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

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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 the orientation of faults. Faults optimally oriented for reactivation are marked in red.

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, 7a, 7b).

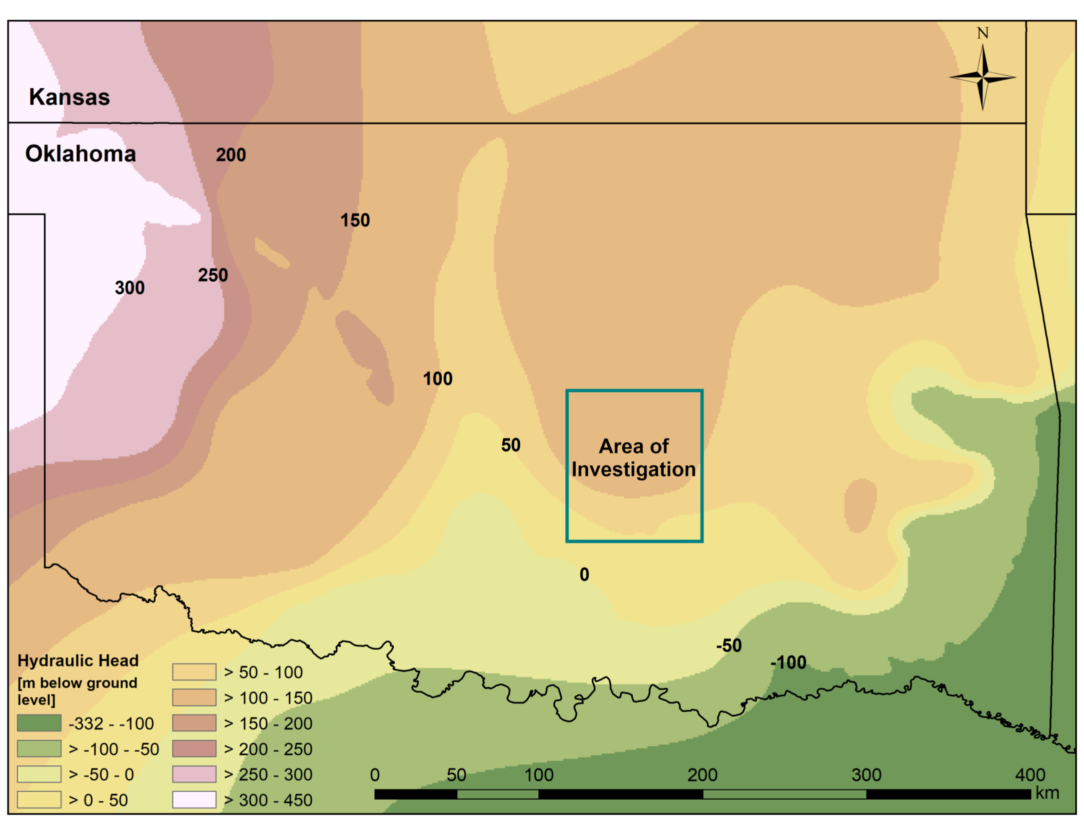

Fig. 3: Interpolated hydraulic head of the Arbuckle Formation in m below surface. Numbers in the map area mark isolines. Original isolines from Nelson et al. (2015).

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. 7c). The calculated stress-differences have been added to the initial stress state (Fig. 4) to obtain the spatio-temporal evolution of DMF (Figs. 5, 6).

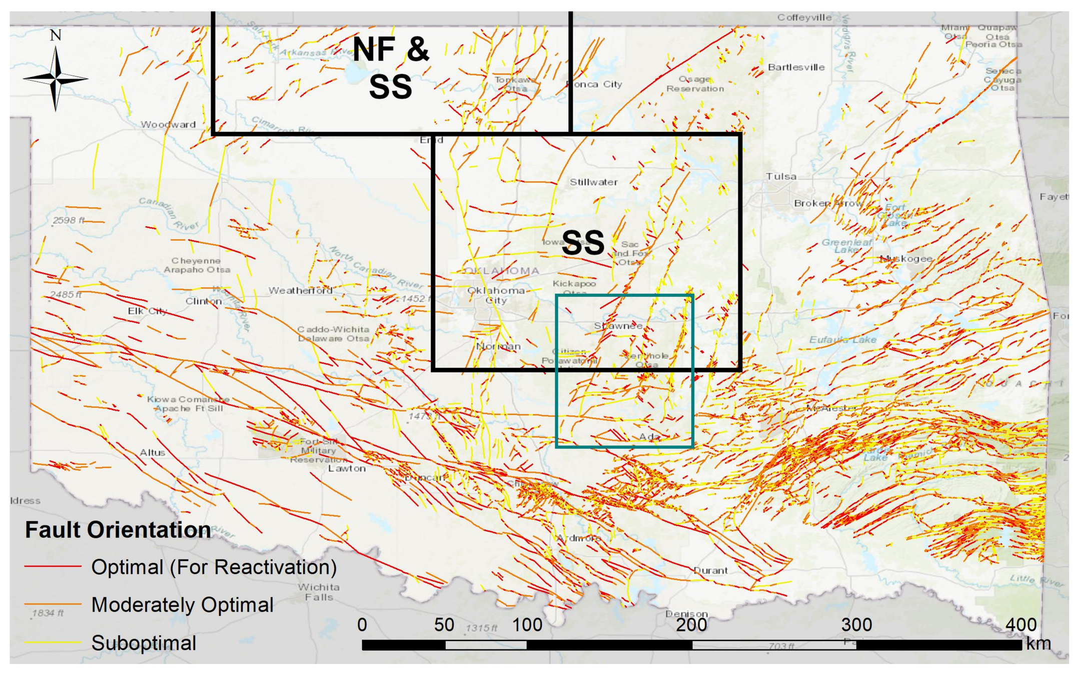

Fig. 1: Fault orientations regarding reactivation (Darold & Holland, 2015) and stress regimes in Oklahoma (Alt & Zoback, 2017; Schwab, 2016; McNamara et al., 2015). NF = Normal Faulting, SS = Strike Slip. Area of Investigation is indicated by the green box.

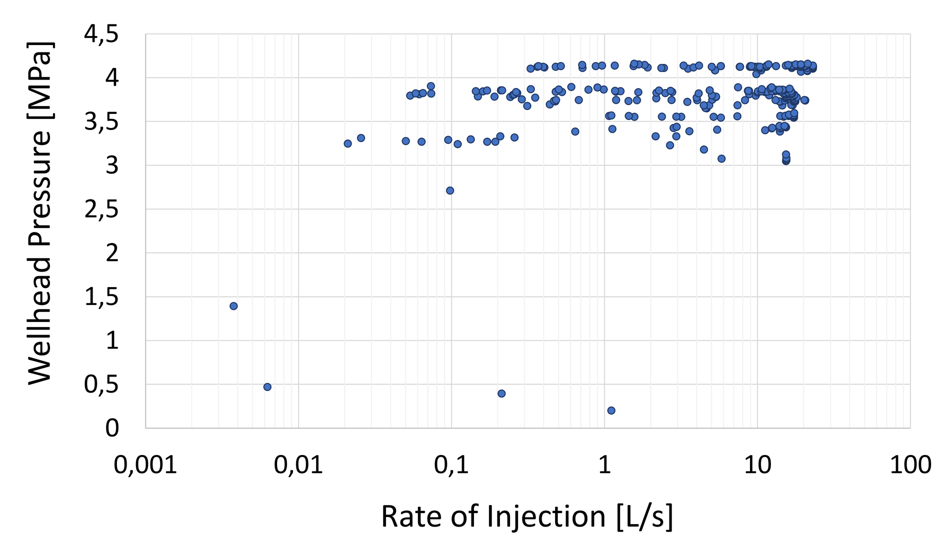

Fig. 2: Wellhead pressure and rate of injection for the Adkisson 1-33 well. The maximum wellhead pressure reached + the water column in the well could be equivalent to S_h.

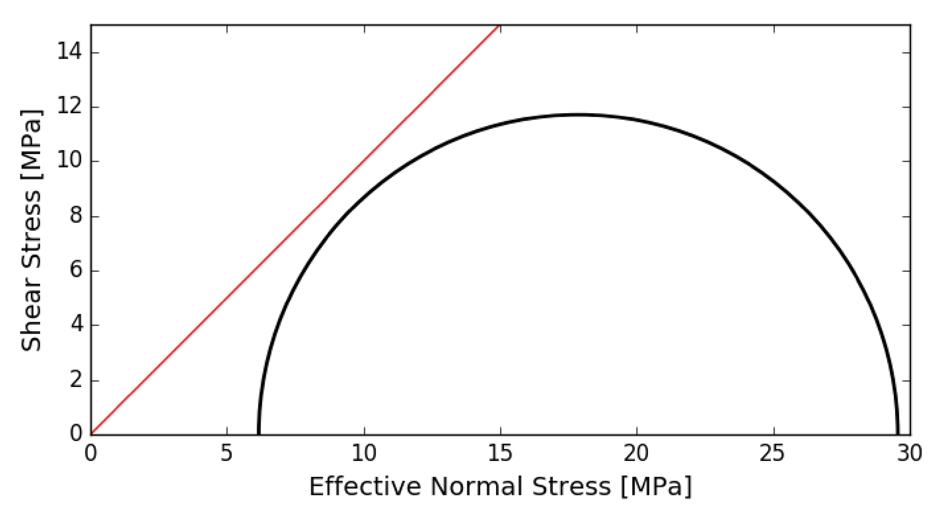

Fig. 4 : Mohr Circle for S_{Hgrad} = 24.7 MPa/km, S_{hgrad} = 13 MPa/km, hydraulic head = -50 m, depth = 2 km.

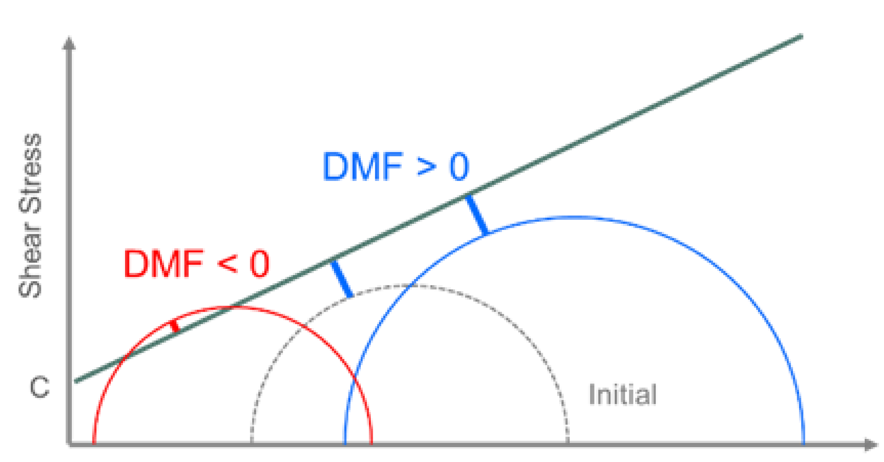

*Fig. 5: DMF assignment: If the **d**istance to the **M**ohr Circle to the **f**ailure (or reactivation) envelope (DMF) is >0 faults are not reactivated. If the state of stress exceeds the failure envelope (DMF <0) optimally oriented faults can be reactivated.*

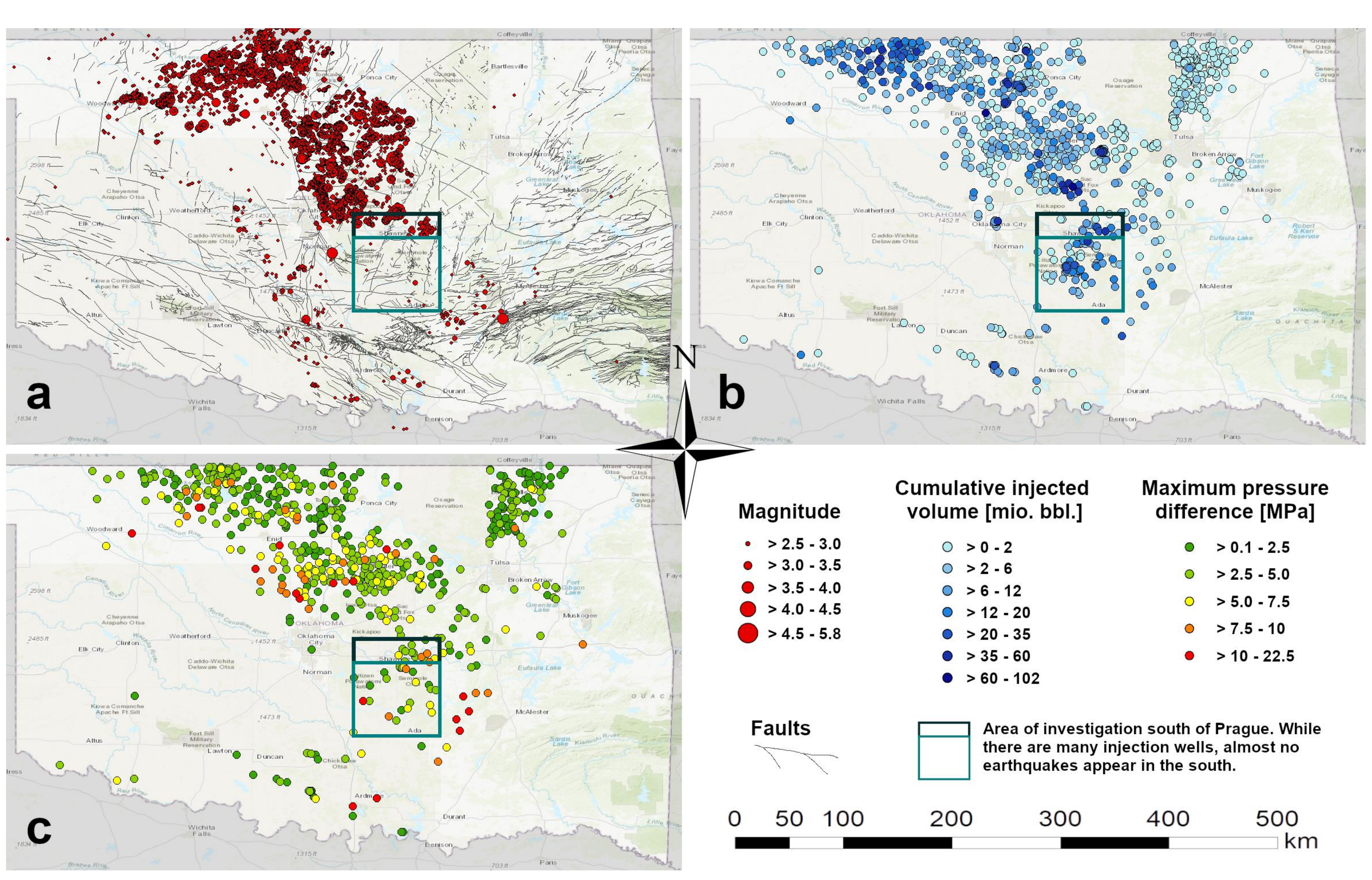

Fig. 7: Earthquakes, cumulative injected volume and maximum pressure differences between undisturbed pore pressure at injection depth and maximum bottomhole pressure directly at the well location. All values were calculated for the years 2006 - 2016. Earthquakes (2009 - 2016) from USGS (n.d.), Faults from Darold & Holland (2015), Injection data from OCC (n.d.).

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

- S_H orientations are well known (Alt & Zoback, 2017) with a N85°E S_H-azimuth.
- Magnitude data are rare. Relative stress magnitudes can be derived from the style of faulting. 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.
- To estimate S_h-magnitudes we analyzed injection pressures in 15 wells and derived minimum values of the S_h gradient of 12.0 - 12.9 MPa/km (Fig. 2). 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).
- For the calculation of effective stresses a Biot coefficient of 0.96 was assumed.
- 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 (Figs. 3, 4) compared to hydrostatic conditions.
- The differences between undisturbed pore pressures and injection pressures (wellhead pressure + pressure of water column between water table of aquifer and topographic surface) are partly larger than 2.5 MPa and may locally reach even more than 10 MPa (Fig. 6).

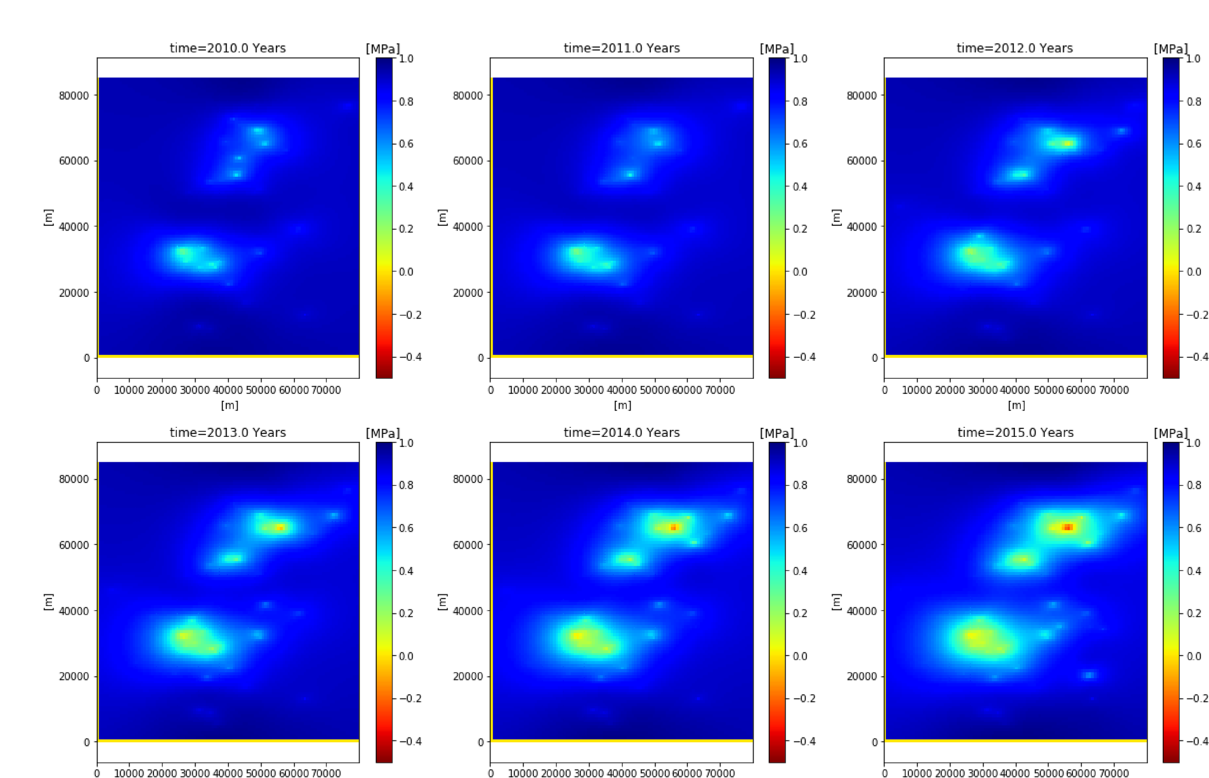

Fig. 6: DMF (Fig. 5) distribution for the area of investigation. The negative DMF values in the north point to induced seismity. In the South the likelihood for fault reactivation is smaller. Both correspond to the observations.

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.

Conclusion:
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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