Analysis of injection data for pore pressure and minimum horizontal stress magnitude estimates in the Arbuckle Formation

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1. Seismicity in Oklahoma

The increase in seismicity in Oklahoma, which has been seismically relatively quiet before 2009, is considered to result from minor pore pressure increase due to huge waste water injection into the highly permeable Arbuckle formation, which caused the reactivation of basement faults. Fig. 1 shows the stress regimes and orientation of faults.

For critically stressed faults and hydrostatic pore pressure in the Arbuckle, existing numerical models show, that small pressure perturbations already lead to seismicity (e.g., Goebel et al., 2017; Keranen et al., 2014; Schoenball et al., 2018). Furthermore, the assumption of nearly critically stressed faults is somewhat contradictory to the low seismicity before wastewater injection. Additionally there are also regions with massive injection and faults optimally oriented for reactivation but without seismicity (Figs. 1, 3a, 3b).

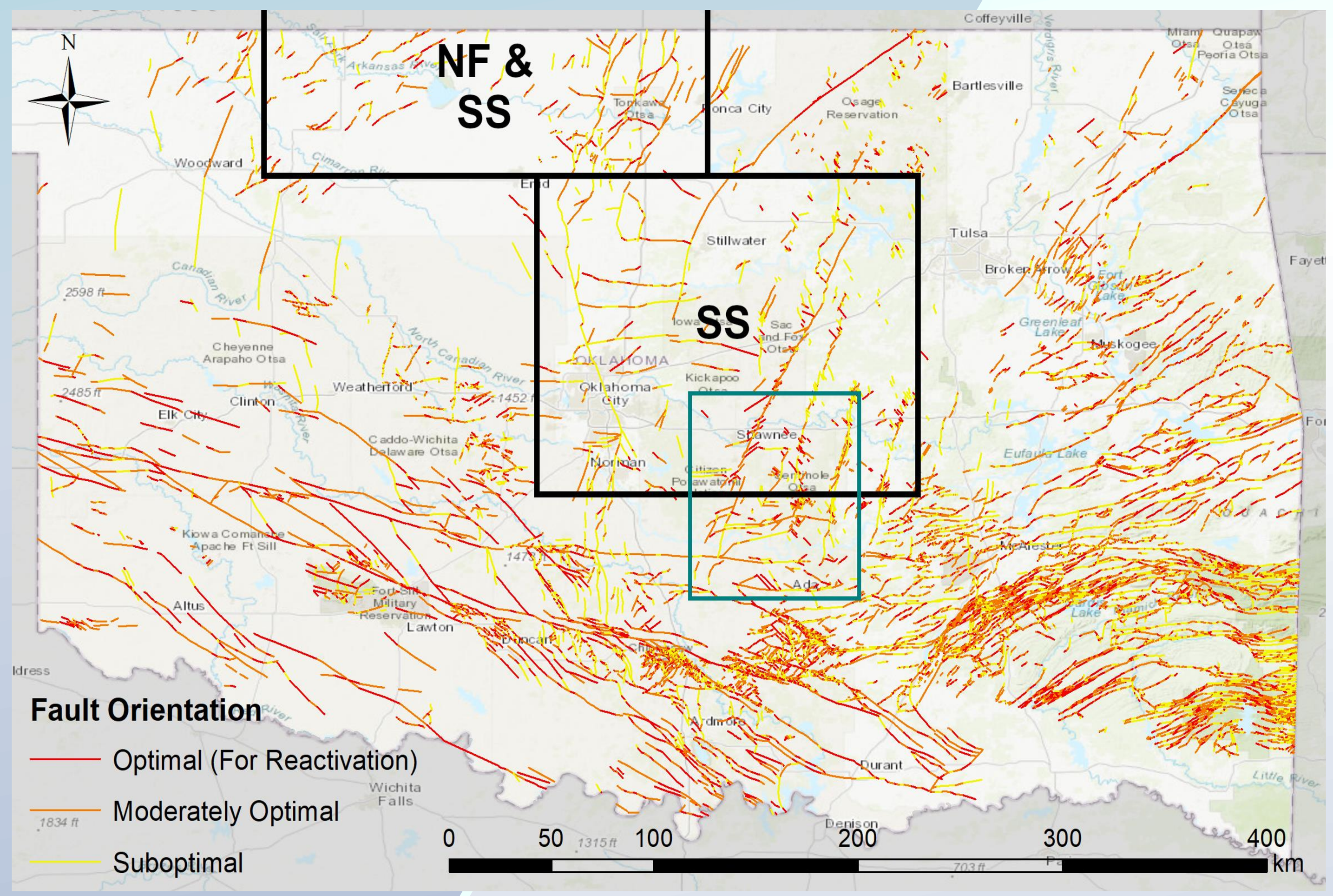

Fig. 1 Fault orientations regarding reactivation (Darold & Holland, 2015) and stress regimes in Oklahoma (Alt & Zoback, 2017; Schwab, 2016; McNamara et al., 2015). NF = Normal Faulting, SS = Strike Slip. Area of Investigation is indicated by the green box.

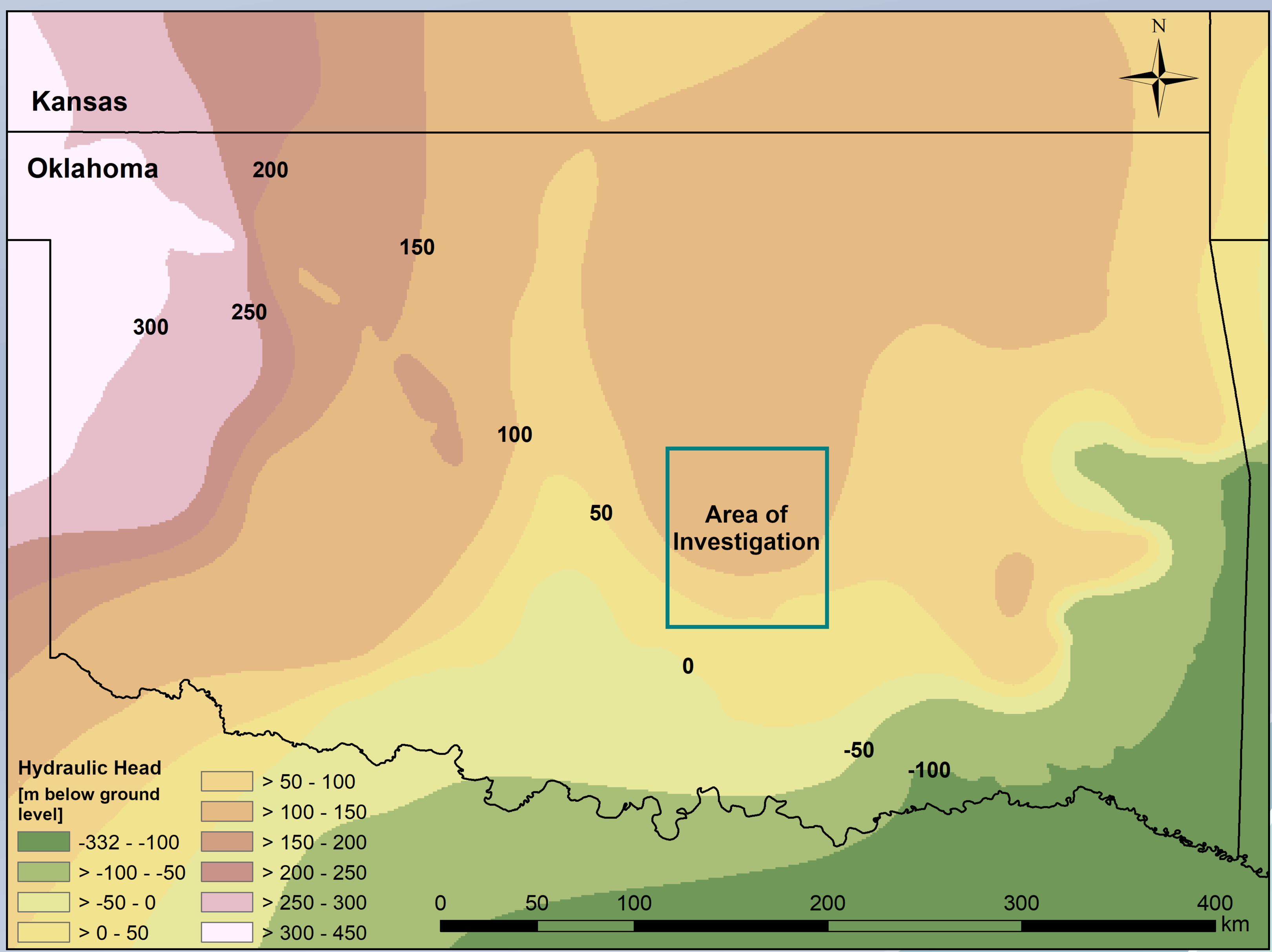

Fig. 2: Interpolated hydraulic head of the Arbuckle Formation in m below surface. Numbers in the map area mark isolines. Original isolines from Nelson et al. (2015).

2. Area of Invastigation

In the area of investigation the induced seismicity was beginning in 2011 in the north and is still lacking in the south. Average annual injection rates of 87 wells have been used to calculate the stress changes from pore pressure variations (Fig. 3c). The calculated stress-differences have been added to the initial stress state to obtain the spatio-temporal evolution of DMF (distance of Mohr circle to failure) (Fig. 4).

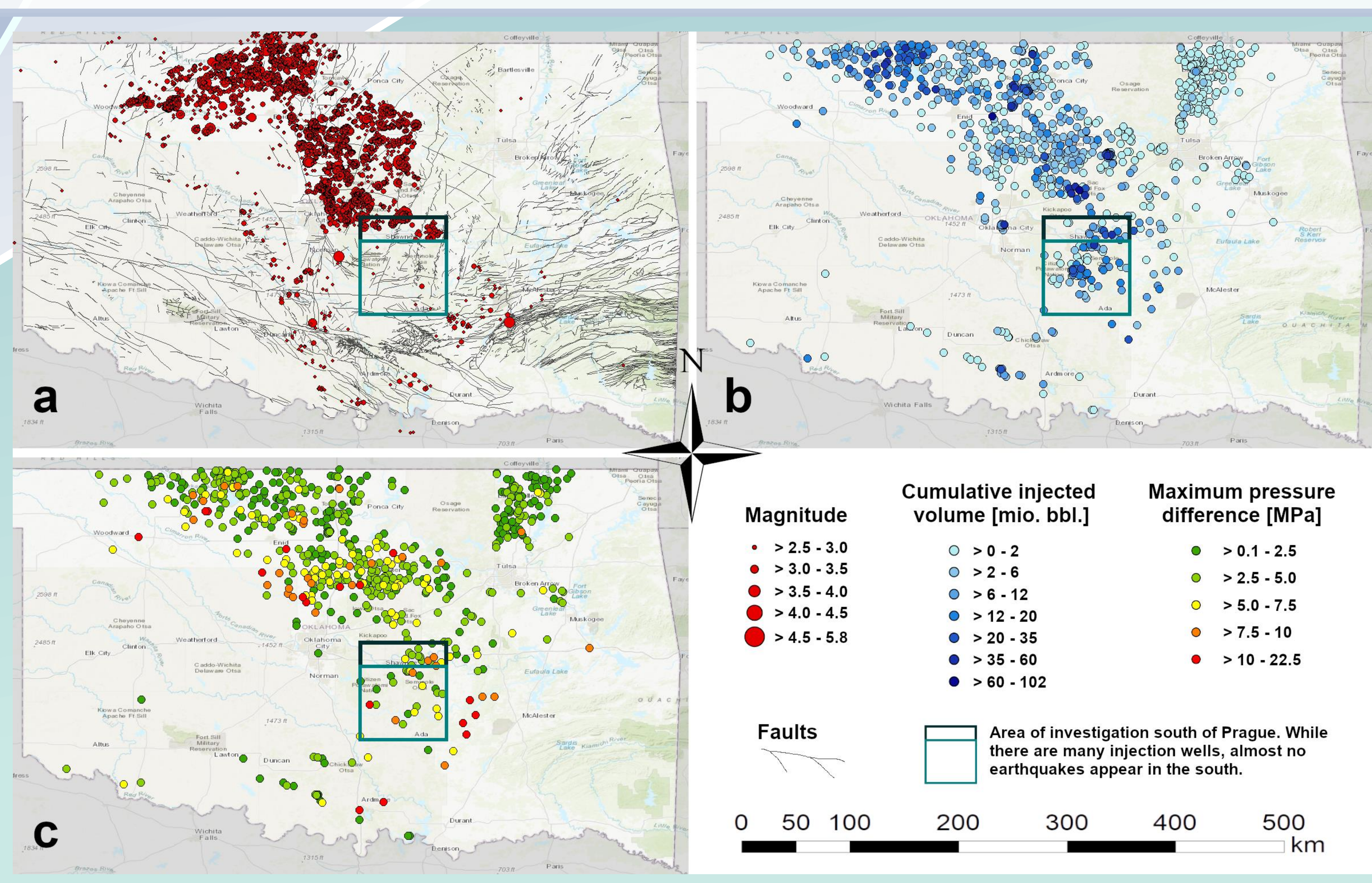

Fig. 3: Earthquakes, cumulative injected volume and maximum pressure differences between undisturbed pore pressure at injection depth and maximum bottomhole pressure directly at the well location. All values were calculated for the years 2006 - 2016. Earthquakes (2009 - 2016) from USGS (n.d.), Faults from Darold & Holland (2015), Injection data from OCC (n.d.).

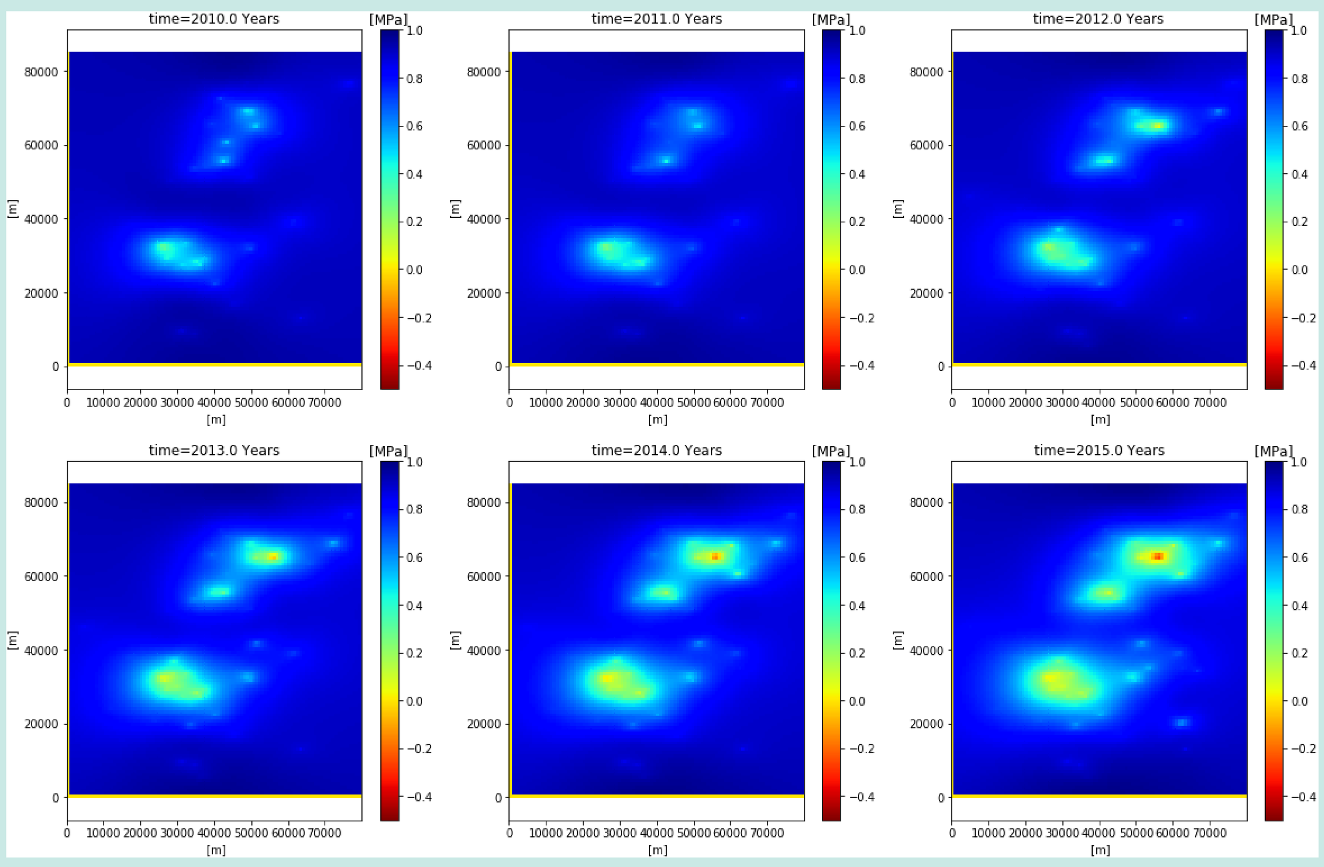

Fig. 4: DMF distribution for the area of investigation. The negative DMF values in the north point to induced seismicity. In the south the likelihood for fault reactivation is lower. Both correspond to the observations.

3. Assumptions

We considered the state of stress and pore pressure (hydraulic heads) of the Arbuckle:

- S_H-azimuth is N85°E (Alt & Zoback, 2017).
- While stress magnitude data are rare, the seismicity shows strike slip faulting (SS) in S-Oklahoma and SS and normal faulting (NF) in the north, indicating S_H-magnitude ≅ S_V-magnitude.
- From injection pressures, we derived minimum values of the S_h gradient of 12.0 - 12.9 MPa/km. The S_V-gradient is ca. 24.7 MPa/km. For the following we assume that the S_H-gradient is slightly larger.
- We assumed cohesionless faults with a coefficient of friction of 1.0 which results from a step rate test at KGS 1-32 well in Kansas (Schwab, 2016).
- The Arbuckle is mostly underpressured. We analyzed injection pressures, pore pressures and hydraulic heads in 955 wastewater disposal wells.
- Hydraulic heads of the Arbuckle can reduce the pore pressure and increase effective stresses, leading to less critically stressed faults (Fig. 2) compared to hydrostatic conditions.
- The differences between undisturbed pore pressures and injection pressures (wellhead pressure + additional water column pressure) are partly larger than 2.5 MPa and may locally reach even more than 10 MPa (Fig. 3).

4. Conclusions

The results show that the onset of seismicity in the north is around 2012 whereas the optimally oriented faults in the south are less likely to be reactivated.
The spatiotemporal distribution of induced seismicity in the area of investigation can be explained by the reactivation of faults due to massive wastewater injection by pore pressure stress coupling without the prerequisite of naturally critically stressed faults.

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