THE IN-SITU STRESS FIELD OF A GEOTHERMAL RESERVOIR IN THE ROTLIEGEND OF THE NE GERMAN BASIN: IMPLICATIONS FROM 3D STRUCTURAL MODELLING

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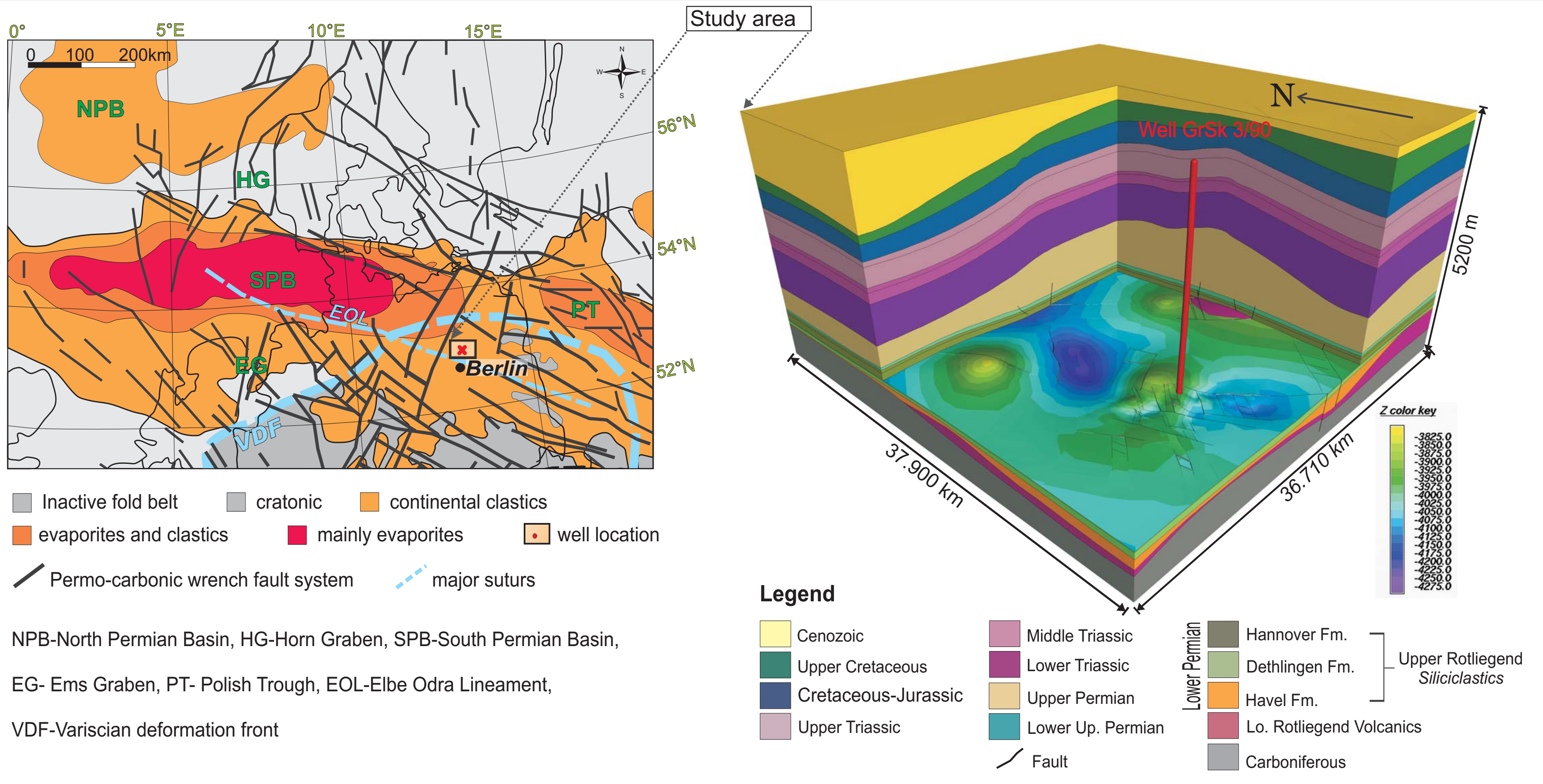


Main objectives

- Determination of the in-situ stress field in deep red beds building up the geothermal reservoir at Groß Schönebeck in the NE German Basin (NEGB) by both empirical and analytical approach.
- The empirical approach is based on the frictional equilibrium taking into account various possible stress ratios.
- The analytical approach is based on fracture mechanical borehole breakout analysis and simulation to back-calculate the driving forces at the borehole wall and the far field stresses.
- Development of a 3D structural model to image the current fault pattern.
- Understanding fault behaviour in the current stress field by calculating shear and normal stresses along the fault planes in the vicinity of the geothermal well.

Fig. 1. *Left: Structural lithofacies map of the Lower Permian (Rotliegend) in the South Permian Basin (SPB). The NE German Basin is part of the SPB (synthesis of Gast and Gundlach 2006, Ziegler and Dezes 2005, Ziegler 1990, Scheck and al. 2002)*
Right: 3D structural model of the Groß Schönebeck area developed from pre-existing seismic and well data. The geothermal well is located at a structural high of the Rotliegend sediments.

Methods of stress field determination

Empirical by using the frictional equilibrium

- Geometrical constraints in the fault pattern indicate a limited variation of stress regimes, ranging from normal faulting ($S_V>S_H>S_h$) to transtensional ($S_V=S_H>S_h$) to strike slip ($S_H>S_V>S_h$).
- Prediction of limiting stress values for any given stress regime using eq. (1) and assuming Andersons faulting theory and the Mohr- Coulomb criterion.
- Applying the known stresses S_V and S_h and eq. (1), in the reservoir the value for S_H is limited between 78 MPa and 100 MPa as shown by the stress regime polygons.

The frictional equilibrium for the geothermal reservoir is (after Jaeger and Cook, 1979):

$$\sigma_{1eff}/\sigma_{3eff} = (\sigma_1 - Pp)/(\sigma_3 - Pp) = [(\mu^2 + 1)^{1/2} + \mu]^2 = 3.12 \qquad \text{eq. (1)}$$

applying a friction coefficient $\mu = 0.85$, a pore pressure $Pp = 0.43*S_V$ and a vertical stress SV=105 MPa, σ_1 and σ_3 are the maximum and the minimum principal stresses, respectively

thus the stress boundaries are
$S_H \leq 3.10*S_V$ (for $S_h=S_V$)
$S_h \geq 0.55*S_V$ (for $S_H=S_V$)
with SH and Sh as maximum and minimum horizontal stresses

In a normal fault stress regime ($\sigma_1=S_V$; $\sigma_3=S_h$)
$S_H \leq 0.78*S_V$
$S_h \geq 0.55*S_V$

In a transtensional stress regime ($\sigma_1=S_V$, $S_H=S_V$)
$S_H \leq 1.00*S_V$
$S_h \geq 0.55*S_V$

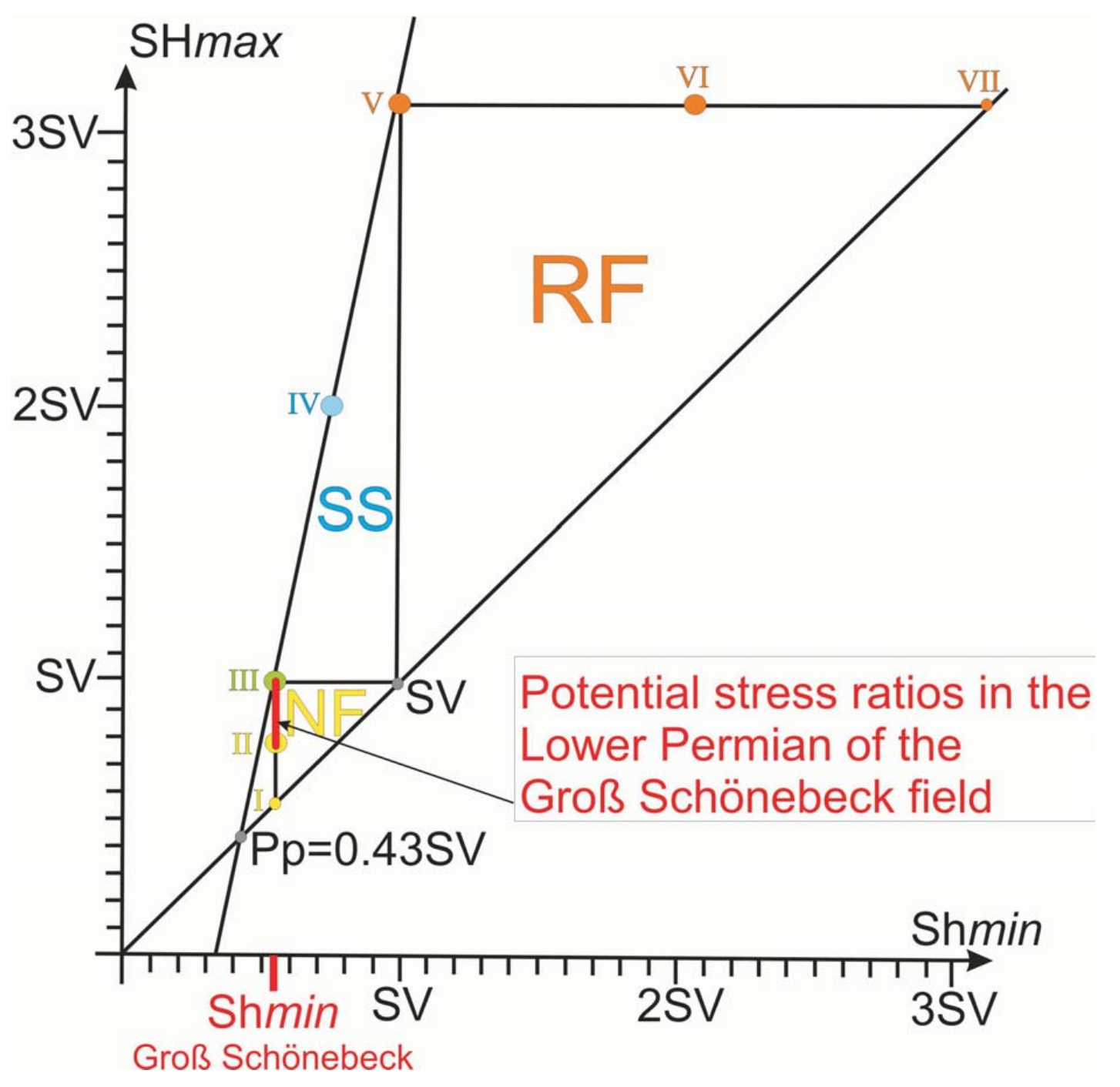


Fig. 2. *Allowable horizontal stresses and stress ratio with related stress regimes in the crust based on the frictional equilibrium (after Peška and Zoback, 1995). The stress polygon is normalized to S_V and is related to the crust in the NEGB in the vicinity of the Groß Schönebeck compartment. The minimum horizontal stress is known from hydraulic fracturing campaigns, S_h ~ 50 MPa (Moeck et al. Submitted).*

In a strike slip stress regime ($\sigma_1=S_H$; $\sigma_3=S_h$)
$S_H \leq 2.10*S_V$
$S_h \geq 0.79*S_V$

Analytical by borehole breakout analysis and simulation

- For the fracture simulation a 2D Boundary Element Code was used based on a fracture mechanical failure criterion.
- All relevant input parameter were determined in laboratory and have a physical meaning.
- The simulator FRACOD^{2D} can handle Mode I (tensile) and Mode II (shear) fracturing.
- Time-dependent (subcritical) fracture growth can be processed in multiple regions with multiple initial fractures.

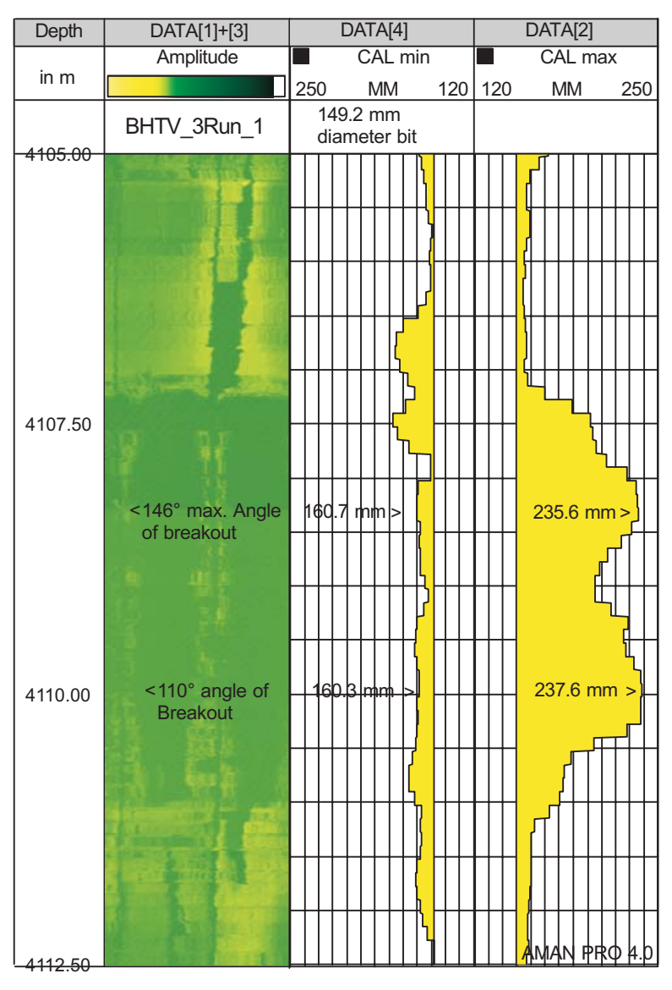


Fig. 3. *The breakout angle is about 145°, observed in the well GrSk 3/90. During a lift test the mud pressure in the breakout horizon was reduced to 3.7 MPa causing the breakouts.*

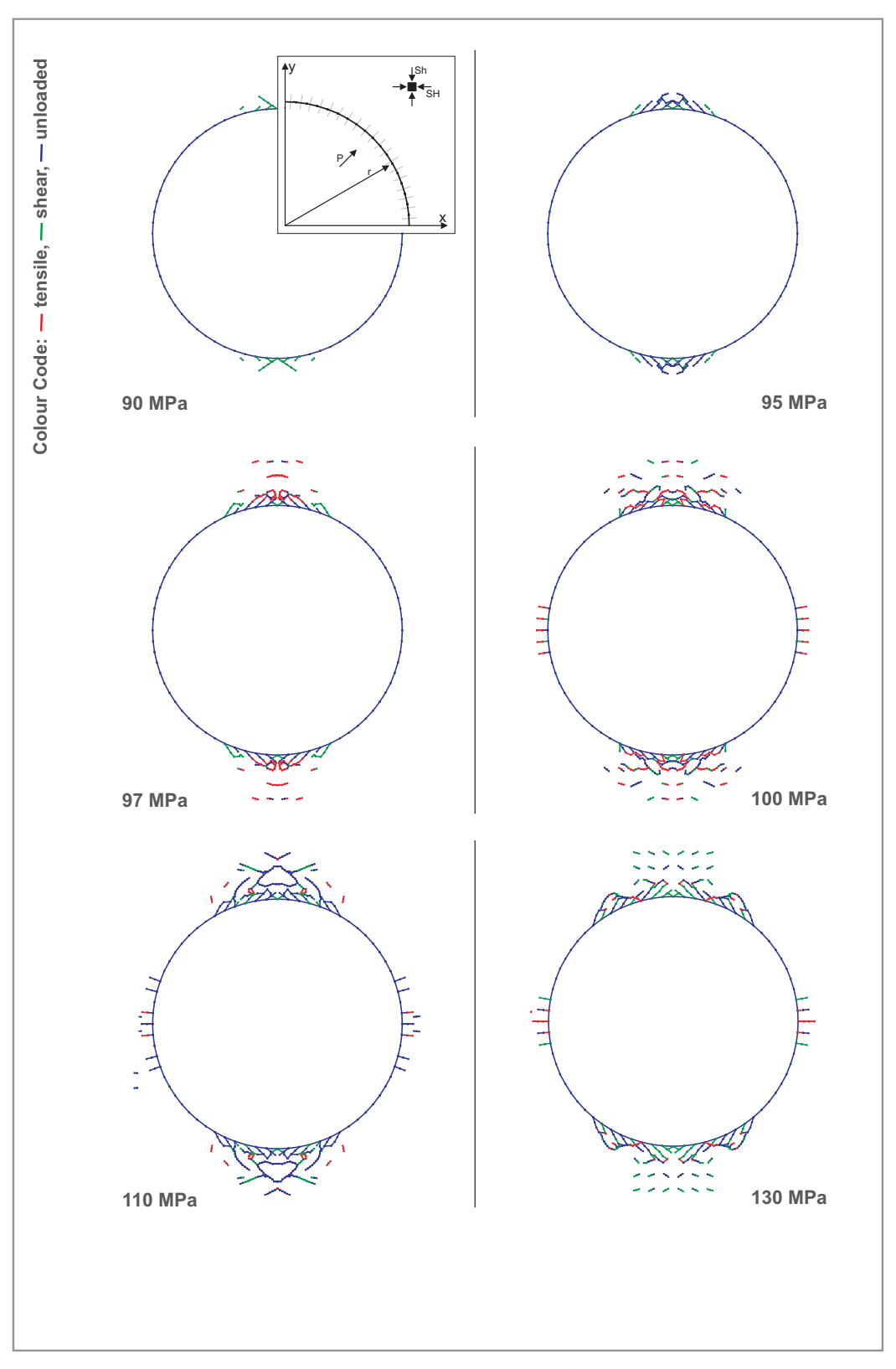


Fig. 4. *Examples of breakouts resulting from the modelling at a mud pressure of 43.5 MPa, S_h = 50 MPa, and varying S_H.*

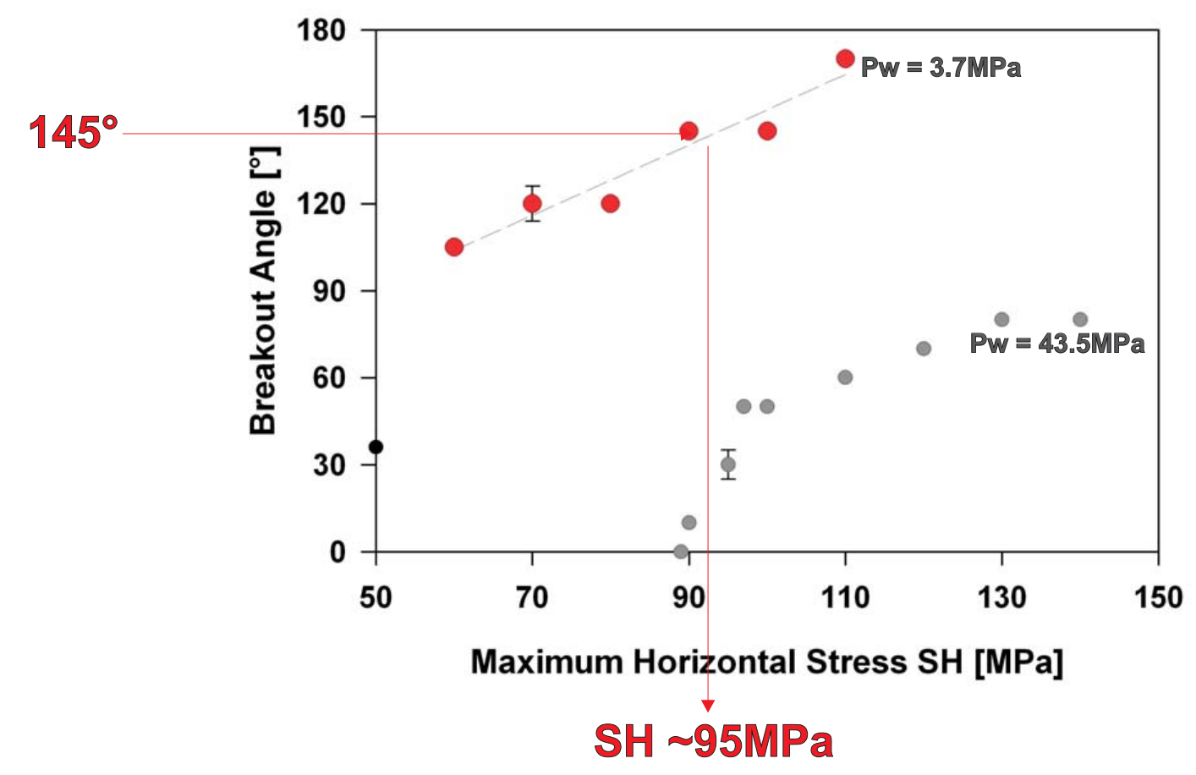


Fig. 5. *At reduced mud pressure (3.7 MPa) the breakout angle should be 145° with a max. horizontal stress S_H~95 MPa.*

Variation of the maximum horizontal stress S_H at different mud pressures yields a breakout geometry using FRACOD^{2D}.

At high mud pressure (43.5 MPa) no considerable breakouts should be initiated at the applied SH.

Results and conclusions

Slip tendency on faults

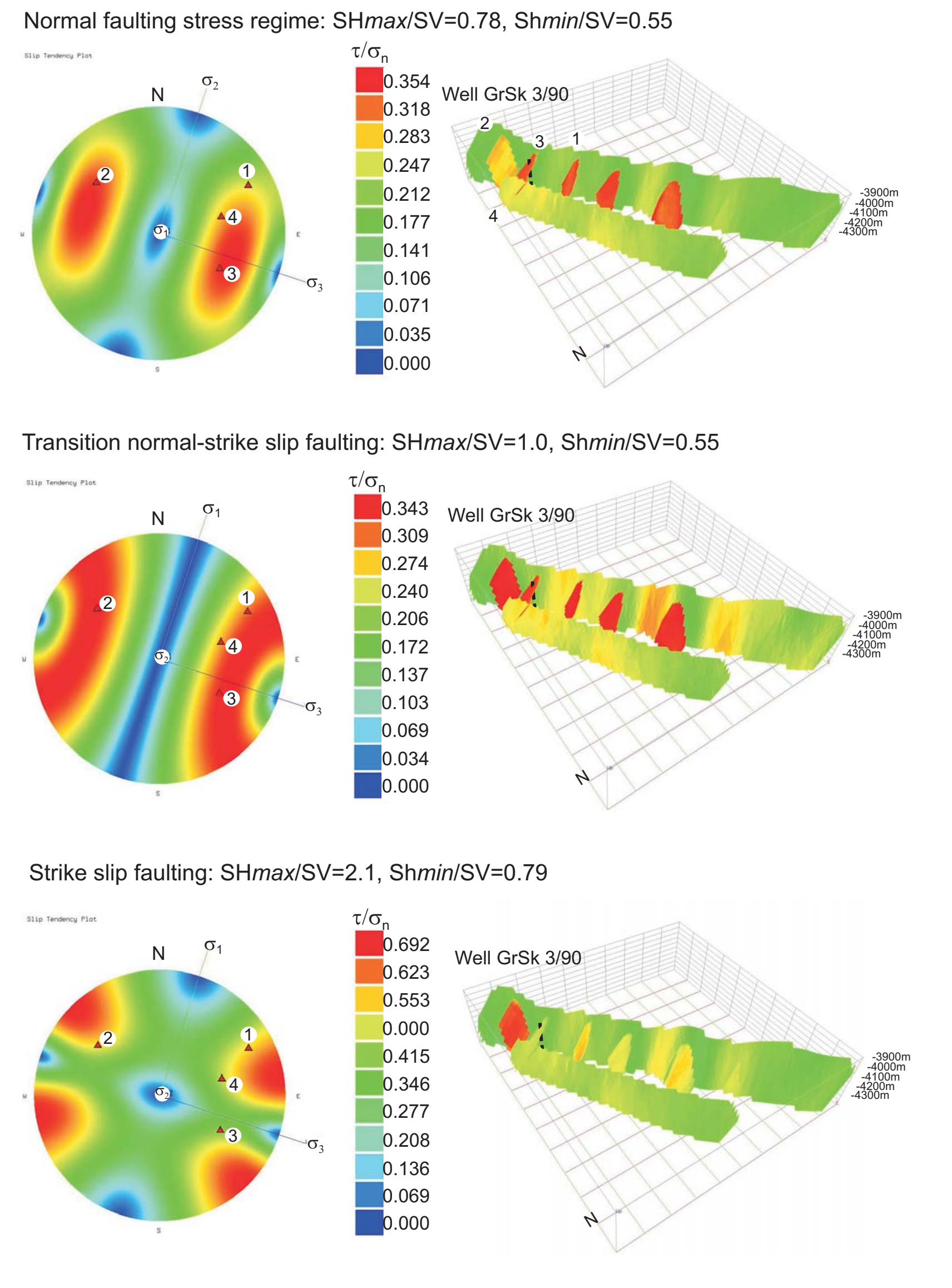


Fig. 6. *Stress state plot for the four fault planes near the geothermal well GrSk 3/90. Faults are displayed as poles in the lower hemisphere projection and visualized in the 3D fault model. The slip tendency for a given fault pole is indicated on the colour scale. Red indicates a high slip tendency, blue indicates a low slip tendency (Moeck et al. submitted).*

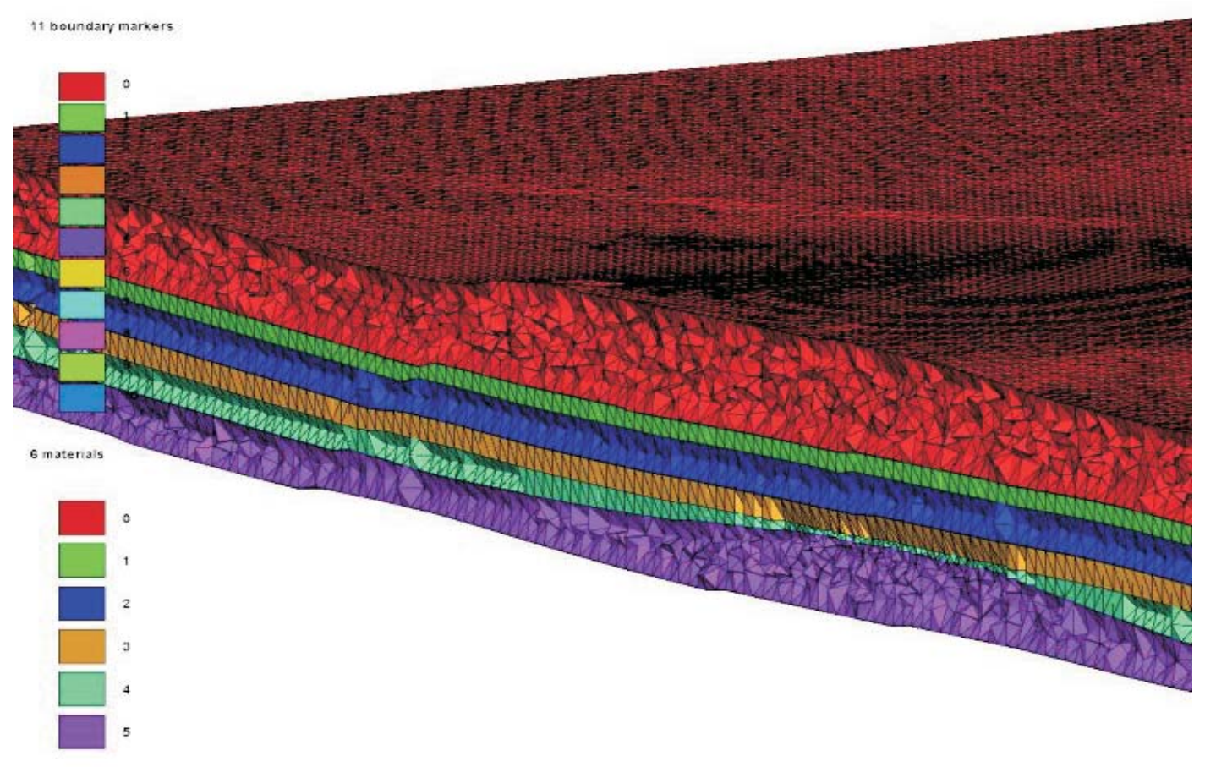
No	Fault plane Dip azimuth direction/dip angle	Stress Regime	SlipTend	τ_{smax} (%)	DilTend
1	242/72	NF	0.25	71.2	0.62
2	**129/57**	NF	0.34	94.7	0.65
3	**300/50**	NF	0.34	96.8	0.57
4	255/46	NF	0.29	81.3	0.42
1	242/72	TT	0.31	89.5	0.43
2	**129/57**	TT	0.34	99.6	0.62
3	**300/50**	TT	0.34	98.0	0.57
4	255/46	TT	0.29	83.9	0.37
1	242/72	SS	0.54	77.3	0.49
2	**129/57**	SS	0.52	75.6	0.80
3	300/50	SS	0.40	57.9	0.82
4	255/46	SS	0.47	67.5	0.66

Results

- The values of slip and dilatation tendency can be compiled together with the maximum slip tendency of each fault and in the three possible stress regimes, which are provided by the stress field calculation above.
- The faults with the highest slip and dilatation tendencies in the normal faulting (case II in Fig. 2) and transitional (case III in Fig. 2) stress regimes, are the NE-SW striking faults (fault number 2 and 3 in Fig. 6 and the table above).
- Faults with a high slip tendency are critically stressed faults with a high amount of shear stress. The have a high reactivation potential.
- Faults with a high dilatational tendency bear low shear stresses and low normal stresses.
- Depending on the rock type, either critically stressed (Barton et al. 1995) or dilatational faults (Gudmundsson et al. 2002) act as hydraulically conductive pathways in fractured reservoirs.
- The understanding of the state of stress helps to describe the reservoir condition in terms of fluid flow.

Conclusions

- The combination of fault throw analysis from a 3D structural model and the empirical approach based on the frictional equilibrium provides a limitation of the possible in situ stress regime in the Lower Permian of the Groß Schönebeck geothermal aquifer system.
- Compared with the results from a geomechanical analysis of borehole breakouts the stress regimes and their magnitudes seam reasonable.
- A lot of other studies say there is a strong relationship between stress state along faults within the current stress field and their hydraulic conductivity (either as shear or as dilatational fault).
- Therefore, the fault orientation related to the current stress field may influence their hydraulic conductivity.
- Stress field determination is not only important for considerations of borehole stability and fault reactivation due to reservoir treatments but also for understanding reservoir flow behaviour.



Outlook and future work

- Reconstruction of geometry by volume mesh generation of the 3D structured model of the Groß Schönebeck reservoir
- Coupled process simulation incorporating data from stress field/fault analysis
- Modelling case studies of fluid flow in faulted systems related to the current stress field

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