Tectonic Stresses - A Profile down to the Mid-Crust

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Up to now determining the stress orientation and in particular the stress magnitude from in-situ measurements is limited to an approximate maximum depth of 3-4 km. Deep drillholes, such as the KTB, offer a unique opportunity to literally deepen our understanding of the mechanic stresses in the crust using in-situ measurements.

The knowledge of the stress orientation and magnitude and its behaviour with depth contributes a great deal to the understanding of tectonic processes. Hence the determination of stresses belongs to one of the most important geoscientific problems which can be studied in deep drilling projects, such as the KTB.

For this reason, an integrated stress measuring strategy (ISMS) was developed within the KTB project, to obtain a most complete depth profile of the stress alteration as possible. The magnitude of the minimum horizontal stress S_h was determined with the help of hydraulic fracturing (HF) experiments in the pilot borehole (Baumgärtner et al., 1990) and with a modified HF-test at a depth of 6 km in the main borehole (Engesser, 1993). Because the magnitude of the maximum principal horizontal stress S_H from the HF-test could only be determined with high uncertainty, a method was developed to estimate the magnitude of S_H from a combined evaluation of breakouts and drilling-induced fractures. We will first dwell on establishing the stress orientation from these failure structures .

Stress orientation

The compilation and processing of breakouts is carried out with the Borehole Televiewer (BHTV) and the four arm caliper tool. Figure 1a shows the distribution and orientation of the breakouts between 3 km and 6 km (Brudy et al., 1993). Apart from small local variations, the overall orientation along the depth range is nearly constant at N59°±18°, which means the S_H orientation is N149°±18°. To determine the orientation of S_H it is assumed that breakouts form on the borehole wall at an angle of 90° to the orientation of S_H. This is supported by previous laboratory and field experiments, where the S_H orientation was known from different methods.

A further method used in determining the orientation of S_H is the evaluation of drilling-induced fractures, which form parallel to S_H along the borehole wall. Vertical drilling-induced fractures are observed primarily through Formation MicroImager (FMI) and Formation MicroScanner (FMS) measurements. Both tools produce an image of the electrical conductivity of the borehole wall, differing only in the degree of coverage.

The distribution and orientation of the drilling-induced fractures between 3 and 6 km is shown in Figure 1b. A nearly constant stress orientation is observed here as well with an average value of N166°±17°.

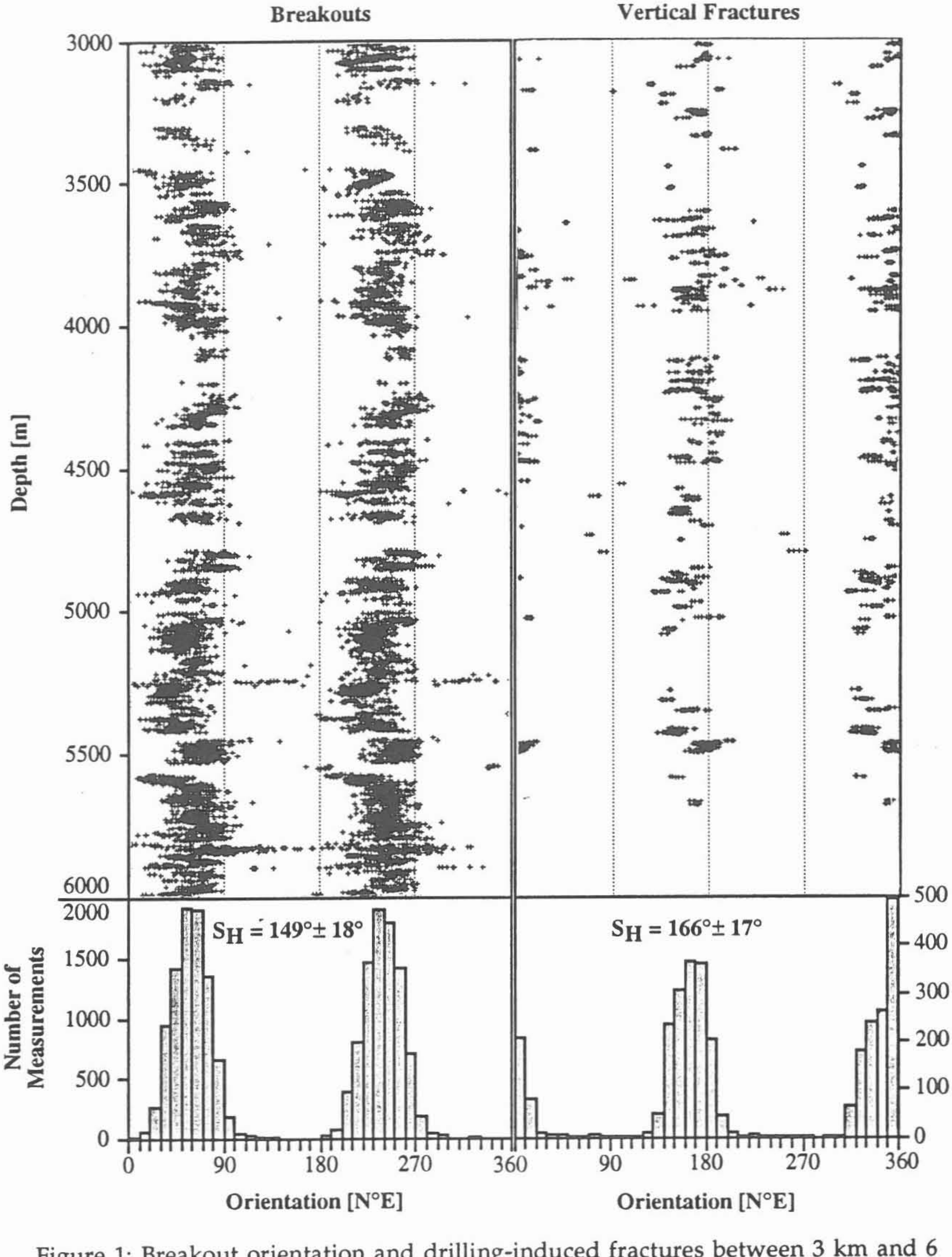

Figure 1: Breakout orientation and drilling-induced fractures between 3 km and 6 km in the KTB main borehole

In the first zone, directly below 6000 m (Fig. 2), the fractures are oriented at N170°±9°, which corresponds with the orientation of the fractures above 6000 m. The second zone around 7000 m has fractures tending slightly more north-south (N182°±21°) and has a noticeably higher scattering of the fracture orientations. This zone corresponds in depth with the section, where the SE1 intersects the borehole. (Hirschmann, 1993). The deepest zone in which vertical drilling-induced fractures were found (7600 m - 7800 m) indicates an orientation of fractures of N177°±11°, identical to those above the 7000 m zone. Below 7800 m and in between the above mentioned zones, no fractures were found. Due to the partially very poor data quality in those zones, it should not be ruled out that cracks formed but remained undetected. The mean value for the orientation of S_H in the section between 6000 m and 8600 m results in N178°±20°.

Since the FMI/FMS tool also logs caliper data, the measurements can be interpreted as ordinary four arm caliper tool logs. The S_H orientation from this evaluation is displayed in Figure 3. As in the analysis of the drilling-induced fractures, this analysis also shows no significant rotation of the stress field in the area of the SE1 reflector. This analysis results in a mean S_H orientation of N171°±17°. Below 8300 m the orientation of the breakouts coincides with the deviation direction of the borehole. Thus the breakout orientation may not reflect the correct orientation of the stress field.

A summary of the results of the stress orientation is given in the following table:

Breakouts:	BHTV	3-6 km	N149°±18°
	BGT	3-6 km	N159°±23°
	FMS	6-8.6 km	N171°±17°
Drill.-Ind. fract.:	FMI	3-6 km	N166°±17°
	FMS	6-8 km	N170°-182°

All these analyses indicate an approximately constant NNW-SSE S_H orientation over the entire depth. These results are probably the deepest stress orientation values determined to date from borehole logs.

Stress magnitude

Not only the stress orientation but also the stress magnitude is established. It is assumed that the vertical stress is a principal stress, i.e. the magnitude of one principal stress is given by the gravitational load of the hanging wall rock. The minimum horizontal principal stress is determined with the help of the HF experiments in the pilot hole and with the modified HF-experiment in a depth of 6 km in the main borehole. Left to be determined is the maximum horizontal principal stress S_H. This evaluation comprises two methods: (1) The analysis of breakouts and (2) the analysis of drilling-induced fractures. Since both structures occur at the same depths in the main borehole, the stress magnitudes must comply with the limitations from both estimates.

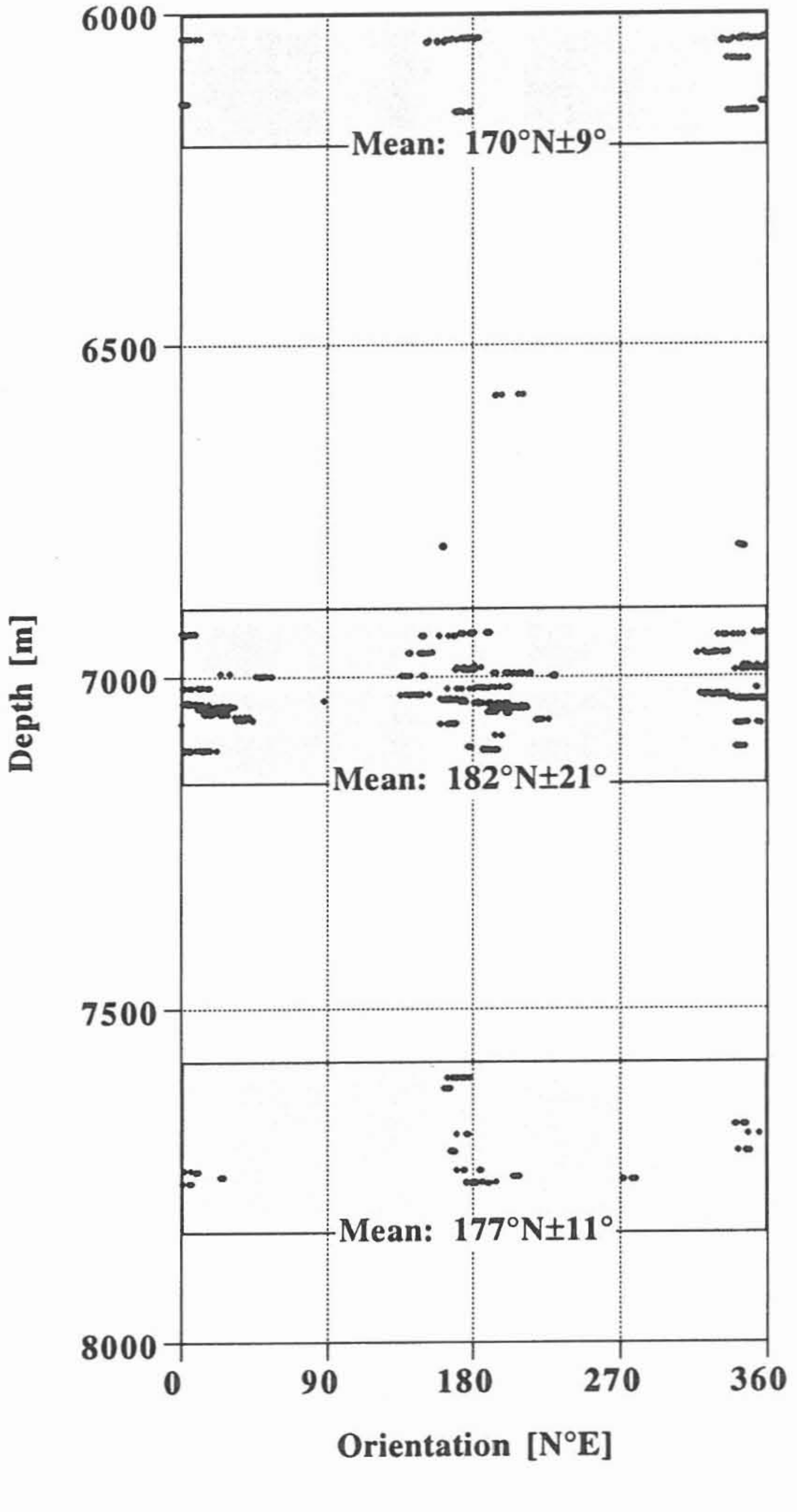

Figure 2: Orientation of drilling-induced fractures between 6 km and 8.6 km in the KTB main borehole

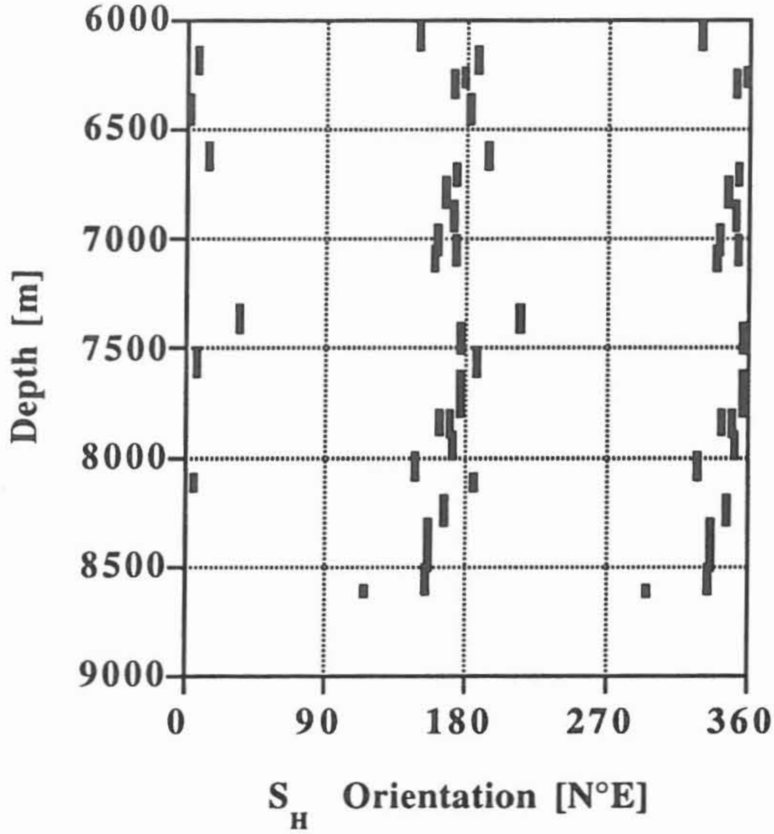

Figure 3: S_H orientation determined by the analysis of breakouts from four-arm caliper data recorded by the H-FMS. The mean orientation of S_H is N171°±17°.

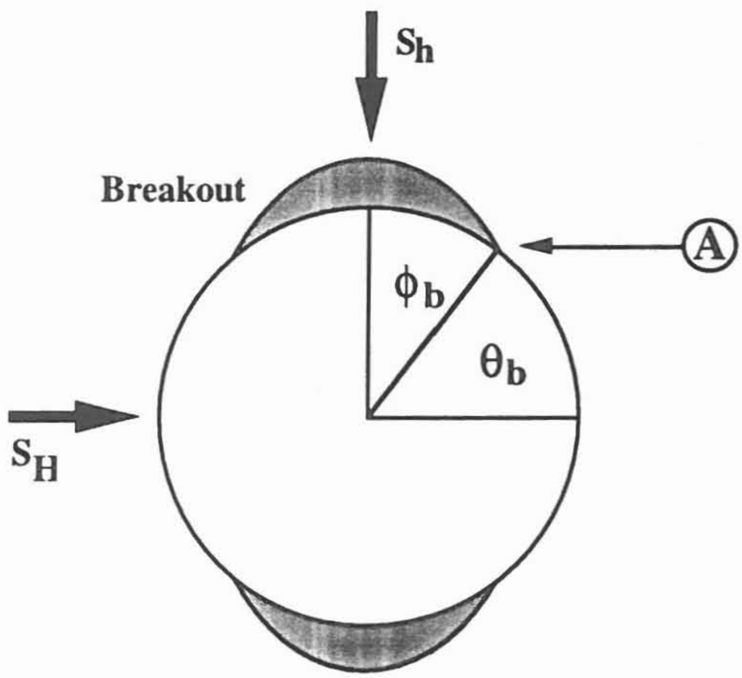

Figure 4: Breakouts form at the wellbore wall in the direction of the least horizontal principal stress S_h. 'A' marks the point of onset of the breakout at the undisturbed borehole wall.

In order to estimate the magnitude from breakout evaluations one assumes that the tangential stress at the outset point of the breakout on the borehole wall corresponds to the effective in-situ rock strength. This point is marked with (A) in Figure 4. From this analysis the following equation results for S_H.

$$S_H = \frac{C_{eff} + P_b}{1 - 2\cos(\pi - 2\phi_b)} - S_h \frac{1 + 2\cos(\pi - 2\phi_b)}{1 - 2\cos(\pi - 2\phi_b)}$$

C_{eff}: effective rock strength, $2\phi_b$: Breakout aperture angle

Drilling-induced fractures occur in the direction of the minimum tangential stress at the borehole wall. Since this stress is generally weakly compressive, they will not form without additional tension, caused by the pumping pressure while the drilling and the cooling of the borehole wall due to the circulation of drilling mud. Considering these influencing factors the following equation is found for estimating S_H:

$$S_H = 3S_h - P_f - \sigma_T - P_0$$

with

$$\sigma_T = -\alpha E \Delta T / (1 - \nu)$$

α: thermal expansion coefficient, E: Young´s modulus, ΔT: Temperature change, ν: Poisson-Ratio, P_f: Pressure in the drilling mud, P_o: Pore fluid pressure

Since it is unknown which thermal tension σ_T and which pumping pressure P_f was necessary, to produce the fractures, one uses the extreme assumptions for the estimation. Either the cracks formed at the maximum induced thermal stress and at the maximum pumping pressure, or they formed uninfluenced by cooling and pumping pressure.

The results of these estimates are summarized in Figure 5. Open and closed squares indicate the results of HFexperiments. Marked with VF_L and VF_U are the top and bottom limits respectively from the analysis of drilling-induced fractures. Top and bottom limits from the breakout analysis (corresponding to high and low rock strength) are denoted by vertical bars. Since both failure structures, breakouts and fractures, occur in the same depths, the sought after value of S_H must be within the overlapping section of both estimates.

A further limitation of the possible stress magnitude was carried out with the aid of the occurrences of breakouts (gray shaded area). The increase of breakout occurrences with depth indicates, that in greater depth even the more solid rock sections break increasingly. Therefore, in greater depths the stress magnitude can no longer be placed at the lower limit of the breakout estimate, since under those circumstances only the less stable rock sections of the drillhole would fail and an almost continuous breakout observation could not be explained.

The state of stress in 3 km, 4 km, and 6 km depth are represented in a Mohr diagram (Fig. 6). The measured shear stresses correspond to those found using the

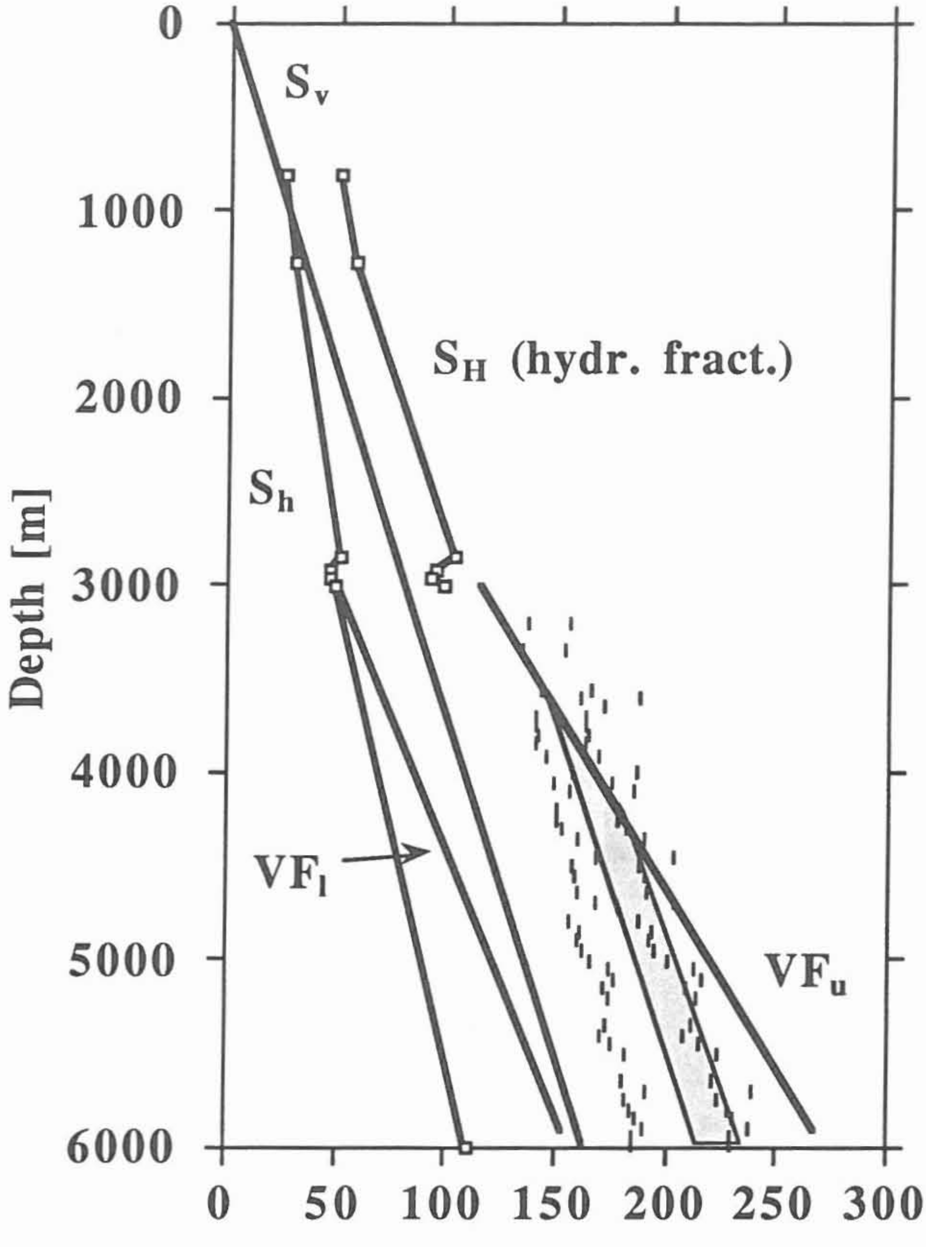

Figure 5: Profile of the stress magnitudes up to a depth of 6 km in the KTB. S_V is the vertical load of the rock. The results of Hydraulic Fracturing tests are represented as open squares. The bottom and top limits for the S_H magnitude, resulting from the analysis of drilling-induced fractures are denoted by VF_l and VF_u respectively. The magnitude range, resulting from breakout analysis, is marked by vertical bars. The value span for the S_H magnitude, found with the help of combined analysis involving breakout occurrences, is shaded gray.

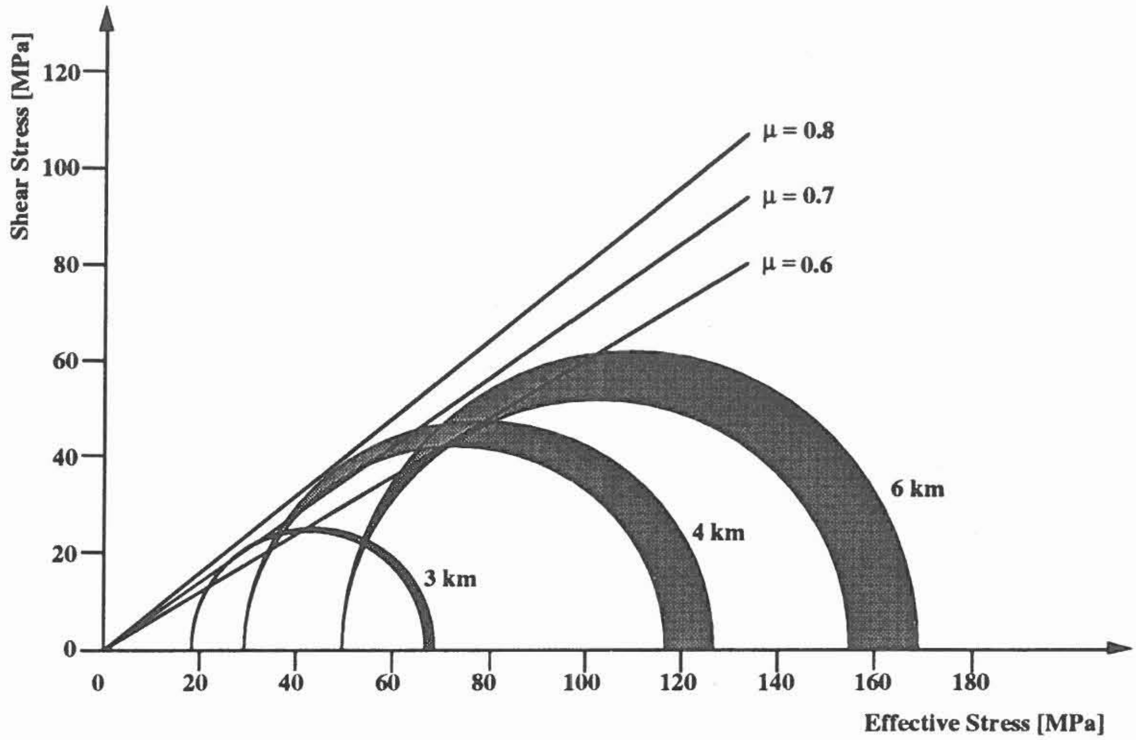

Figure 6: The calculated states of stress in 3 km , 4 km, and 6 km depth are displayed as a Mohr diagram. These states of stress correspond with the assumption that the brittle crust is in a failure equilibrium at preexisting faults with coefficients of friction between 0.6 and 0.8.

Coulomb theory for the brittle failure of rocks with friction coefficients determined in a laboratory under approximate hydrostatic pore pressure conditions. The shown Mohr diagram implies that the crust is in a state of failure equilibrium at preexisting faults with coefficients of friction between 0.6 and 0.8. These values for the coefficient of friction correspond with results of laboratory tests which obey the so called Byerlee law (Byerlee, 1978). The investigations presented here support the theoretical concepts, which are generally the base for establishing stress-depth profiles, for the first time up to a depth of 6 km.

Calculation of the borehole geometry from repeat BGT measurements

Since there are no BHTV measurements between the depths of 7.2 km and 8.6 km, it was nevertheless attempted to develop a method for determining the orientation of breakouts and possibly also the angle of aperture within acceptable accuracy. The only available information about the borehole geometry are caliper measurements from the BGT as well as from the H-FMS tool. With the help of an inverse calculation using the total caliper values available in one depth, the ellipse which best fits the data is found. This procedure yields an elliptical cross section of the drill hole at every depth. The mean deviation of the data from the calculated ellipse is normally less than half a centimeter.

The elliptical cross sections can be displayed as a radius image matching that of a BHTV Image. The procedure was tested between the depths of 6 km and 7.2 km and yields good results. A comparison to BHTV data from the same depths confirms the orientation and proportions of the breakouts.

To successfully employ this inversion procedure we recommend repeat logging of identical depth sections using the BGT tool. Presently we are establishing a minimum necessary amount of measurements which still yields reasonable results.

Outlook

A further HF test for determining the minimum horizontal principal stress S_h is planned below 9 km. The stress orientation can be found from the analysis of drilling-iduced vertical fractures from FMS logs and with the help of repeat four arm caliper logs. As it has already been conducted for the depth section 3 to 6 km, the estimate of the magnitude of the maximum horizontal principal stress S_H with the help of breakouts and induced cracks shall be conducted for greater depths.

Acknowledgments

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References

Baumgärtner, J., F. Rummel, and M.D. Zoback, *Hydraulic Fracturing in situ Stress Measurements to 3 km Depth in the KTB Pilot Hole VB*, In KTB Report 90-6a, ed. Bram, K., J.K. Draxler, W. Kessels, and G. Zoth. 353-399. Hannover: NLfB-KTB, 1990.

Brudy, M., K. Fuchs, and M.D. Zoback, *Stress orientation profile to 6 km depth in the KTB main borehole*, In KTB Report 93-1, p. 281-300. Hannover: 1993.

Byerlee, J.D., *Friction of rocks*, Pure Appl. Geophys., 116: p. 615-629, 1978.

Engeser, B., E. Huenges, W. Kessels, J. Kück, and L. Wohlgemuth, *The 6000 m hydrofrac test in the KTB main borehole design, implementation and preliminary results*, In KTB Report 93-3, p. 301-336, Hannover: 1993.

Hirschmann, G., *KTB Hauptbohrung - what's beneath the seismic reflector SE1?*, In KTB-Report 93-2, p. 141-144. Hannover: 1993.