Application of the Integrated Stress Measurement Strategy to 9 km Depth in the KTB Boreholes

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Introduction

Estimates of the magnitude and orientation of the three principal stresses are presented to a depth of 9000 m at the KTB (Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland) drill site. The site is located in the Oberpfalz region in northeastern Bavaria at the western border of the Bohemian massif. Metamorphic rocks, mainly highly folded and steeply dipping gneisses and massive amphibolites were encountered at depth. A continuously-cored pilot hole reached a final depth of 4 km in 1989 and the main hole is stopped at a final depth of 9.1 km end of 1994.

The opportunity to measure the stress in the continental crust to great depth in this project is quite unique and of considerable interest for investigation of the stress magnitudes in the crust. Numerous investigators have introduced theoretical strength profiles for the crust, which basically separate the crust in an upper brittle and lower ductile part. The strength in the brittle part is controlled by the frictional strength of preexisting, favorably-oriented faults, whereas the strength of the lower ductile part is described by flow laws for appropriate rock types, temperatures and strain rates.

Fundamentally, theoretical stress profiles are based on laboratory results and the assumption that the crust is in a state of failure equilibrium. To verify this actual in-situ stress measurements at depth are needed. All data currently available in intraplate regions (McGarr and Gay (United States, South Africa) (1978), Zoback and Healy (Cajon Pass, California) (1992), Rummel (Scandinavia, Central Europe) (1986), Pine et al. (Cornwall, England) (1983), Baumgärtner et al. (KTB, Germany) (1990), Barton et al. (Fenton Hill, New Mexico) (1988) ) are consistent with the concept that stress magnitudes in the crust are in equilibrium with the frictional strength of the crust and that laboratory derived coefficients of friction $\mu$ in the range of 0.6 to 1.0 can be applied to faults in situ.

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The Integrated Stress Measurement Strategy - ISMS

Aim of the ISMS is the determination of the complete stress tensor as function of depth that means the determination of the magnitude of the principal stresses and their orientations. The vertical stress $S_v$ is assumed to be a principal stress, which is shown to be a reasonable assumption by Brudy and Zoback (1993) and by Brudy et al. (1995) from the analysis of drilling induced fractures at the borehole wall and their orientation with respect to the wellbore axis. The determination of the stress tensor at the KTB site basically relies on three methods: 1. Hydraulic fracturing (HF) to 3 km depth and modified HF experiments at 6 km and 9.1 km, 2. analysis of breakouts and 3. analysis of drilling induced tensile fractures at the wellbore wall.

**Stress Orientation**

Using analysis of borehole breakouts a profile for the orientation of the horizontal principal stresses is established for the entire depth interval from 3.2 km to 8.6 km (Figure 1a) (Brudy et al., 1993, 1995). Apart from minor local variations the mean orientation of $S_H$ of N160°E±10° is about constant with depth. No significant trend of the $S_H$ orientation and no large scale zones with markedly different $S_H$ orientations can be identified. The value of N160°E±10° is consistent with other determinations of stress orientation in the area and with the general stress orientation in Central Europe described by Müller et al. (1992).

Figure 1b shows the standard deviation associated with each depth interval and the corresponding reciprocal number of measurements in the interval. We display the reciprocal number of measurements as it simplifies the distinction between well-constrained (low standard deviation and low reciprocal number) and poorly-constrained intervals (high standard deviation and high reciprocal number).

The change in stress orientation seen below 7.2 km can possibly be explained by slip along the SE1 plane, a prominent fault plane cross-cutting the borehole between about 6.9 km and 7.2 km depth. This slip event could have reduced the shear stress on the plane and thus, caused $S_H$ to be approximately perpendicular to the SE1 plane. This hypothesis is supported by the fact, that in a strike slip stress regime as it is determined to 9 km depth in KTB, very high shear stresses are induced on planes oriented parallel to the SE1 plane. The stress magnitudes and orientations indicate that planes parallel to the SE1 with a coefficient of friction between 0.6 and 0.8 are at the verge of failure. Therefore, we think it is plausible that the presently observed abnormal stress orientation at the SE1 plane may be caused by a slip event along the fault, reducing the shear stress.
on it. Calculations by Shamir and Zoback (1992) and by Barton and Zoback (1994) show that the perturbation of the stress field due to slip events on faults crosscut by the borehole can cause reorientations of borehole breakouts.

![Graph showing stress orientations and standard deviation](image)

Fig. 1a (left): Using the most reliable stress orientation data from any depth a profile of the orientation of $S_H$ in the depth section 3.2 km to 8.6 km is derived. For this profile breakout orientations derived from Borehole Televiewer (BHTV) measurements were used between 3200 m and 6800 m, below this depth the breakout analysis of four-arm caliper data recorded by the BoreholeGeometry Tool (BGT) and the Formation MicrScanner (FMS) is used. The stress orientations derived from the different logs are averaged over depth sections of 50 m. Except an abrupt change in stress orientation at about 7200 m the orientation of $S_H$ is quite constant over the entire depth interval.

Fig. 1b (right): Standard deviation and the reciprocal number of measurements are given for each 50 m depth interval of Figure 1a. High values of both, standard deviation and reciprocal number of measurements indicate a badly constrained stress orientation and vice versa.

**Stress Magnitude**

The magnitude of the least horizontal principal stress $S_h$ and of the maximum horizontal principal stress $S_H$ to 3 km depth were determined by classical HF. Modified HF allowed only to estimate a lower boundary for the magnitude of $S_h$ to 9.1 km depth. Therefore breakouts and drilling-induced fractures both are used to estimate the magnitude of $S_H$. In the following we first discuss the estimation of the magnitude of $S_H$ from the analysis of breakouts and later from the analysis of drilling induced fractures.
Fig. 2: To 3 km depth magnitudes of $S_H$ and $S_h$ are determined from hydraulic fracturing tests in the pilot hole (open and filled squares, respectively). Below this depth modified hydraulic fracturing experiments at 6 km and 9.1 km depth were used to limit a range of possible $S_h$ magnitudes.

Following Barton et al. (1988) and Vernik and Zoback (1992) the magnitude of $S_H$ is determined from breakout analysis by equating the circumferential stresses at the borehole wall at the edges of the breakout to the in-situ compressive rock strength $C_{eff}$. In other words this means that the breakout formation stops at the point at the wellbore wall where the hoop stress is equal to the compressive in-situ rock strength. Solving for $SH$ leads to

$$S_H = \frac{C_{eff} + P_{hydrost}}{1 - 2 \cos(\pi - 2\phi_s)} - S_s \frac{1 + 2 \cos(\pi - 2\phi_s)}{1 - 2 \cos(\pi - 2\phi_s)}$$

(1)

$C_{eff}$ is the effective in-situ rock strength (Vernik and Zoback, 1992), $P_{hydrost}$ the fluid pressure in the well (hydrostatic) and $2\phi_s$ the breakout opening angle. The second term in this formula which involves the magnitude of $S_h$ is of minor influence on the value of $S_H$. The fluid pressure $P_{hydrost}$ is calculated as the hydrostatic pressure exerted by the mud column and the magnitude of the minimum horizontal stress $S_h$ is estimated from hydraulic fracturing.
experiments. The opening angle of the breakouts is measured from the BHTV data in the main well between 3000 m and 6800 m depth.

Also the analysis of drilling induced tensile fractures allows to estimate the magnitude of $S_H$. These fractures are found in the KTB holes nearly always parallel to the wellbore axis, diametrically opposed at the borehole wall and persisting 0.1 - 1 m along the hole, and cross-cutting other structures like foliation and faults. They were first observed in the pilot hole by Formation MicroScanner (FMS) measurements and later also by BHTV and Formation MicroImager (FMI) logging in the main well. An analysis of the core material available in the pilot well proved that these fractures are not present in the cores and therefore appear not to be pre-existing fractures cut by the wellbore (Röckel et al., 1992).

In the pilot hole calculation of the hoop stress around the wellbore wall induced by tectonic far-field stresses (known from hydraulic fracturing stress measurements) shows that the minimum hoop stress around the wellbore is slightly compressive. Thus, even if we assume the tensile strength to be negligible, the tensile fractures are not expected to occur. Thus, additional sources of tensile stress (related to the drilling process itself) are needed to explain the formation of these fractures. Other sources of tensile stress are: (i) the thermal stress $\sigma_T$ induced by cooling of the borehole wall due to circulation of relatively cold drilling-mud and (ii) increased borehole pressure during drilling operations. Both additional stresses are uniform around the wellbore and therefore do not influence the orientation of the fracture, but they are needed to lower the hoop stress so far to allow initiation of a fracture. Thus, the circumferential stress $\sigma_{\theta\theta}$ acting on the borehole wall is the sum of tectonic stress, thermally induced stress $\sigma_T$, and mud pressure $P_f$

$$\sigma_{\theta\theta} = S_H + S_h - 2(S_H - S_h)\cos(2\theta) - \Delta P - \sigma_T - 2P_0$$  \hspace{1cm} (2)

$\Delta P$ is the difference between the pressure of the drilling mud $P_f$ and the porefluid pressure $P_0$. The pressure of the borefluid $P_f$ is calculated by

$$P_f = P_{\text{hydros}} + 0.95 \cdot P_{\text{surf}}$$

as the sum of the hydrostatic pressure $P_{\text{hydros}}$ of the mud and 95% of the pumping pressure at the surface $P_{\text{surf}}$. Using 95% of the pumping pressure applied at the surface to calculate the downhole pressure assumes that there is only about 5% pressure loss. This is justified by that fact that in the KTB well a thixotropic mud is used, which transmits the first pressure peak when the pumps
start with very little pressure loss down the hole. When the mud starts to flow commonly much higher values for the dynamic pressure losses have to be used. As we are only interested in the peak pressure the rock ever experienced during drilling we use this very small value for the pressure loss. The angle \( \theta \) is measured from the azimuth of \( S_H \).

The minimum tangential stress concentration is found at angles \( \theta \) of 0° and 180° and controls the occurrence of tensile fractures. Fractures are formed, if the tangential stress reaches zero (in rock without tensile strength) or becomes sufficiently negative to overcome the tensile strength of the rock. As for the hydraulic fracturing the pore pressure is neglected for the initiation of the drilling induced fractures.

\[
\sigma_{\theta} = 3S_h - S_H - \sigma_T - P_f
\]

Assuming that the fractures initiate at \( \sigma_{\theta0} = 0 \) (rock with no tensile strength) we can solve equation (3) for \( S_H \) and estimate the magnitude of \( S_H \) using the value of \( S_h \) available from the modified hydrofrac tests at 6 km and at 9.1 km and the conventional hydrofrac tests to 3 km in the pilot hole.

\[
S_H = 3S_h - \sigma_T - P_f
\]

As it is not known how much cooling and/or pumping pressure was necessary to initiate the fractures we consider the following two extreme possibilities. The fractures form without the help of any cooling or pumping pressure (\( \sigma_T = 0, P_{surf} = 0 \)). Then (4) turns into

\[
S_H = 3S_h - P_{hydrot.
}

which gives an upper bound for the magnitude of \( S_H \). The second possibility assumes that the fractures need the complete amount of thermally induced stress \( \sigma_T \) and mud pressure \( P_f \) available in the respective depth section to initiate. This assumption leads to a lower boundary for the magnitude of \( S_H \) corresponding to equation (4) using upper bound values for \( \sigma_T \) and \( P_f \).

In order to estimate the magnitude of \( S_H \) with equations (4) and (5) from the occurrence of drilling-induced tensile fractures the magnitude of \( S_h \), the mud pressure during drilling \( P_f \) and the thermally induced stress \( \sigma_T \) have to be known. The magnitude of the least horizontal principal stress \( S_h \) is derived from measurements carried out in the pilot well and in the main well. To find the actual \( S_h \) value for depths between 3 km and 6 km we interpolated between the
single measurements. The mud pumping pressure $P_{\text{surf}}$ is continuously recorded at the surface and the thermally-induced stress is calculated following Stephens and Voigt (1982) and Moos and Zoback (1990) by

$$\sigma_T = -\frac{\alpha E \Delta T}{1 - \nu}$$

(6)

Here $\alpha$ is the thermal expansion coefficient, $E$ the Young's modulus, $\nu$ the Poisson's ratio, and $\Delta T$ the temperature difference between the undisturbed rock temperature $T_i$ and the mud temperature $T_0$. The induced thermal stress ranges between 15 MPa and 35 MPa and the maximum downhole pressure has values between 55 MPa and 80 MPa, which is about 30 MPa above the hydrostatic mud pressure at any given depth.

Both methods, the analysis of breakouts and of drilling-induced fractures are calibrated in the pilot well where independent control on the magnitude of $S_H$ is given by the hydraulic fracturing measurements. It is shown that both methods are capable of estimating a reliable range of magnitudes for $S_H$. The estimation from the breakout analysis gives a narrower range for $S_H$ than the analysis of tensile fractures, but both estimations include the value of $S_H$ determined in the hydraulic fracturing measurements. This gives us confidence for the use of the ISMS in the main well to actually determine a range of values for $S_H$ at depth, where $S_H$ could not be determined from conventional hydraulic fracturing.

Each of the methods gives an upper and lower bound for the magnitude of $S_H$. In Figure 3 the bounds given by the fracture analysis are presented by solid lines marked with $V_{H_u}$ and $V_{H_l}$, respectively. The bounds resulting from the breakout analysis are given by the dotted lines. The breakout analysis is carried out only in the relatively isotropic amphibolites, which restricts the analysis to depth below 3200 m. These results are displayed in Figure 3 together with the vertical stress $S_v$ and the least horizontal stress $S_h$ which is interpolated stepwise between the actual measurements both in the pilot and in the main well (filled squares) and the $S_h$ estimate from the modified HF tests (open quadrangles). The values of $S_H$ determined from conventional hydraulic fracturing in the pilot well are plotted as open squares.

As mentioned above the actual magnitude of $S_H$ has to satisfy both estimations, because both failure modes occur at the same depth. Thus it is defined by the overlap of the two estimations.

The state of stress, we estimate, is consistent with a frictional equilibrium on faults with a coefficient of friction of $\mu$ between 0.6 and 0.7. The estimated stress
magnitudes presented as Mohr circles in Figure 4 clearly demonstrate that the crust has, at least to 7.7 km depth, is at the verge of failure on optimally oriented pre-existing faults. This also indicates that the crust is capable to sustain high shear stresses and to transmit plate boundary forces.

![Graph showing stress vs. depth with various lines and symbols representing different stress states.]

**Fig. 3:** Using the lower bound estimate for \( S_H \) magnitudes for \( S_H \) are estimated from the occurrence of breakouts (dotted lines) and the occurrence of drilling induced fractures (solid lines). As both failure modes occur at the same depths the actual magnitude of \( S_H \) has to be inside the overlapping area of the two estimations.

**Conclusions**

The orientation of the principal stresses at the KTB site is determined by analysis of borehole breakouts and drilling-induced tensile fractures to a depth of 9 km. The occurrence of mainly vertical drilling-induced fractures at the wellbore wall strongly supports the assumption that the vertical stress is a principal stress along major sections of the borehole. The orientation of the greatest horizontal principal stress is determined by various methods both in the pilot and main well to range between N148°E and N166°E. Apart from local variations the stress orientation is constant with depth. Only below the SE1 plane at about 7200 m depth a significant change in the stress orientation to a value of N220°E is observed.

The absolute magnitude of the principal horizontal stresses is determined in the pilot hole by conventional hydraulic fracturing and in modified hydraulic
fracturing experiments at 6 km and at 9.1 km depth bounds could be placed on
the magnitude of $S_h$. The magnitude of $S_H$ for the depth section below 3 km is
estimated by the combined analysis of breakouts and drilling-induced fractures.
As both types of failure occur in the entire depth interval between 3 km and 7.7
km the actual magnitude of $S_H$ has to satisfy both estimations. This leads to a
significant reduction in the uncertainty of the single estimations. The differential
stresses found in this analysis reach values of about 110 MPa in a depth of 6 km
and of 180 MPa at 7.7 km. Plotting these stresses for the appropriate pore pressure
as Mohr diagrams shows that faults with coefficients of friction $\mu$ between 0.6 and
0.8 are on the verge to slip. These values are assumed to be realistic for intraplate
faults and are found in laboratory test for rock friction. Finding these stress states
in the crust means that the stress magnitudes are limited by the frictional
equilibrium on preexisting optimally oriented faults. If the stresses try to increase
above this equilibrium state slip on faults occurs and consequently reduces the
stress back to the equilibrium state. The measurements and estimations
presented here are the deepest justification of this concept which is commonly
assumed for construction of strength profiles throughout the brittle part of the
crust.

The results also indicate that the upper, brittle part of the crust in areas of
moderately high heat flow as Central Europe is capable of supporting forces
equivalent in magnitude to plate driving forces. Thus, in areas, where the
strength of the upper mantle is assumed to be low, the brittle crust is expected to
act as a 'stress guide'.
Fig. 4a: see below

Mohr - Diagram at 7.7 km

Fig. 4b: The stress states estimated at 3 km, 6 km (Figure 4a) and 7.7 km depth indicate that the crust supports high shear stresses. They also demonstrate that the crust is in a failure equilibrium on pre-existing, optimally oriented faults with coefficients of friction of 0.6 to 0.8. The use of lower bound and upper bound values for Sh leads to the two different Mohr-circles presented at 7.7 km depth.
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