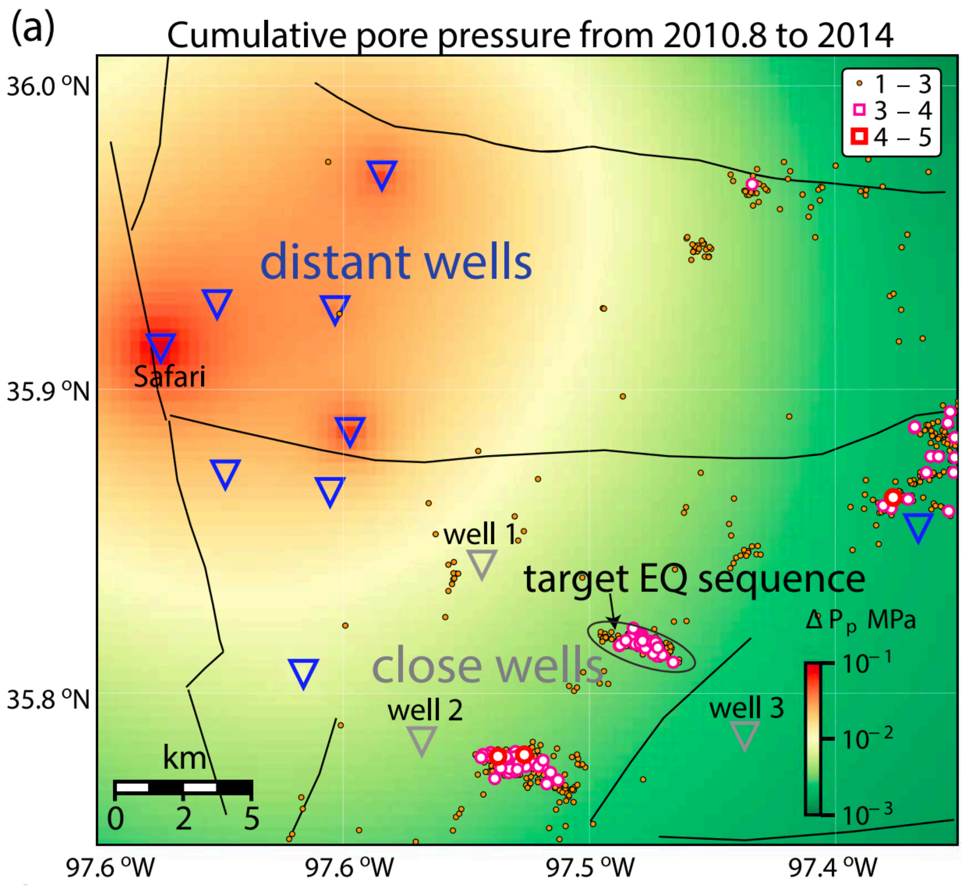
(2) Basement faults have relatively lower diffusivity, similar to tectonic active regions.

(3) The migration direction along basement faults may differ from large-scale migration direction.

(4) A majority of diffusivity migrating clusters exhibit downward migration, consistent with stress triggering from the overlaying Arbuckle group

Influence of injection on source processes with the Guthrie sequence.

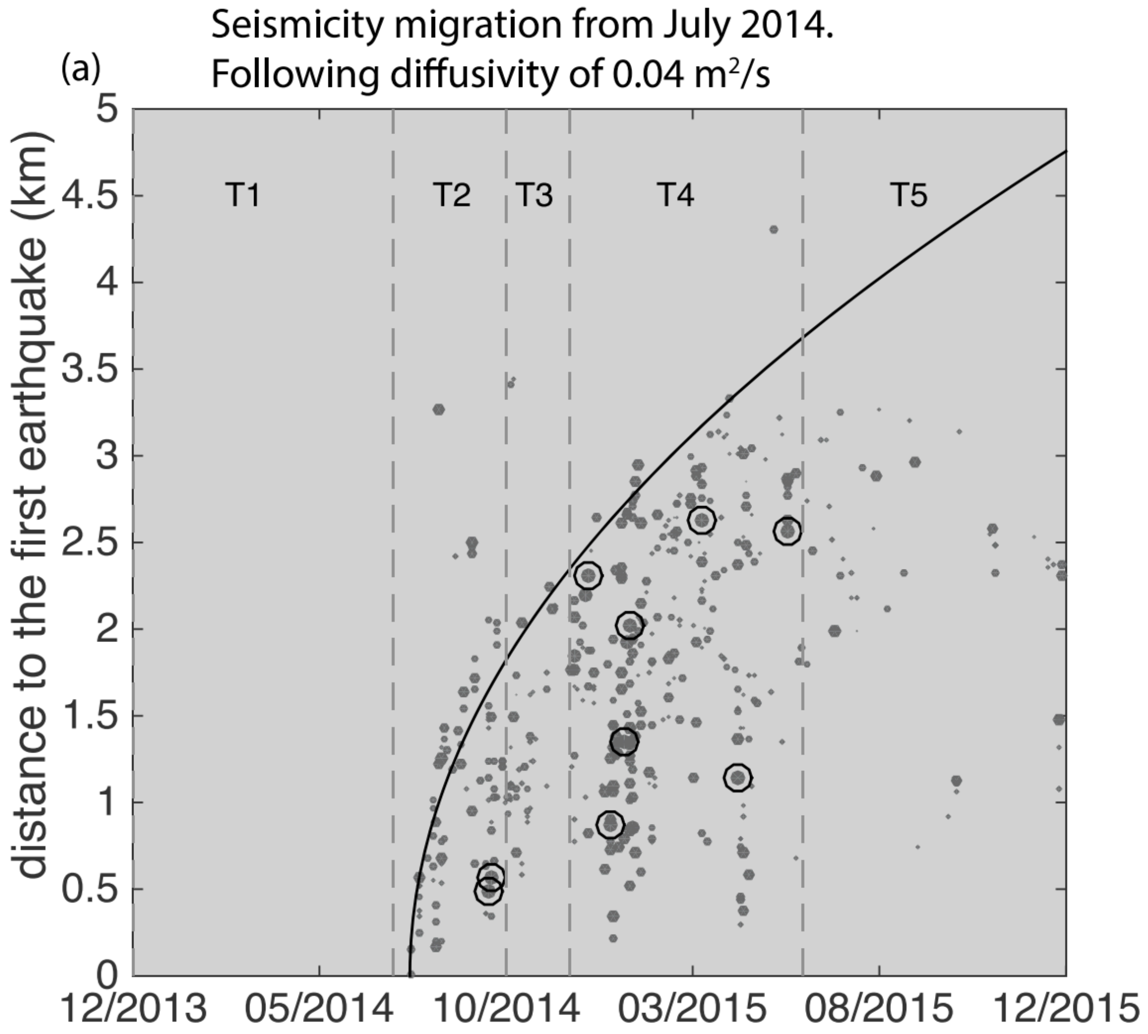


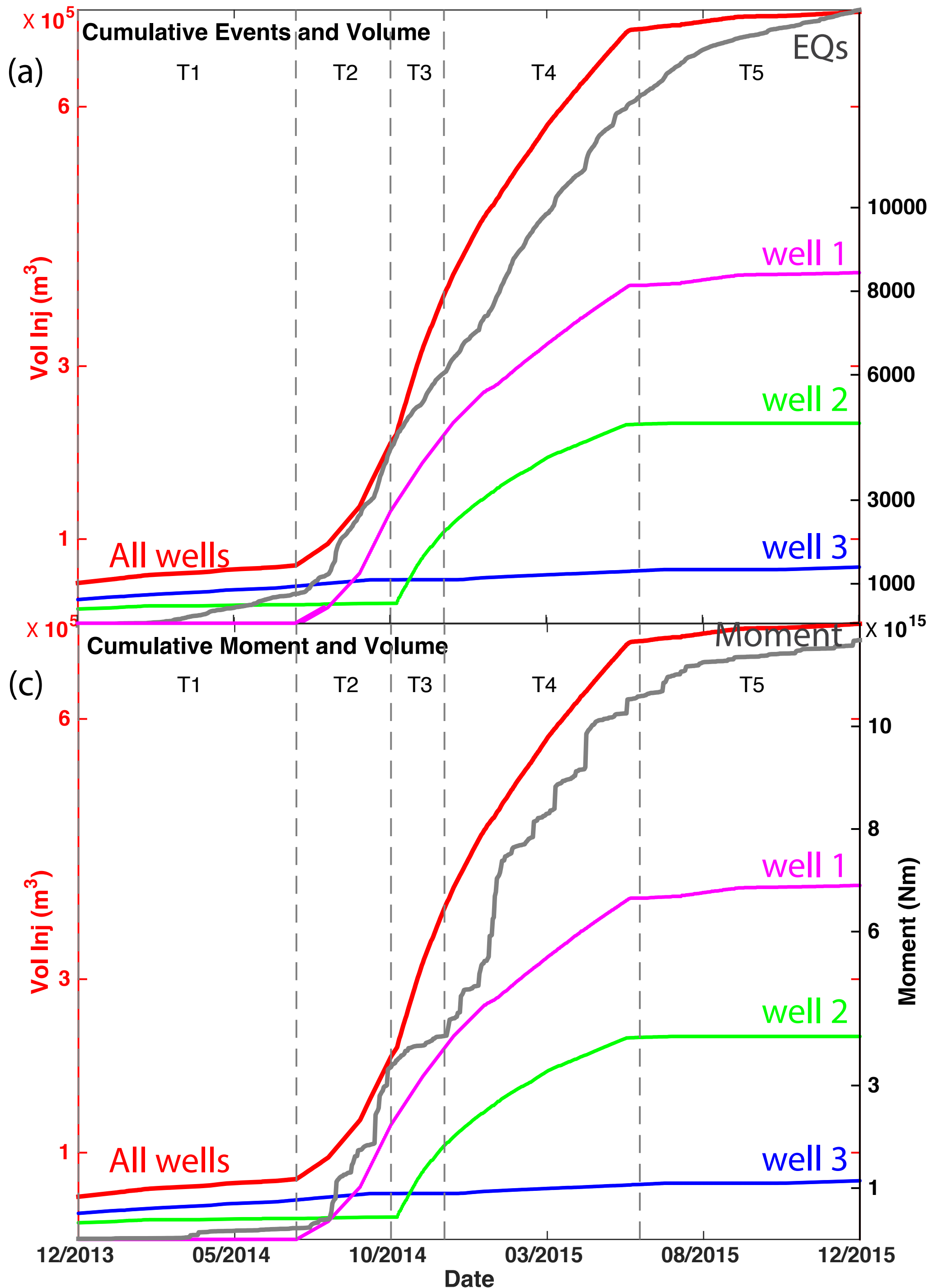


Chen et al., 2018

(1) Strong correlation between injection volume from nearest three wells and seismicity
(2) Clear diffusive migration starting from July 2014, with diffusivity of 0.04 m^2/s.

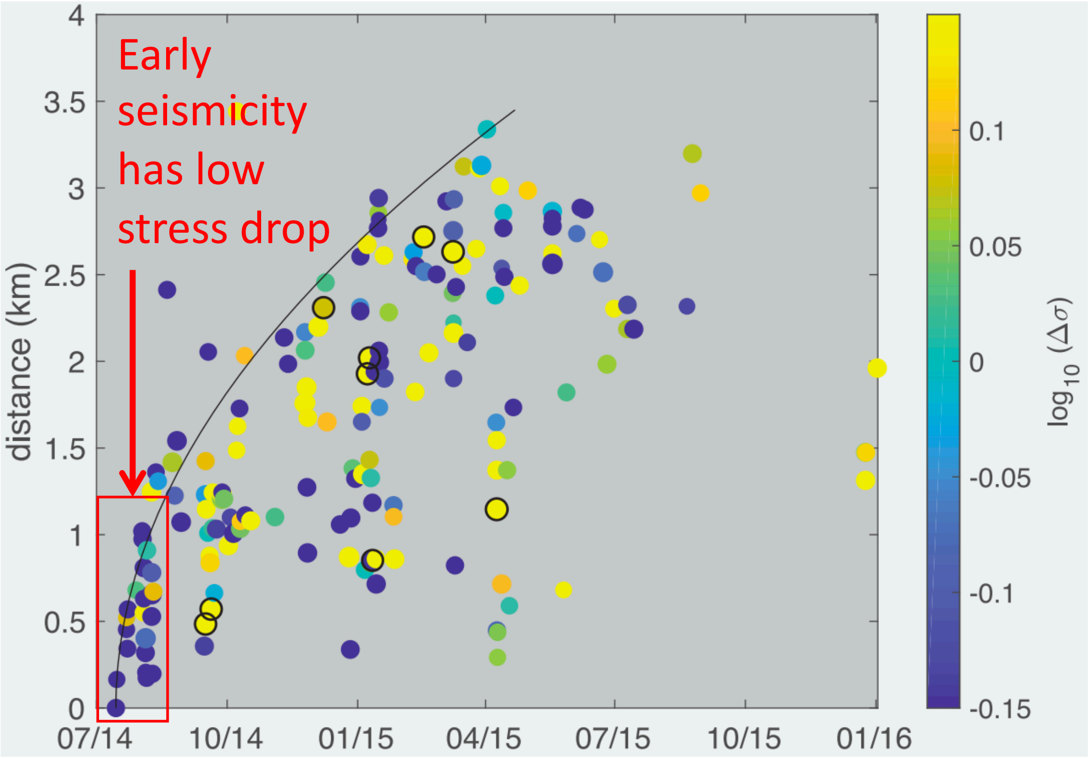
Chen et al., 2018

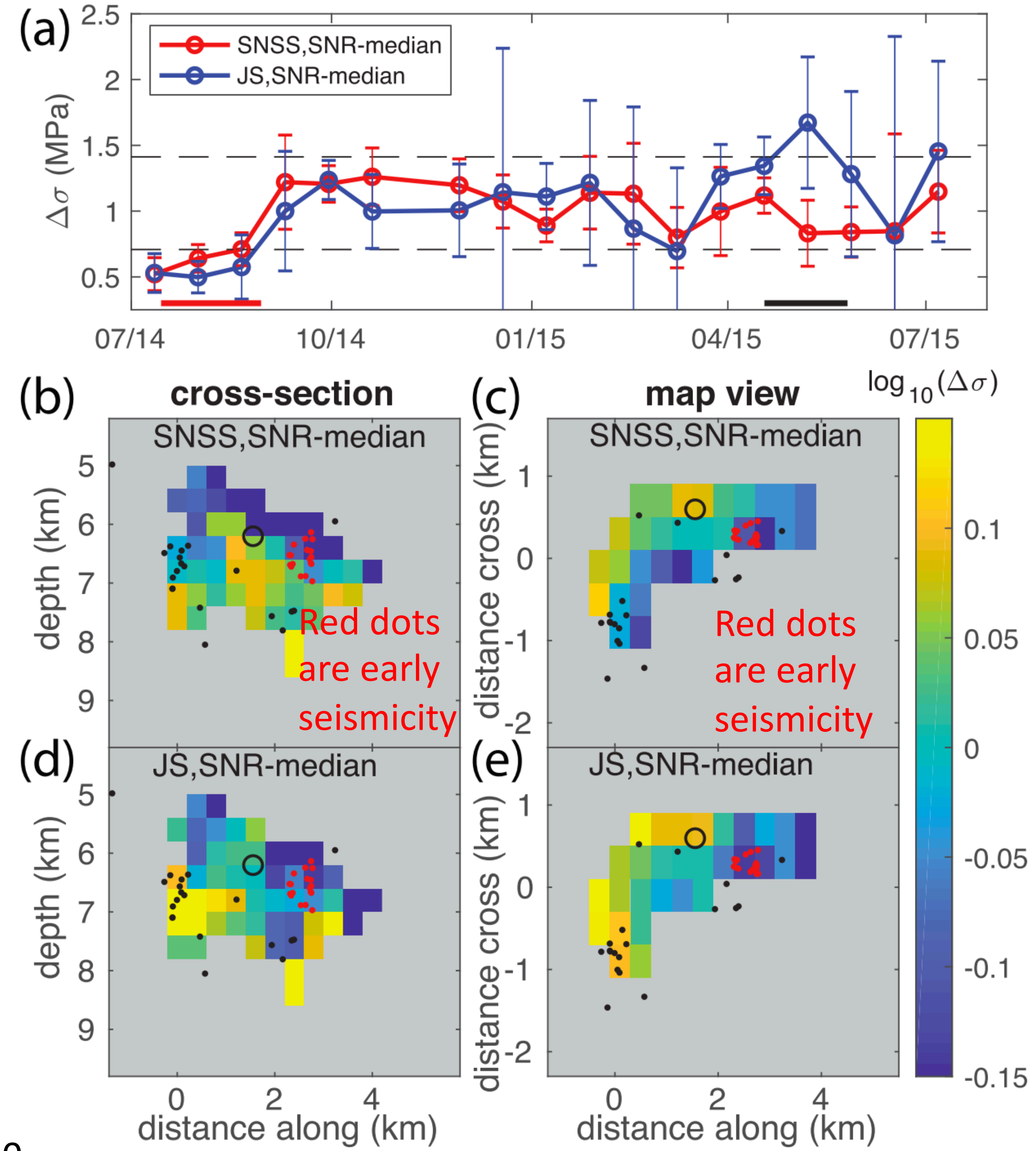




(1) Clear low stress drop during the early stage of fault activation using two different methods.

(2) The earliest seismicity (red dots) are concentrated within a small patch of low stress drop.





Chen & Abercrombie, 2020

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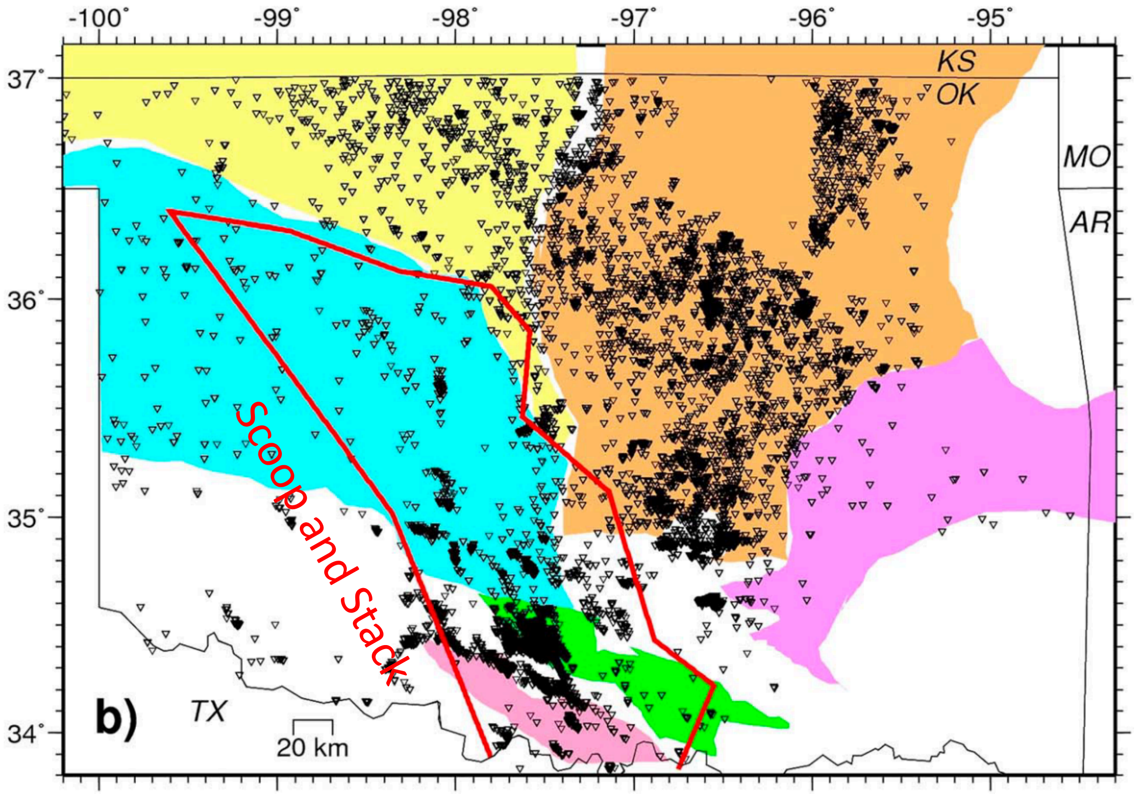
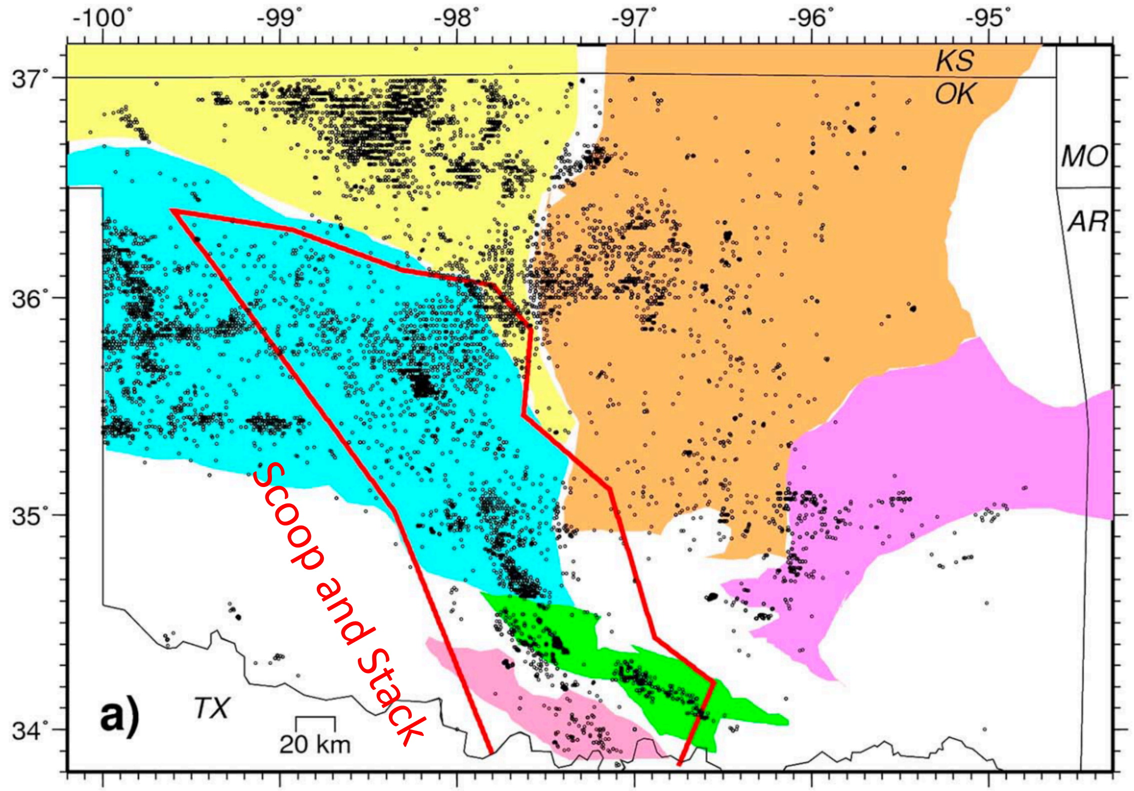
- Question #4: How does hydraulic fracturing affect earthquake occurrence?
  - Statewide analysis & Detailed seismic interpretation in one area

Wastewater Disposal (left) VS Hydraulic Fracturing (right)

colored polygons representing the predominant basins (Anadarko: cyan, Ardmore: green, Marietta: pink, and Arkoma: purple) and platforms (Anadarko: yellow and Cherokee: orange)





Stack: Sooner Trend (oil field), Anadarko (basin), **Canadian and Kingfisher** (counties)
Scoop: the South Central Oklahoma Oil Province play

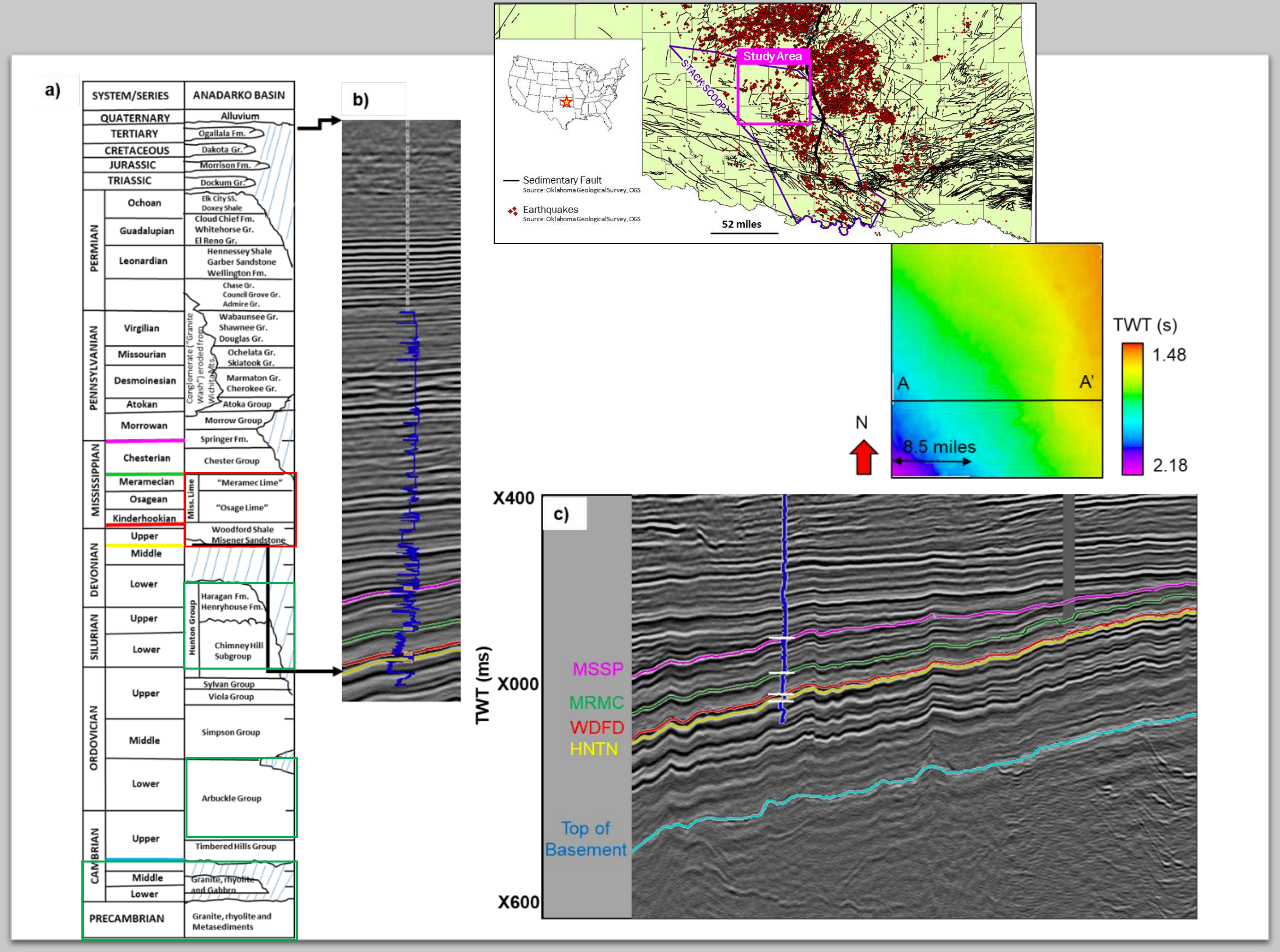
Skoumal et al., 2018

3D seismic data and earthquakes

Target formation for unconventional exploitation: Mississippian Woodford and Meramec

Fracture mapping: Woodford/Meramec, Hunton Group, Arbuckle Group (wastewater injection layer in Oklahoma), Top of basement

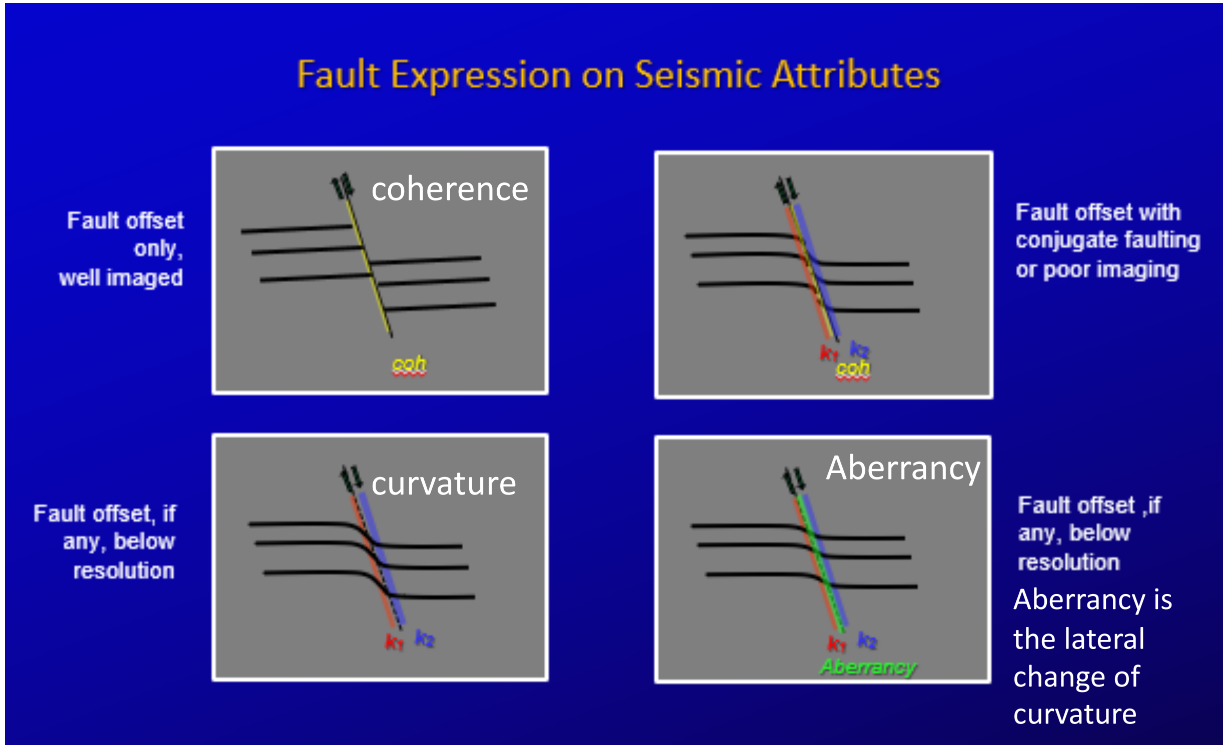
Earthquakes: From OGS catalog, correlate with mapped faults.

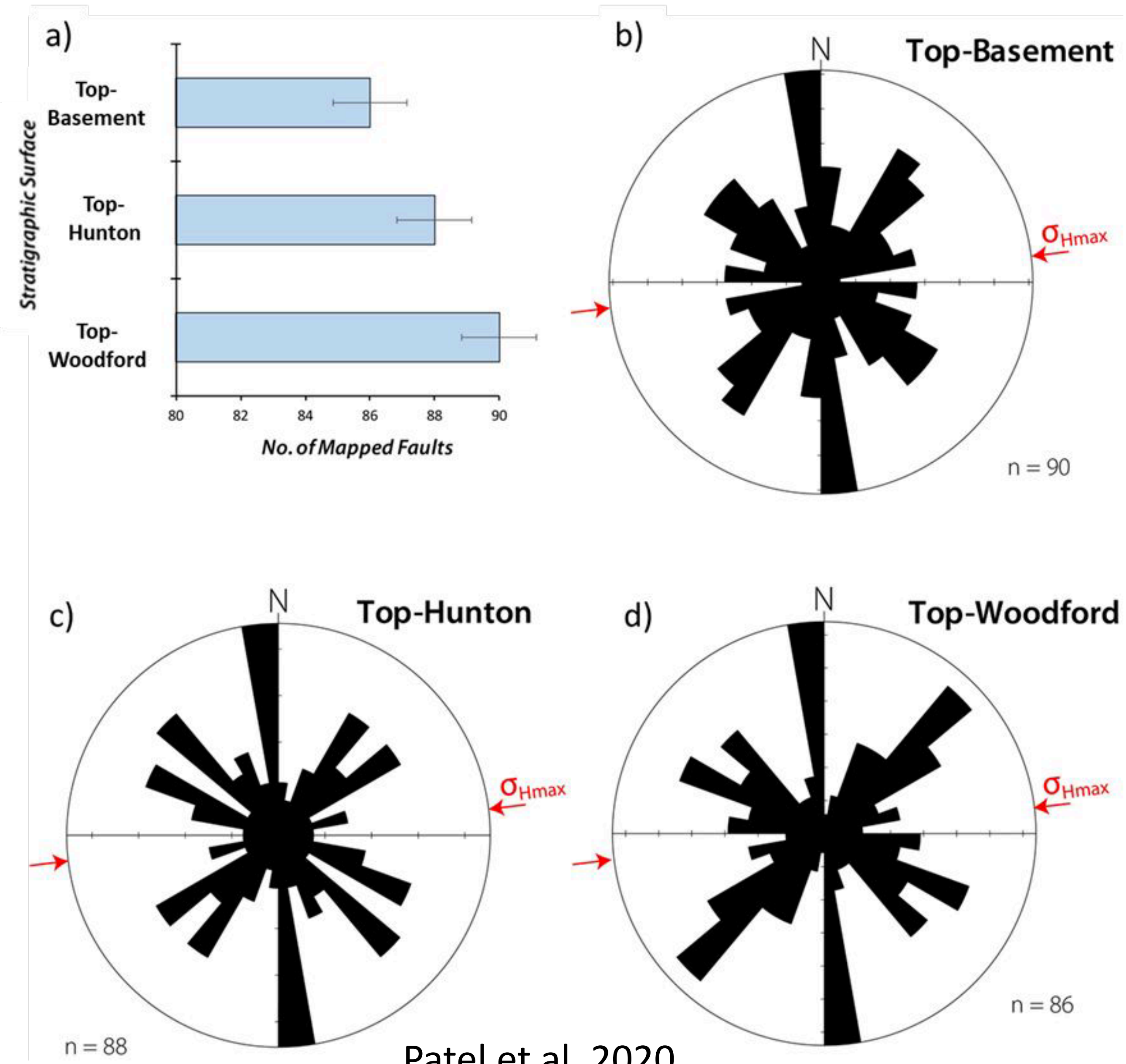


Patel et al, 2020

Seismic attribute analysis

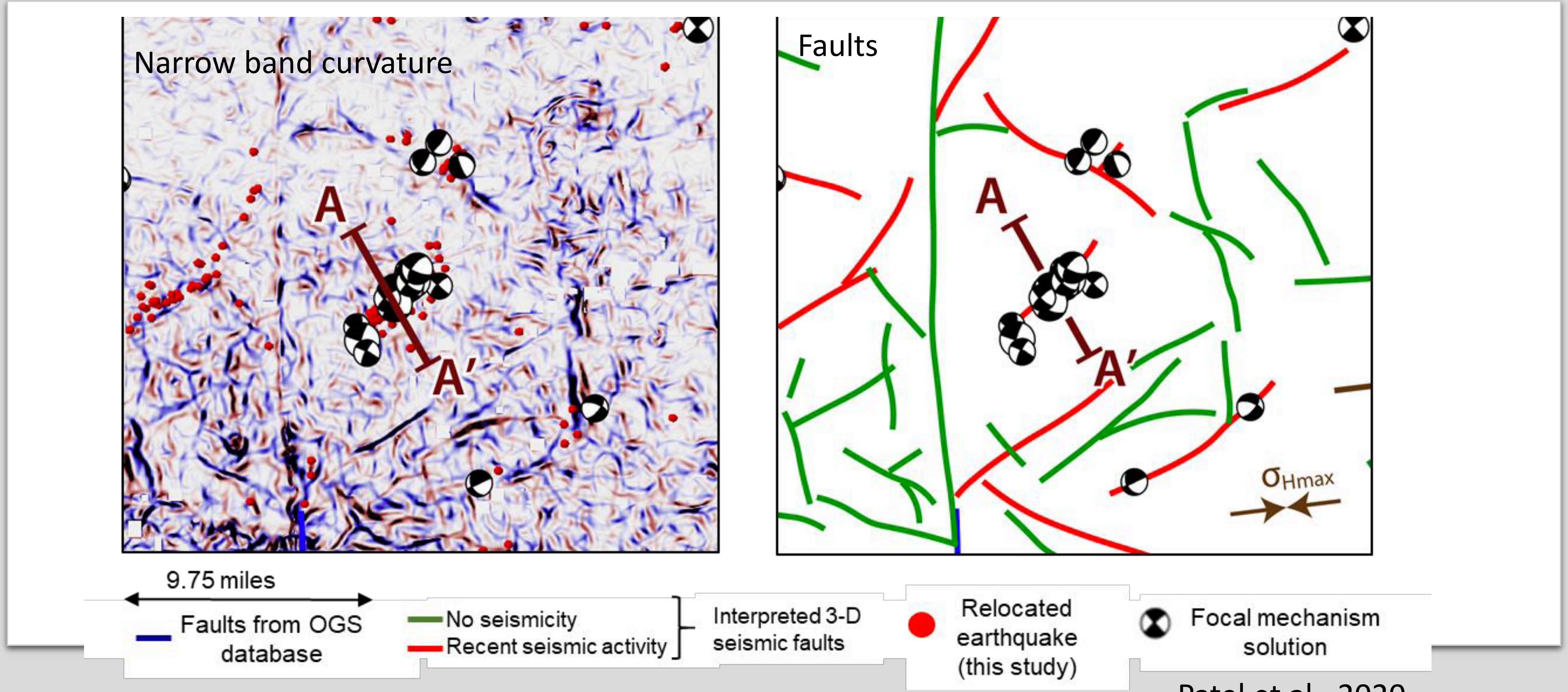
- Using bandlimited analysis for seismic data: 30-55 Hz.
- Aberrancy and Curvature best illuminate basement rooted faults
- N-S, NW and NE trending faults extend from the basement to shallower sediment layers Hunton and Woodford formations.





Patel et al, 2020

Curvature attribute illuminates lineaments that host earthquakes, reveals more faults than OGS fault database.



Patel et al., 2020

Summary of wastewater disposal and hydraulic fracturing

- Large-scale long-range triggering is facilitated by high diffusivity in the Arbuckle group where wastewater disposal occurred.
- Hydraulic fracturing operation has narrower space influence windows than wastewater disposal wells.
- Oklahoma basement rock behaves similarly to crystalline basement in other tectonically active regions in terms of seismicity clustering.
- Fluid injection may influence earthquake source parameters during fault activation.

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THANK YOU!

QUESTIONS?