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Large-Scale Migration Patterns of Wastewater-Induced Earthquakes in the Central U.S

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Observed Seismicity Patterns

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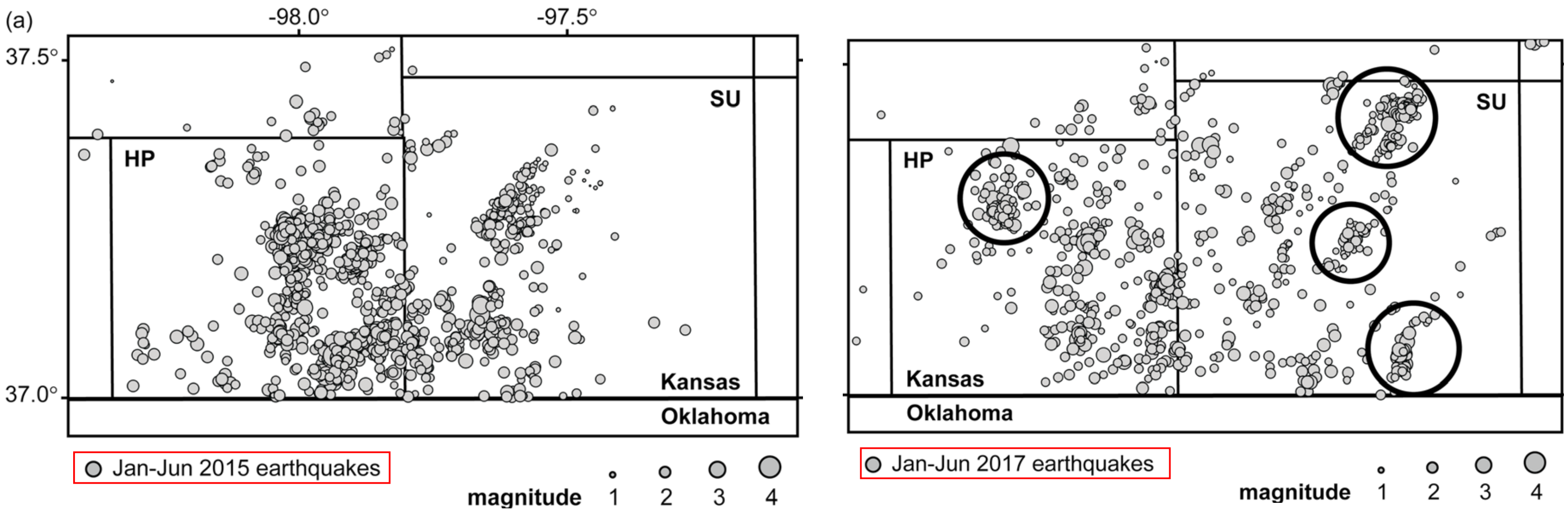

1. Migration of seismically active zone towards the north-east

Peterie et al., 2018

Observed Seismicity Patterns

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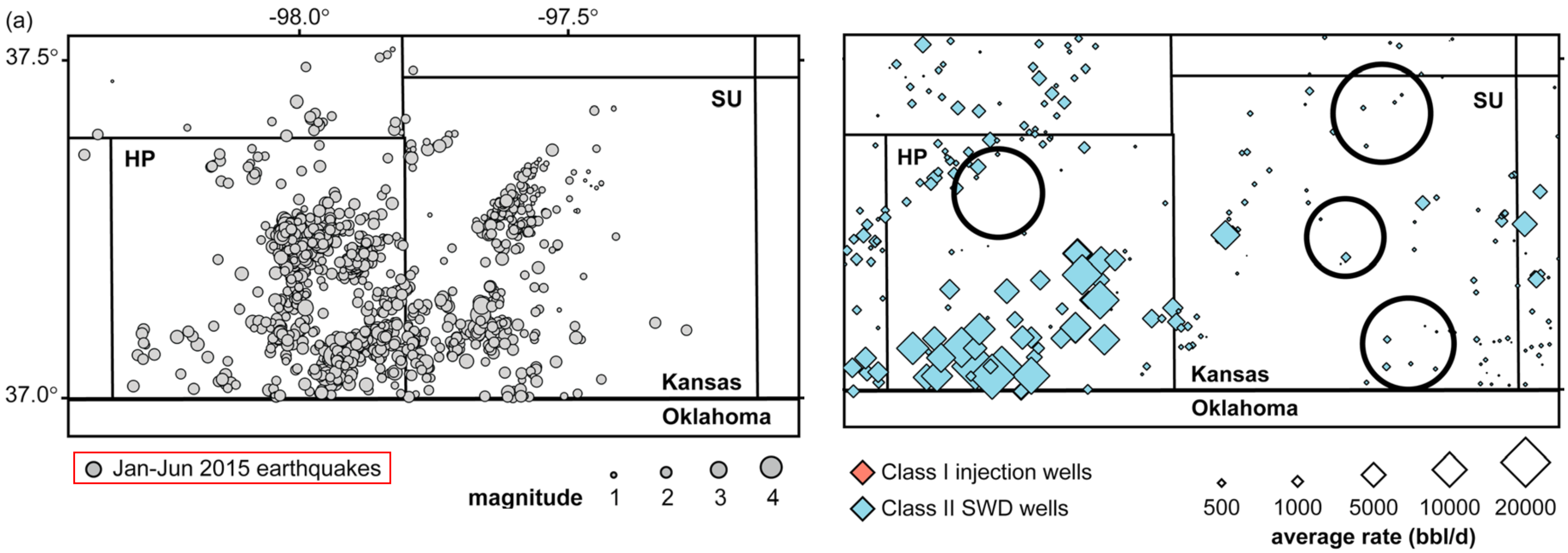


2. Earthquakes occur far from disposal wells

Peterie et al., 2018

Aims

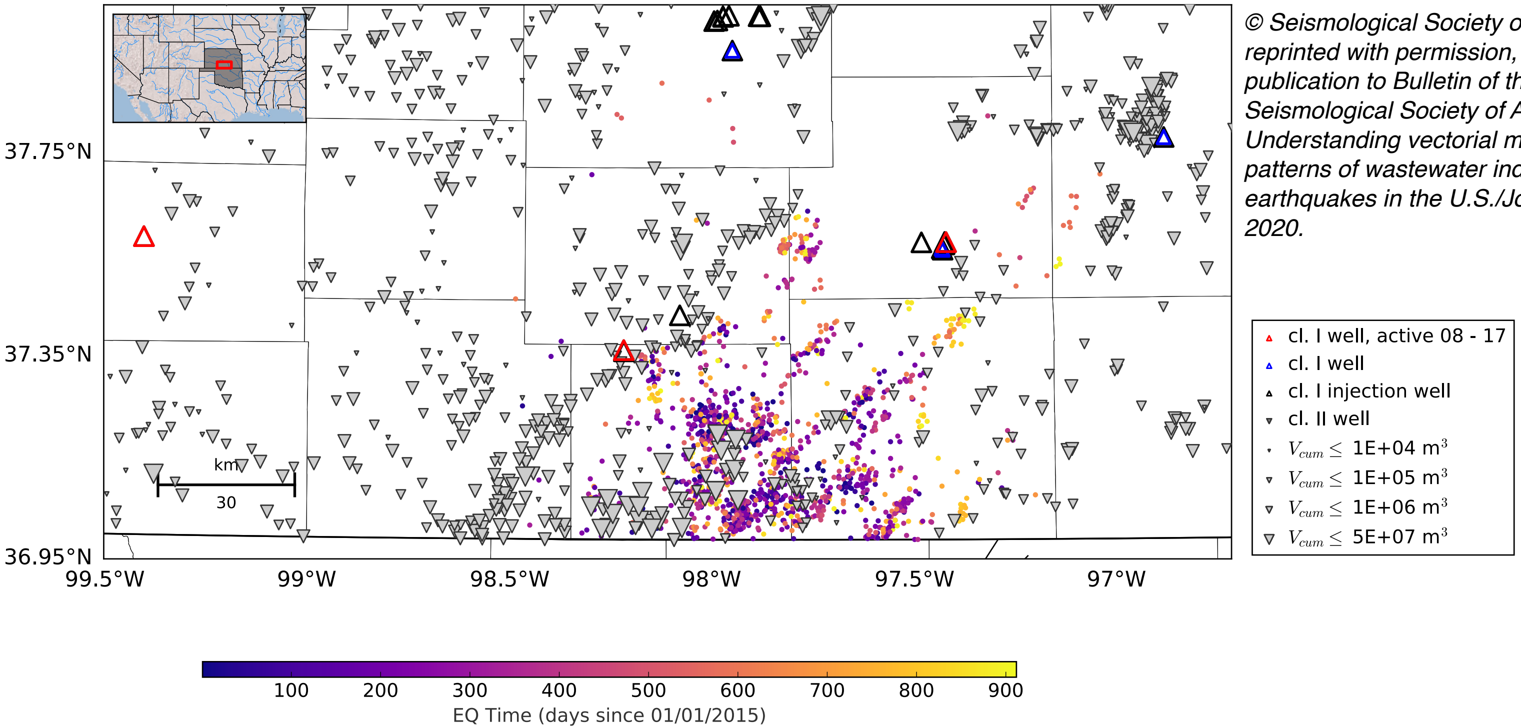
What is the spatio-temporal relation between the large-scale wastewater disposal and earthquake locations?

Can we numerical resolve and explain the observed features?

Which mechanisms and parameters control the seismicity and its propagation towards the NE?

Cross-Correlation

What is the spatio-temporal relation between the large-scale wastewater disposal and earthquake locations?



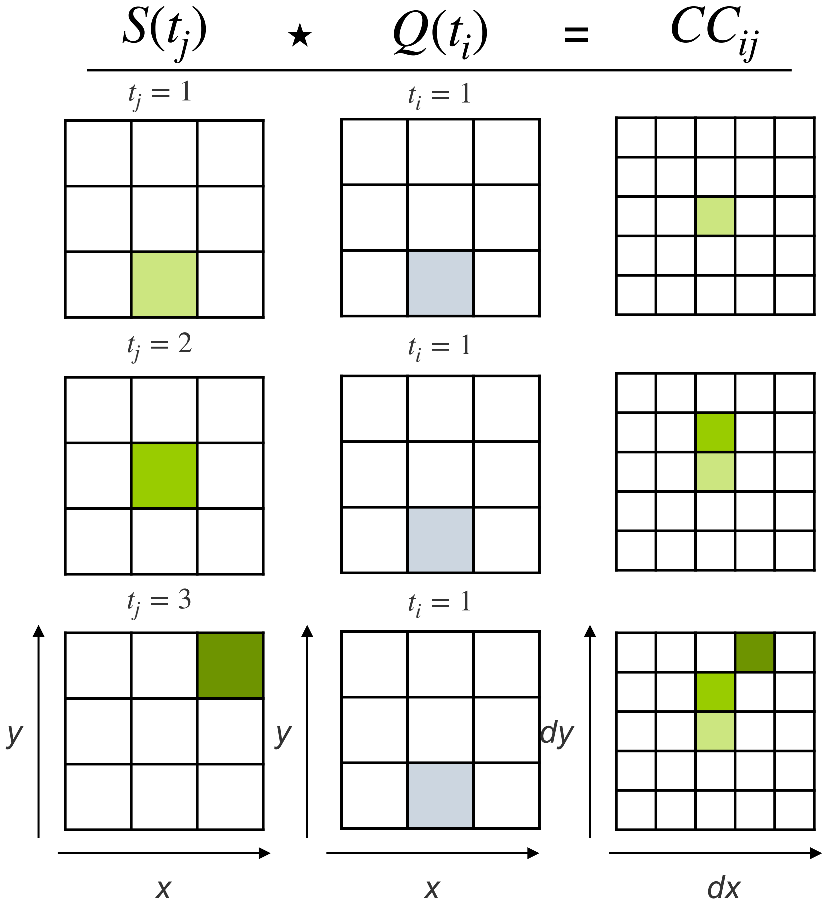
Study area: 37.0°N to 38.0°N, 96.7°W to 99.5°W & **time interval:** 01/2015 - 06/2017

Wastewater disposal data: class I wells (Ansari et al., 2019) & class II wells (by Kansas Corporation Commission)

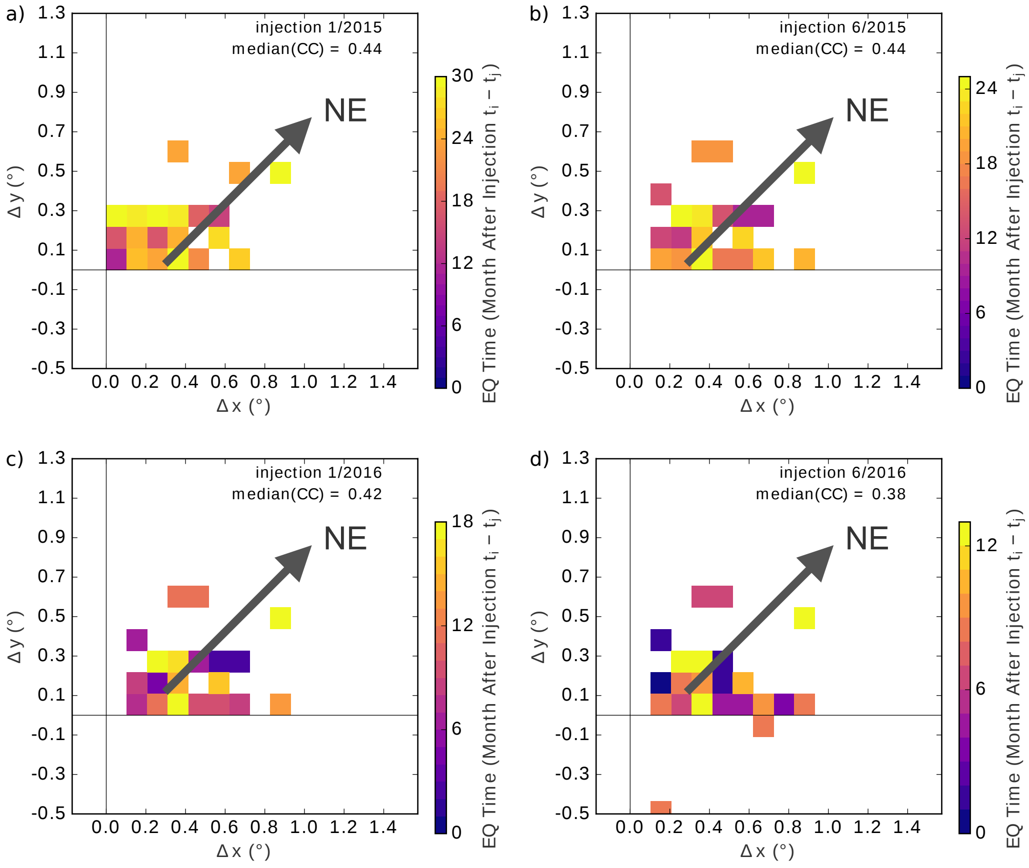
Earthquake catalog: relocated events by Peterie et al., 2018 → remove fore- & aftershocks by declustering (Urhammer, 1986) → use earthquakes with magnitude $M \geq M_c$

Cross-Correlation: **Method**

1. gridding of disposal volumes and earthquakes on 0.1° x 0.1° grids
2. correlate grids for one month of injection data $Q(t_i)$ (middle panels) with grids of earthquake data $S(t_j)$ (left panels) for months $t_j \geq t_i$
3. for each correlation month t_j: select cells with a correlation coefficient $CC_{ij} \geq 0.8 CC_{ij,max}$ and color-code them according to the time delay $\Delta t = t_j - t_i$ (right panel)



Cross-Correlation: **Results**

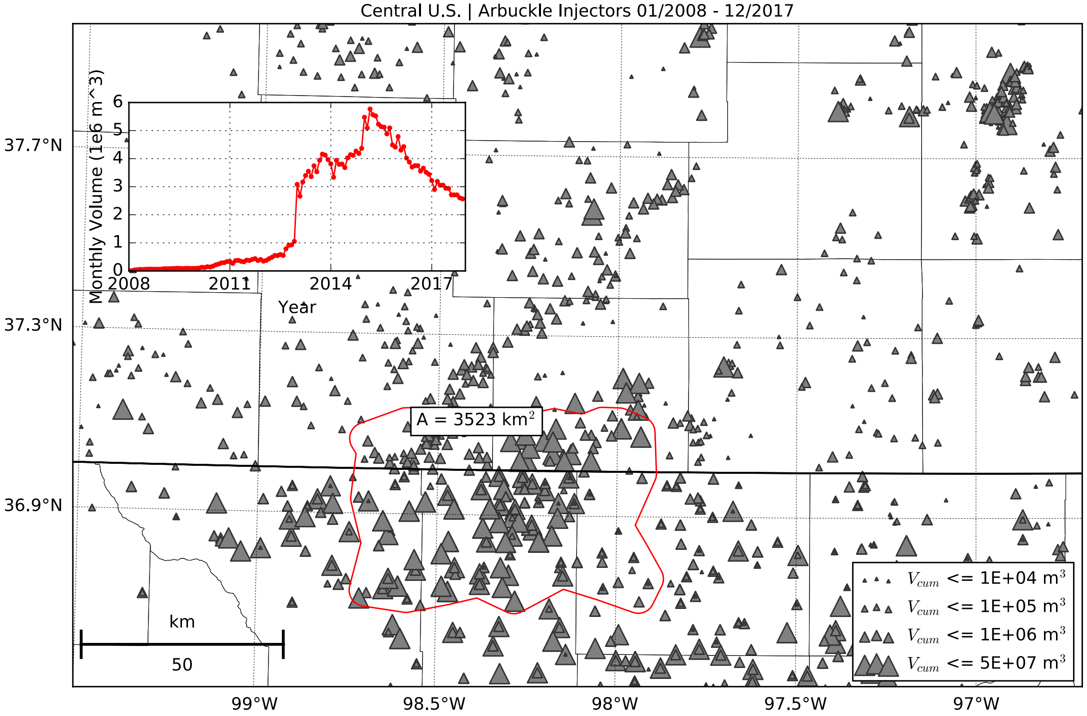


Earthquakes preferably occur towards the NE of disposal wells

Numerical Model

Can we numerical resolve and explain the observed features?

Which mechanisms and parameters control the seismicity and its propagation towards the NE?



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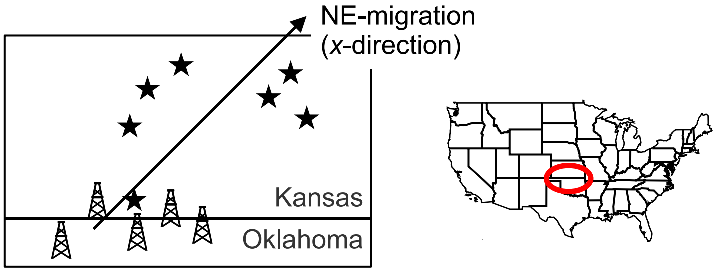
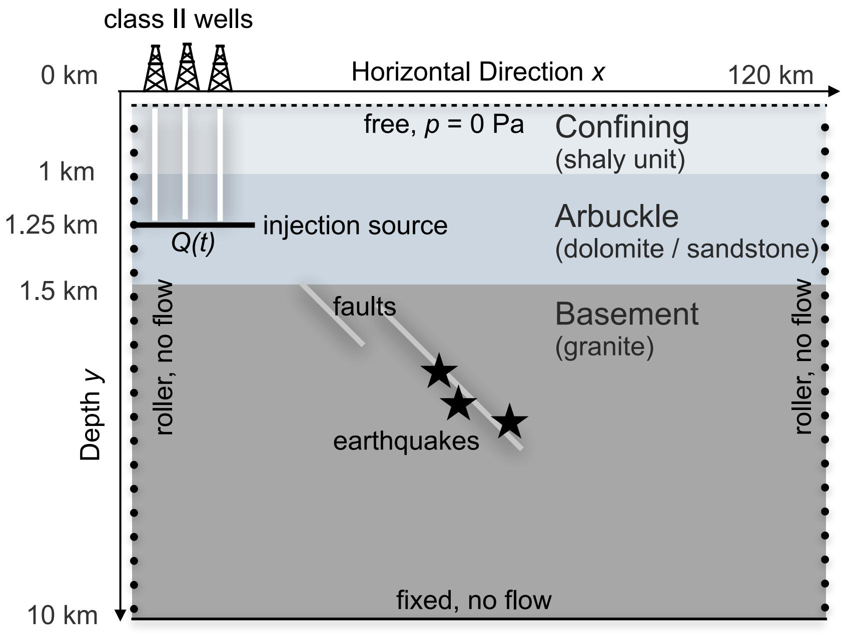
Study area: large volume injection area across northern Oklahoma and southern Kansas

Wastewater disposal data: 01/2008 - 12/2017, class II wells (by Kansas and Oklahoma Corporation Commissions)

Numerical Model: Method

- 2D plain strain model in Comsol Multiphysics®, **solving for pressure and poroelastic stress changes**
- model time 01/2008 to 01/2020
- (horizontal) *x*-axis aligned with the approximated direction of main fault structures (e.g. Schoenball & Ellsworth, 2017) and the direction of earthquake migration (from cross-correlation)
- (vertical) *y*-axis aligned with depth below the surface
- injection source at 1.25 km depth, defined by cumulative monthly disposal rate in the large volume injection area
- basement permeabilities: 0.1 mD, **1mD**, 10 mD (e.g. Rothert & Shapiro, 2007)
- Arbuckle permeability: 100 mD





Numerical Model: Pressure Changes

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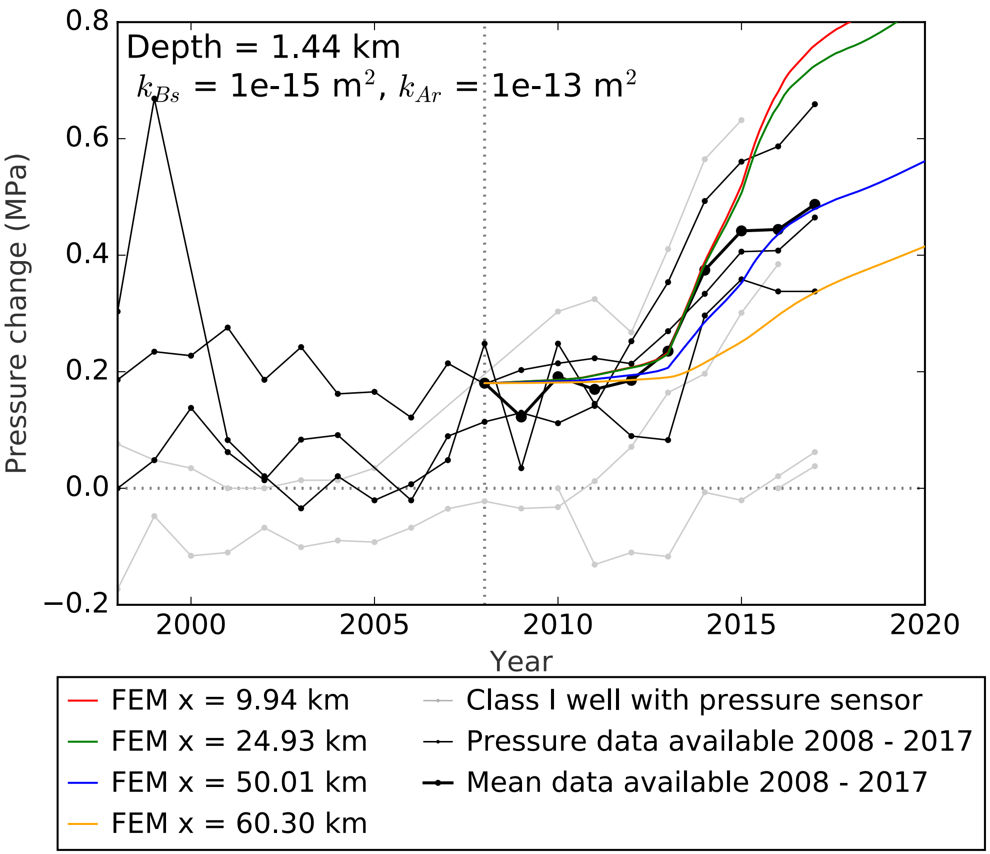
Observation (Ansari et al., 2019):

Distinct pore-pressure increase in the Arbuckle formation at several class I disposal wells.

Mean pressure increase between 01/2008 and 12/2017 from 0.2 to 0.5 MPa (bold black line).

Numerical Model:

Resolved the pressure increase throughout the horizontal extend of the FEM (different colours)



Numerical Model: Stress Changes

Calculate poroelastic stress changes (e.g. Shapiro, 2015):

$$\boxed{\Delta FCS = 0.5\Delta\sigma_d - \sin\varphi\left(\Delta\sigma_m - \Delta p\right)}$$

A preferably oriented, critically stressed fault is destabilised, if:

$$\Delta FCS \geq 0$$

Faults exist which have critical fault strength *C*, uniformly distributed between C_{min} and C_{max}. Shear slip along these faults occurs, if:

$$\boxed{C_{min} \leq \Delta FCS \leq C_{max}}$$

$\Delta\sigma_1 > \Delta\sigma_2 > \Delta\sigma_3$	stress changes in principal stress change direction
$\Delta\sigma_d = \Delta\sigma_1 - \Delta\sigma_3$	differential stress change
$\Delta\sigma_m = 0.5\left(\Delta\sigma_1 + \Delta\sigma_3\right)$	mean stress change

(e.g. Rothert & Shapiro, 2007)

Numerical Model: Stress Changes

The *spatial integral of the stress change rate*:

$$\int_{x_0}^{x_1}\int_{y_0}^{y_1} \Delta \dot{F}CS dz dx$$

x_0, x_1: horizontal model extend

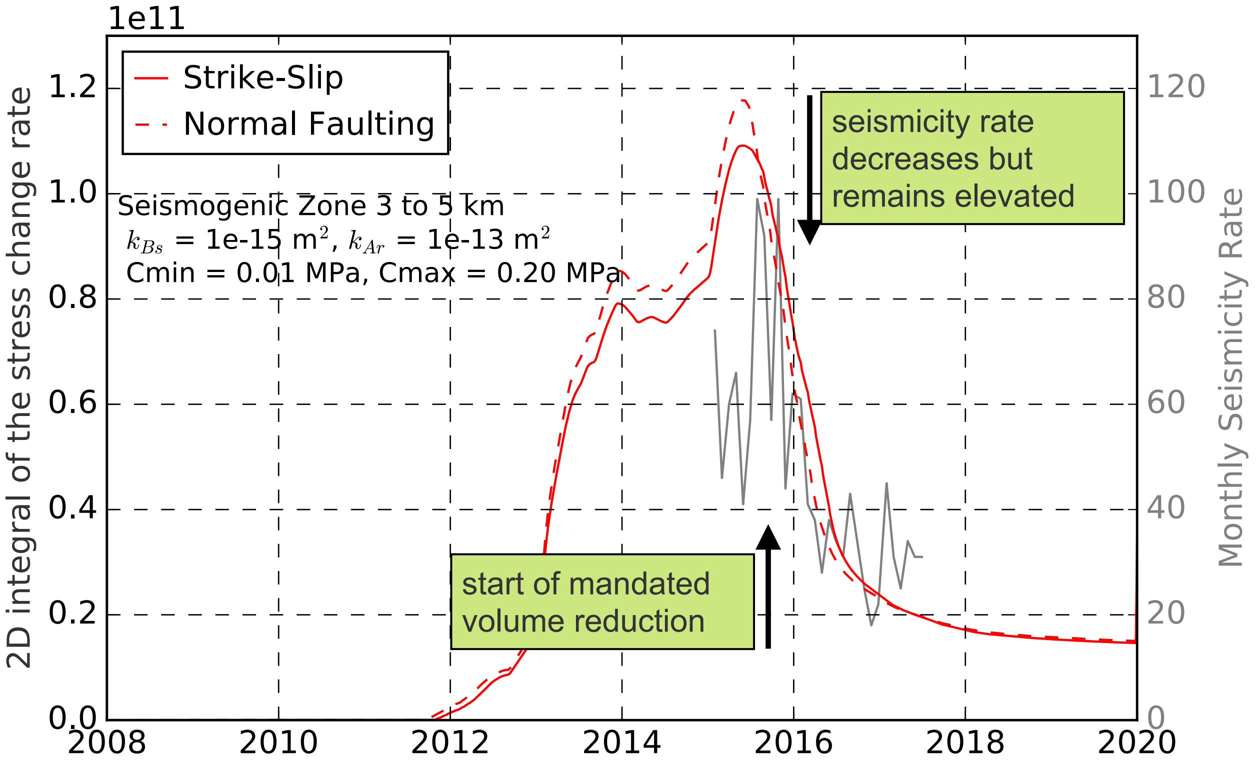
y_0, y_1: seismogenic depth

Only consider values

$$\Delta FCS \geq C_{min} = 0.01 \text{ MPa}$$

$$\Delta FCS \leq C_{max} = 0.2 \text{ MPa}$$

This integral is proportional to the rate of induced events!



Conclusions

- Time-dependent 2D cross-correlation resolved the spatio-temporal relation between wastewater disposal wells and earthquakes in Kansas
  - directional pattern of earthquakes with respect to wells towards east-northeast
  - probably caused by a large-scale permeability anisotropy in the seismogenic basement due to pre-existing faults
- FEM demonstrates that the earthquake occurrences are most probably due to pore-pressure and poroelastic stress changes in the Arbuckle (injection) formation and the crystalline (seismogenic) basement
- The spatial integral of the stress change rate is a valuable tool to reconstruct the observed seismicity rate
- Earthquakes are probable also in times of declining disposal volumes!

References

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