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Induced seismicity in geothermal plays

An evaluation of the variation in fault strength in sandstone reservoirs

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Introduction

Geothermal energy extracted from the Earth's subsurface is a promising technique for obtaining sustainable energy. Current heat production in the Netherlands occurs through the circulation of fluids between two wells in deep (~1.5-3 km) porous reservoirs with a temperature of up to ~100 ºC (Figure 1).

Safe production of geothermal energy requires an evaluation of the risk of inducing earthquakes, resulting from changes in stress that cause fault reactivation (Figure 2). However, fault strength is poorly constrained due to a limited knowledge of the processes that control its evolution in the millions of years after tectonic motion has stopped. Cohesion, one of the fault strength parameters, is particularly poorly constrained due to the difficulty in reproducing the relevant processes on laboratory time-scales. Here, we show first results of experiments aimed at evaluating the contribution of cohesion to fault strength for faults within the Rotliegend and Schieland sandstone reservoirs (Figure 3).

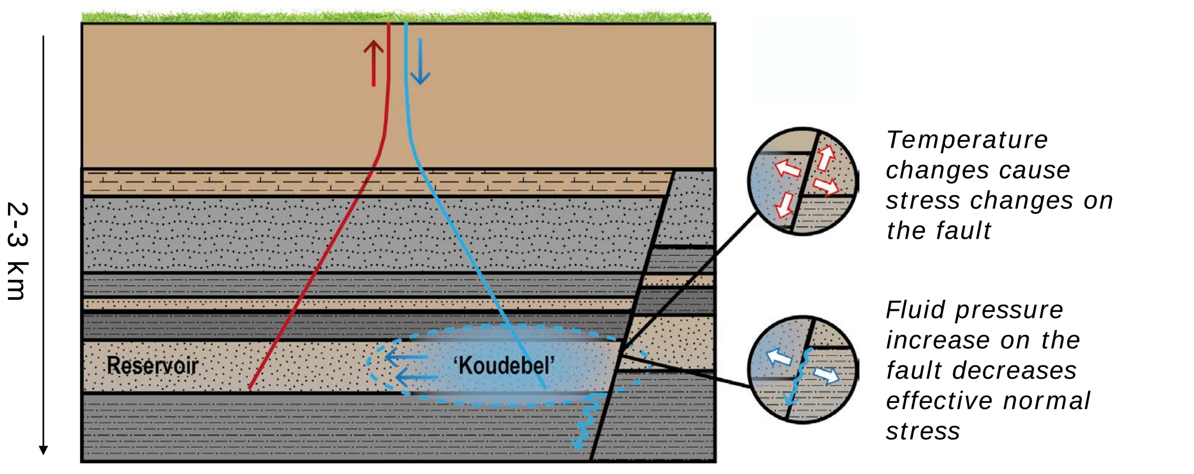


Figure 1: Diagram illustrating the principle of geothermal energy production and two mechanisms to potentially reactivate pre-existing faults

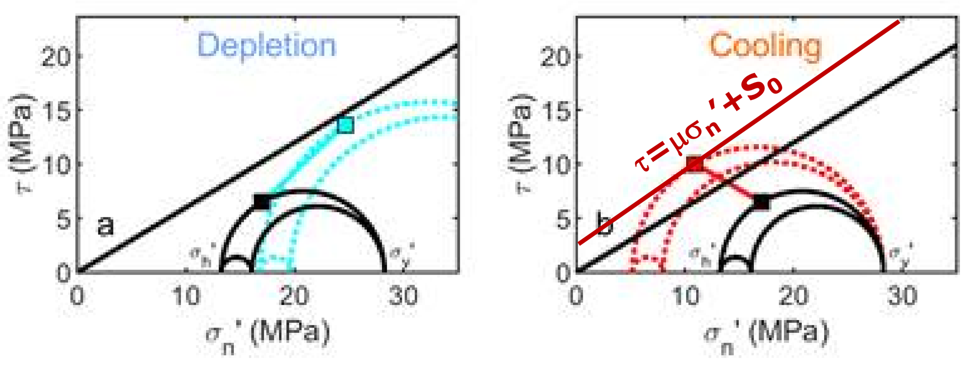


Figure 2: Diagrams illustrating the fundamental difference between fluid production (a) and circulation (b).

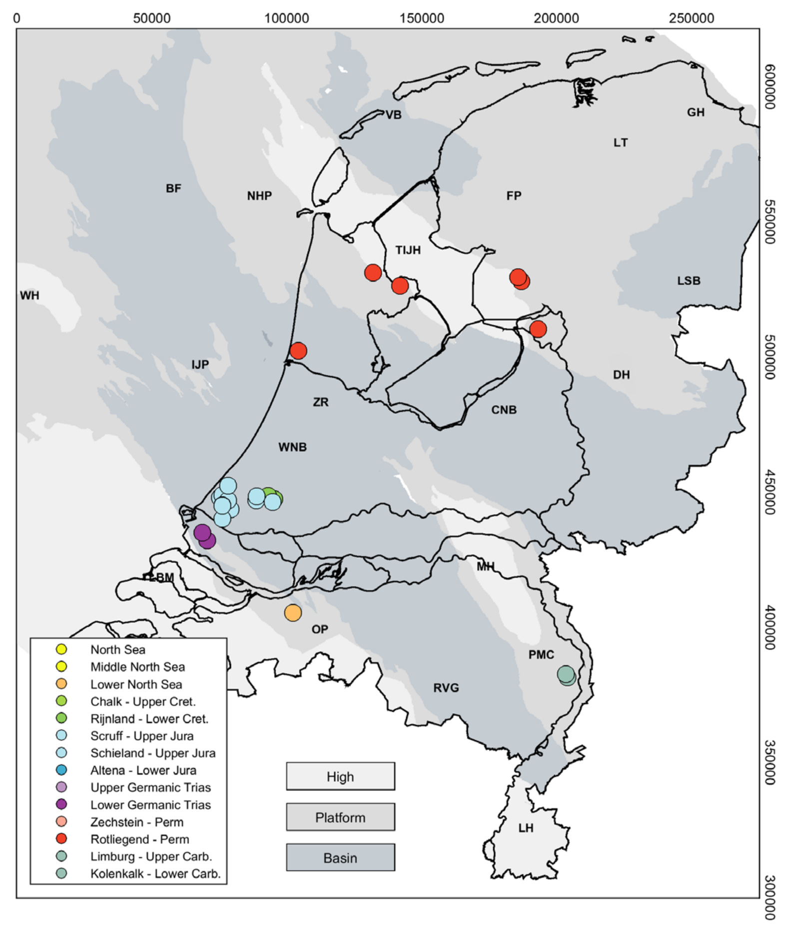


Figure 3: Map of the Netherlands showing current geothermal projects and the formations in which they produce (from Buijze et al., 2019)

Methods

- Simulated fault gouge (powders) of quartz, Rotliegend and Schieland sandstone formations.
- Sheared at v=1 μm/s at T=400 ºC
- σ_n^{eff}-stepping 30-120-30 Mpa
- Holds of 10-100-1000 seconds to determine reactivation strength (τ_{peak})

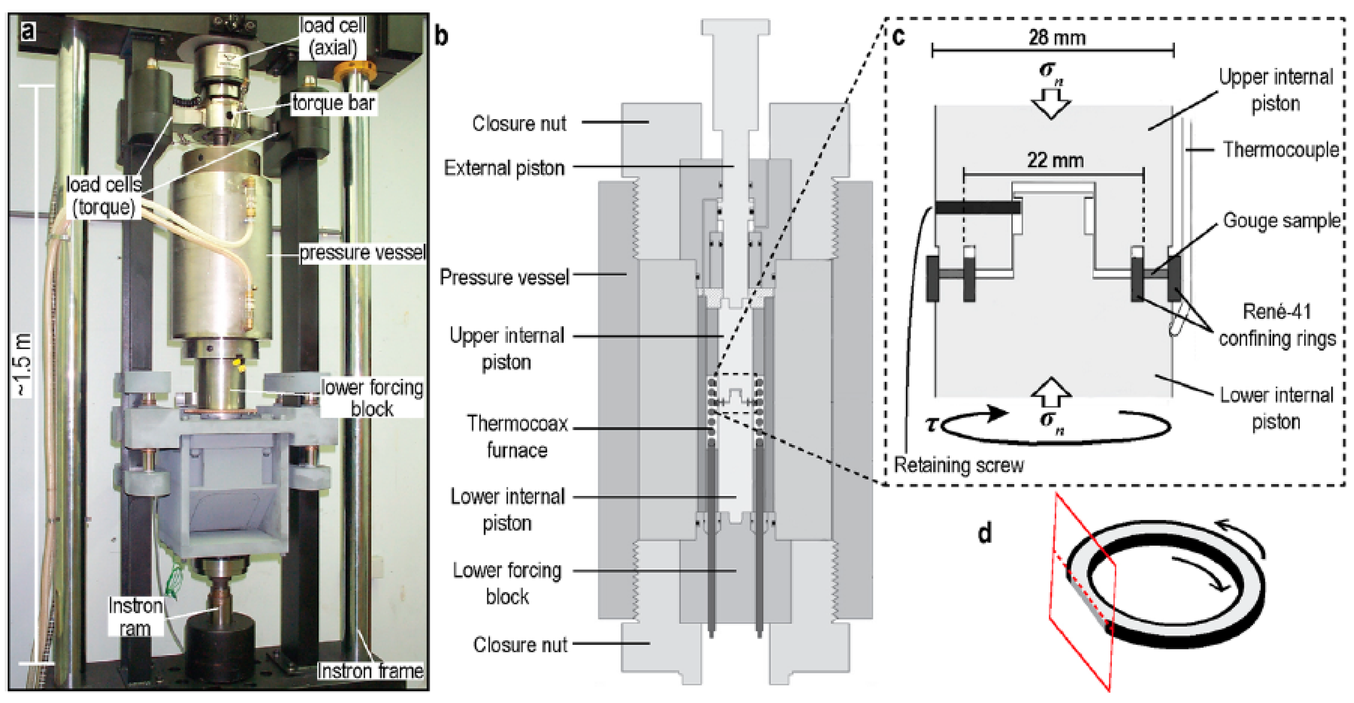


Figure 4: Picture of the unique hydrothermal rotary shear apparatus at the HPT Laboratory (a) and diagrams showing the configuration of the pressure vessel (b), sample assembly (c) and sample configuration (d). From Verberne et al (2015).

Results

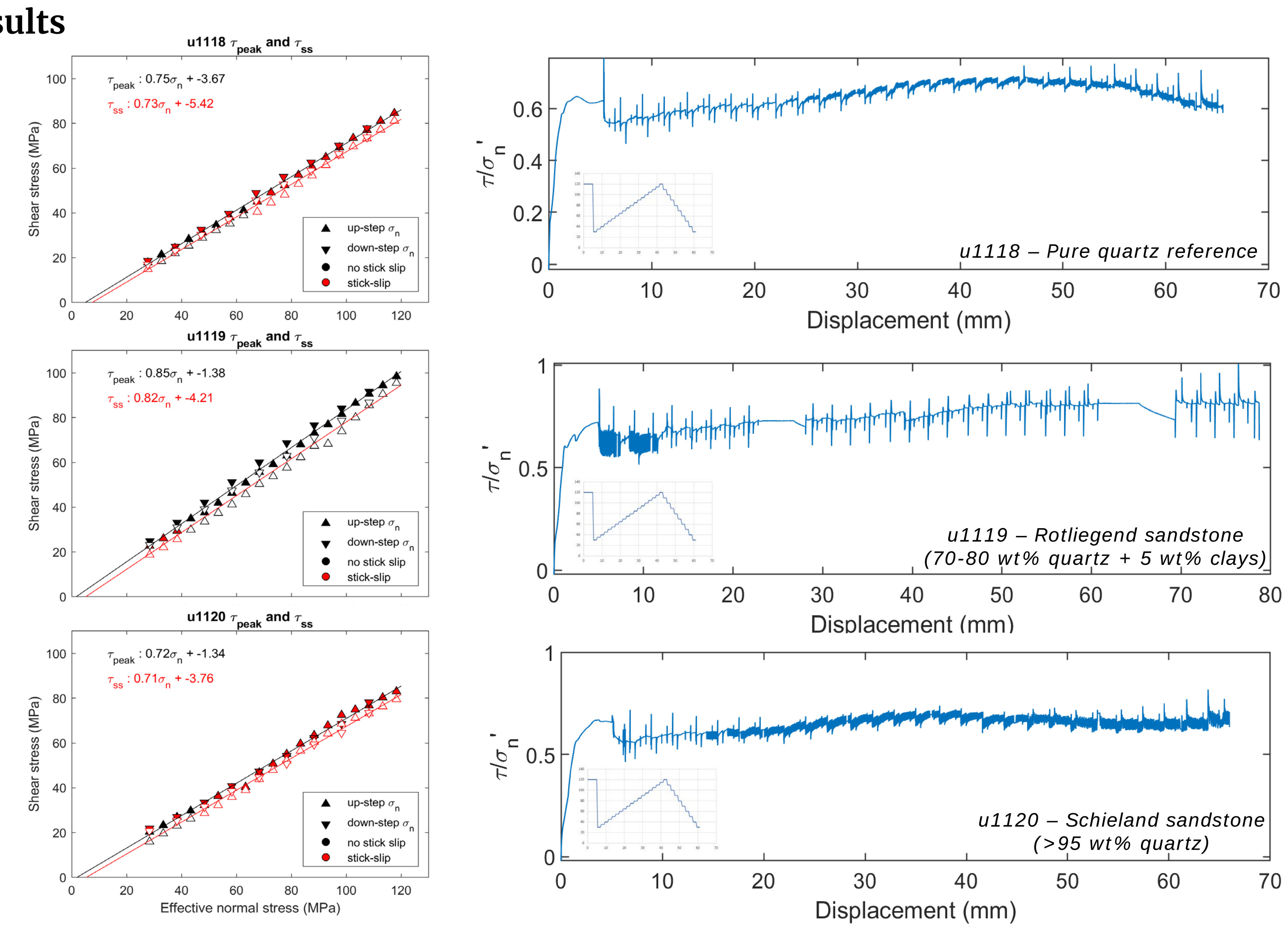


Figure 5: Shear stress vs. effective normal stress plots of the peak (after 1000 seconds hold) and steady state shear stress with linear fits. Slopes indicate the friction; intercepts gives the cohesion. Data are derived from the run plots on the right-hand side.

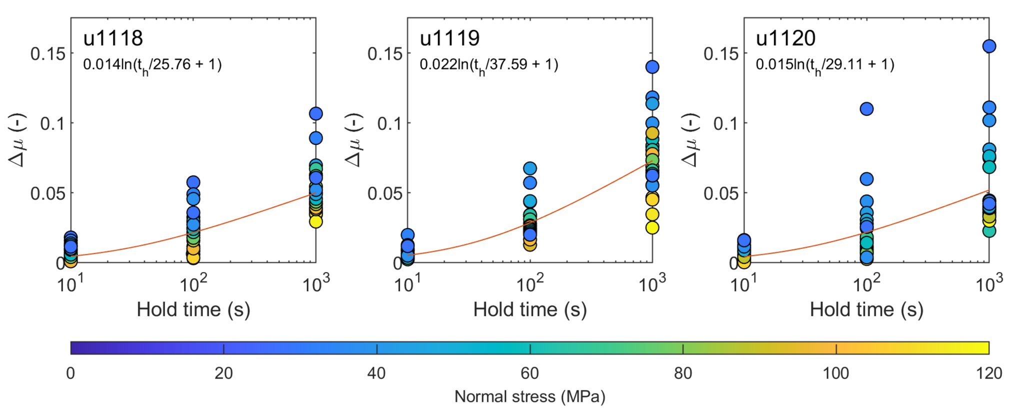


Figure 7: Difference between peak and steady state friction as a function of log hold time. Slopes give healing rates β

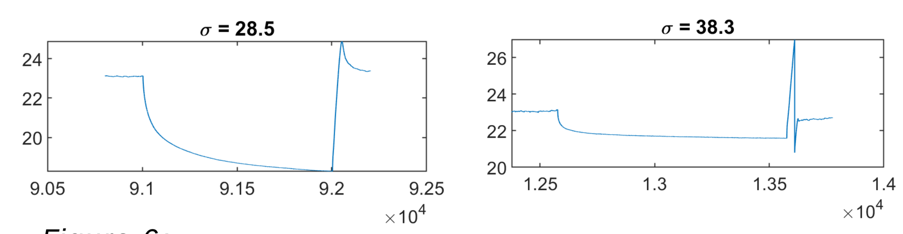


Figure 6: Examples of stable (left) and unstable (right) slip reactivation

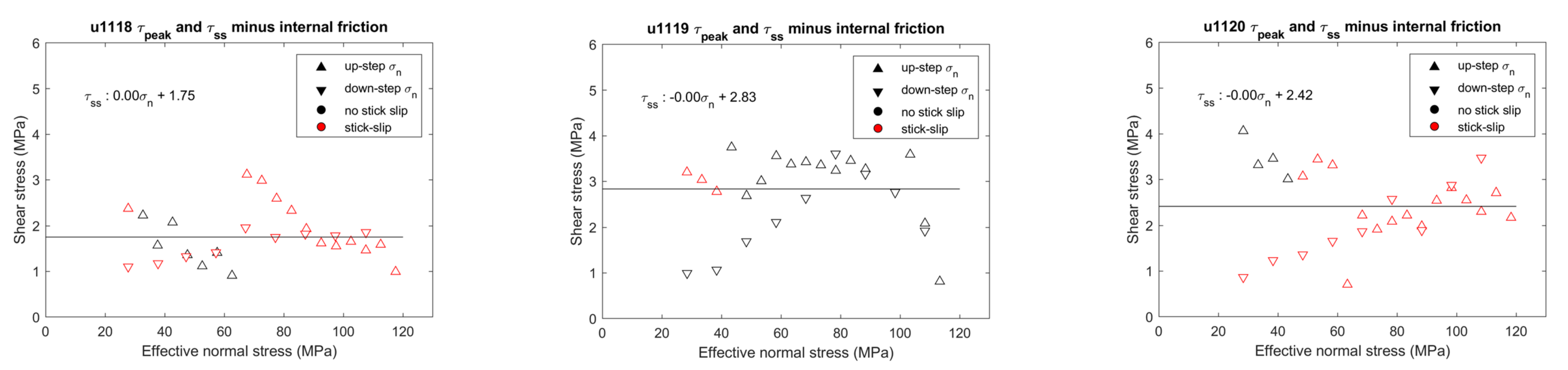
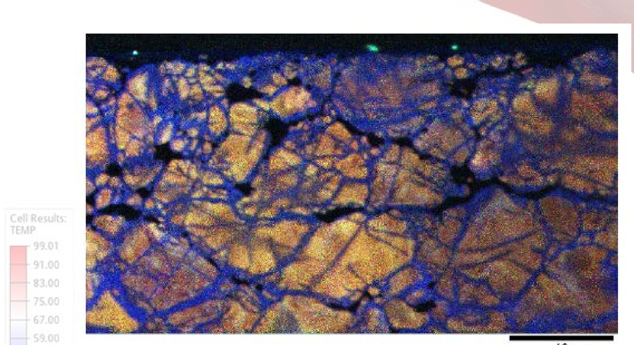


Figure 8: Strength change, i.e. cohesion gain, obtained by correcting (τ_{peak}-τ_{ss}) for internal friction as a function of effective normal stress for the three lithologies investigated. Cohesion gain after a 1000 second is on the order 2-3 MPa.

- Unstable sliding in all samples
- More instabilities in pure quartz and Delft sandstone
- Significant strength gain in all samples tested.
- Change in slope (μ_i) and intercept (S_o) in τ-σ_n^{eff} plot
- Healing rate $\Delta\mu/\ln(t)$ and cohesion gain largest in Rotliegend

Conclusions & future work

- Both friction and cohesion increase with duration of fault inactivity.
- This restrengthening is ignored in seismic hazard analysis
- Future work will include:
  1) further experiments to quantify t and T dependence of increase in friction and cohesion.
  2) microstructural investigation of controlling deformation mechanisms (Figure 9).
  3) development and testing of microphysics-based models and/or empirical equations for extrapolation to natural time and spatial scales.
- Need for field-scale data and outcrop analogues to verify results.



Background: 3-D model of temperature distribution in a geothermal reservoir.

Figure 9: Example of microstructural observation: blue is newly precipitated quartz, sealing fractures.

References

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