SUMMARY

DETERMINATION OF IN-SITU STRESS MAGNITUDE AND ORIENTATION TO 9 KM DEPTH AT THE KTB SITE

Ph. D. Thesis by Martin Brudy

Since the 1960's tectonic processes are described by the theory of plate tectonics. Despite the great success of this theory explaining the various tectonic processes by a single concept, still the forces which drive the plates are known insufficiently. Especially, the questions which forces do act on the plates, where do they act on the plates, what magnitudes do they have, and how and where in the plates are they transmitted, are still under debate. The investigation of the mechanical stresses in the lithospheric plates provides valuable constraints for answering these questions.

The World Stress Map (WSM) project succeeded in compiling a first database on stress orientations and magnitudes derived around the world. While the different methods contributing to this database allowed the determination of the stress orientation in extended regions with sufficient accuracy, still the information on the stress magnitudes is sparse. Up to date the in-situ determination of the state of stress by means of borehole measurements, e.g. hydraulic fracturing, over-coring, and evaluation of borehole breakouts, was constrained to the uppermost three kilometres of the crust. Thus, it was a main goal to achieve a complete and continuous stress profile at one site to as great a depth as technically feasible. The Continental Deep Drilling Project of the Federal Republic of Germany (KTB) with its 4 km deep pilot hole and its 9.1 km deep main hole and a very extensive logging and testing program for the first time provides the opportunity to determine such a stress profile to great depth.

Independent from in-situ measurements analyses of earthquakes and laboratory investigations of the strength of rocks under high temperatures and pressures allowed to develop theoretical strength- and stress profiles throughout the entire lithosphere. It is found that the crust can be subdivided in an upper section which deforms by brittle failure and a lower, plastically deforming section. Both parts are separated by the 'brittle-ductile transition', a zone in which the deformational behaviour of the rocks gradually changes from brittle to ductile and which is

commonly associated with a temperature range from about 300°C to 450°C. Considering the thermal gradient of 29°K/km observed at the KTB site and typical for middle Europe the onset of the brittle-ductile transition should be expected at approximately 10-15 km depth.

After Brace and Kohlstedt (1980) the stresses in the brittle part of the crust are limited by a frictional equilibrium on pre-existing, optimally oriented faults. As the frictional coefficient of rocks is almost independent from temperature, confining pressure and deformation rate - this rule is commonly known as the 'Byerlee law' - according to this mechanical theory of Brace and Kohlstedt stress magnitudes in the brittle crust can be calculated. In the ductile lower crust stresses are determined by the maximum ductile flow stresses (e.g., Carter and Tsenn, 1987).

This thesis for the first time proves the validity of the model proposed by Brace and Kohlstedt to a depth of 7.7 km. The stress profile at the KTB site could only be achieved by combining newly developed methods for stress determination with established methods like hydraulic fracturing and analysis of borehole breakouts. Therefore, new methods for determining stress orientation and magnitude from the analysis of wellbore failures are developed and applied to the KTB boreholes in this thesis. In the framework of the 'Integrated Stress Measurement Strategy' (ISMS) these new methods are combined with hydraulic fracturing tests and thus, allow a determination of the stresses at the hostile conditions at great depth in the KTB mainhole. Therefore, in this thesis with great emphasise drilling-induced tensile wall-fractures are phenomenologically described and a physical description for their initiation is provided and successfully tested. This work also allowed to develop a new method to estimate the stress magnitude from the presence of drilling-induced fractures. These fractures are not only investigated and analysed for the KTB boreholes but also for the geothermal research well at Soultz-sous-Forêts, France, to demonstrate their general occurrence in boreholes and thus, their importance as a new technique for stress determination.

Early work on the estimation of the stress magnitude from the opening angle of borehole breakouts by Barton et al. (1988) and by Vernik et al. (1992) was modified in order to estimate the stress magnitudes at the KTB site by an independent, second method. The fact that both types of failure occur at the same depths along the KTB boreholes allowed to successfully combine the analysis of borehole breakouts and drilling-induced fractures to estimate the magnitude of S_H in sections of the borehole where it could not be determined by hydraulic fracturing.

THE CHAPTERS

Chapter 1 - The Continental Deep Drilling Program KTB

The Continental Deep Drilling Program of the Federal Republic of Germany (KTB) is the first national large scale geoscientific research project in the country. The drill site is situated in north-eastern Bavaria close to the Czech border. Chapter 1 shortly introduces to the geological position of the KTB site at the saxothuringian-moldanubian boundary and to the technical specifications of the two KTB boreholes.

Chapter 2 - Stresses in the Lithosphere

Strength and stress profiles of the lithosphere (the crust and upper mantle) are discussed with special emphasis on their relation to the temperature gradient, the composition, the strain rate and to the observed typical depth distribution of seismicity. The brittle deforming regime is the upper part of the crust (which was penetrated by the KTB boreholes) and thus, the strength and stress profiles in this part of the lithosphere are discussed in detail and are compared to data available in the literature.

The upper, brittle part of the crust is commonly fractured. Therefore, the strength limiting the magnitude of the stresses in the brittle regime is not given by the compressive shear strength of the rock but by the frictional strength of pre-existing faults. Byerlee (1978) noted that the friction of rocks over a considerable range of confining pressures can by described by linear relationships which are independent of the lithology and hold to temperatures of 500°C. This universal friction law has become known as Byerlee's law. Brace and Kohlstedt (1980) stated that the strength of the brittle crust is limited by the frictional strength of faults optimally oriented with respect to the acting stress field and applied Byerlee's law to estimate stresses in the brittle crust. They found that strain relief stress measurements from South Africa and Canada and hydraulic fracturing results from the United States fit within the limits given by the Byerlee law taking into account the appropriate pore pressure for the area of investigation. Zoback and Healy (1984) showed that available stress measurements in intraplate regions associated with active faulting were consistent with estimates based on Coulomb faulting theory and laboratory-derived coefficients of friction to a depth of about 3 km.

As most of the presently available measurements are shallower than 3.5 km, one of the most important issues considering stress distribution in the crust is to gain more reliable data on stress magnitudes as deep as possible. Thus, one of the main purposes of the research described in this thesis is to investigate at the KTB site if the stress magnitudes are controlled by the frictional equilibrium on pre-existing, optimally oriented faults according to the hypothesis by Brace and Kohlstedt (1980).

Chapter 3 - Modes of Borehole Failure

For the investigation of the state of stress three types of borehole failures can be used, 1) borehole breakouts, 2) drilling-induced tensile fractures, and 3) shear failure on pre-existing faults. In this chapter breakouts are discussed in detail as they are extensively used in the following chapters. Shear failure on pre-existing faults is only shortly discussed as it is not observed in the KTB boreholes. Drilling-induced fractures are discussed separately in detail in chapter 4.

Breakouts are zones of failure of the borehole wall in response to high compressive tangential stresses $\sigma_{\theta\theta}$ in the borehole wall. $\sigma_{\theta\theta}$ maxima are located diametrically opposed at the wellbore wall oriented at the azimuth of S_h in a vertically drilled borehole. They elongate the borehole cross-section from the originally circular shape and are observed by four-arm caliper measurements and BHTV logging. The morphology of breakouts is described by three parameters, the orientation q_b, the opening $2f_b$ and the radial depth r_b .

Chapter 4 - Drilling Induced Tensile Wall Fractures

Chapter 4 reports a newly-discovered type of wellbore failure, drilling-induced tensile wall-fractures, revealed by detailed Formation MicroScanner (FMS) / Formation MicroImager (FMI) logging in two scientific drilling projects, the German KTB and the European geothermal research project at Soultz-sous-Forêts (GPK1), France. These fractures are observed in pairs, mostly parallel to the nearly vertical wellbore axes, and on diametrically opposed sides of the borehole walls. In the FMS/FMI images they are visible as near vertical stripes, indicating high electrical conductivity presumably caused by drilling mud invaded in the fractures. Comparison with breakout orientations and induced hydraulic fractures demonstrates that these fractures are clearly related to the tectonic stress field and can be used as reliable indicators for the stress orientation.

The characteristics of drilling-induced tensile fractures are: 1) They occur in pairs on opposite sides of the borehole wall. 2) They can be grouped in two types one trending about parallel to the borehole axis and the others occurring at an angle to the borehole axis (en-echelon type). 3) Their length ranges between 0.1 m and 2.0 m. 4) They clearly occur at the azimuth of the greatest horizontal principal stress S_H (Brudy et al., 1993) where the tangential stresses are least compressive. 5) Usually the traces of the fractures show small kinks and are not perfectly straight.

In both, the GPK1 and the KTB pilot hole, the inclined fractures are restricted in their occurrence to limited depth sections. In the GPK1 well the inclined fractures are clearly associated with natural faults crosscutting the borehole and are restricted to their close surrounding along the borehole. In some cases a gradual change of the fracture orientation with respect to the wellbore axis can be seen while approaching the fault. Shamir and Zoback (1992) describe rotations of breakouts in the Cajon Pass scientific borehole in California and explain them by slip on faults which changes the stress field close to these faults. Similar rotations of breakouts have been described for the KTB pilot hole and the KTB main hole (Brudy et al., 1993) and for several other wells in the United States (Barton and Zoback, 1994) and in Russia (Hickman et al., 1991). All this evidence suggests that also deviated drilling-induced fractures are related to stress changes associated with slip on faults crosscutting the borehole. Theoretical work allows to estimate the angle b by which the principal stress axis deviates from a vertical from the angle w_0 the fracture makes with the vertical borehole axis. For w_0 values between 10° and 30° (as determined for most of the deviated fractures in the KTB pilot hole and the GPK1 well) angles of b between 5° and 25° are found. The occurrence of inclined tensile wall-fractures is restricted to limited depth intervals, close to natural faults cross-cutting the borehole, where the stress field appears to be locally perturbed due to slip on the faults. This leads to the important conclusion that over major sections of the investigated boreholes, the vertical stress is a principal stress.

- Initiation of Drilling Induced Tensile Fractures

The theory developed to explain the initiation and development of the drilling-induced tensile wall-fractures is based on stress analysis for a linear elastic material using a strength of material approach for the initiation of the fractures. The initiation of the fractures can be explained taking into consideration the tectonic stress state, the downhole pressure acting on the borehole wall and the thermal stresses in the borehole wall induced by circulation of relatively cold drilling mud. This is demonstrated by the fracture analysis in the GPK1 and the KTB pilot boreholes where the tectonic stresses were determined independently by hydraulic fracturing experiments in the investigated depth interval. It is further shown that the analysis of the fracture initiation yields a new method to estimate the magnitude of the greatest horizontal principal stress, S_H. The application of this stress measurement method to the KTB main hole allowed to determine the S_H magnitude to 7.7 km depth.

- Fracture Mechanics Approach to the Occurrence of Drilling Induced Tensile Fractures

The initiation and growth of tensile fractures can also be described by the analysis of the stress intensity factor K_I which describes the stress concentration at the fracture tip which is responsible for either growth or stabilisation of the fracture. If the stress intensity factor for certain loading conditions overcomes a critical value which is specific for the material and that is called either the critical stress intensity factor or fracture thoughness K_{Ic}, the fracture grows. Winter (1983) and Rummel and Winter (1983) derive the stress intensity factor for a fracture initiating at the borehole wall under the loads of S_H, S_h, mudpressure in the borehole and mudpressure inside the fracture (Winter, 1983, Rummel and Winter, 1983). Besides these loads also the stress induced by cooling of the rock during circulation is important for initiation and growth of fractures at the borehole wall. Therefore, the stress intensity factor K_I for the thermally induced stress is derived and discussed. This new description of the drilling-induced tensile fracture allows, 1) to estimate a maximum length the fracture extends away from the borehole wall, and 2) to independently estimate the magnitude of S_H.

It is found that the drilling-induced fractures are constrained to the close proximity of the wellbore (much less than one borehole radius). Therefore, the possibility of mud losses through these fractures or significant influx due to connection to the natural fracture system is negligible. This method yields estimates of the magnitude of S_H within the bound given by the first estimate.

Chapter 5 - Determination of the Complete Stress Tensor

In the KTB project major efforts were undertaken to develop a strategy for determining the complete stress tensor; that is, the magnitude and orientation of the three principal stresses, to as great a depth as possible. The continuity of the stress profile along the borehole and its resolution with depth were important aims of the experimental plan (to allow the study of small scale stress variations and their origins) as well as the maximum depth of the stress determinations. As commonly used stress measurement methods, like overcoring, standard hydraulic fracturing, or core-based methods allow neither the determination of a continuous profile nor very deep measurements, alternatives and modifications had to be developed to reach this ambitious goal.

In the so-called 'Integrated Stress Measurement Strategy' (ISMS) the analysis of breakouts and drilling-induced fractures by means of borehole measurements is used to determine the orientation and the magnitude of the principal horizontal stresses. The ISMS assumes that the vertical stress is a principal stress, but as demonstrated in Chapter 4, this assumption seems to be quite valid. To a depth of 3 km it was possible to determine both the magnitude of S_h and S_H by classical hydraulic fracturing experiments (Baumgärtner et al., 1990). Below, the magnitude of the least horizontal principal stress, S_h was determined at 6 km and 9 km depth by hydraulic fracturing tests, which were modified to adjust the equipment and the procedure to the hostile conditions encountered at these great depths in the KTB main hole.

- Stress Orientation

With the assumption that the vertical stress S_V is a principal stress the task to determine the orientation of the greatest horizontal principal stress S_H remains. Besides the determination of the regional stress orientation, also stress variations with depth in various length scales are investigated.

The availability and quality of the borehole measurements resulted in some sections of the borehole being investigated very intensively, whereas in other parts, only an estimation of the stress orientation is possible. Three methods were used to establish a continuous stress orientation profile in the KTB main hole, 1) the analysis of breakouts using four-arm caliper data recorded by the Borehole Geometry Tool (BGT) and the FMS, 2) the identification of breakouts in Borehole Televiewer (BHTV) images and 3) the investigation of drilling-induced tensile fractures using FMS/FMI measurements. Using the most precise and reliable data from each depth a single, best profile for the orientation of the stress is established for the entire depth interval from 3.2 km to 8.6 km. This profile uses the results from the BHTV analysis to 6.8 km depth and for the deeper part the results from the four-arm caliper investigation.

The mean orientation of S_H varies about ±10° around N160°E over almost the entire investigated depth. Apart from this overall constant S_H orientation with depth, a pronounced change in the S_H orientation is seen in the caliper analysis at about 7200 m where it jumps by about 60° from N164° to N220°. Possible explanations of this significant change in the stress orientation are discussed in detail in Chapter 6. Apart from this zone no significant trend of the S_H orientation and no large scale zones with markedly different S_H orientations can be identified.

The mean S_H orientations derived from the analysis of each measurement type varies between N148°E and N182°E. The range of values narrows significantly (N148°E-N171°E) if the orientations determined from drilling-induced tensile fractures at about 7 km and 7.7 km depth are not considered, as they are restricted to short depth intervals. Overall, the average stress orientation appears to be in the interval N150° - N170°. This range of orientation 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).

- Hydraulic Fracturing

Hydraulic fracturing measurements are a critically important part of the determination of the stress in the Integrated Stress Measurement Strategy. At shallow depth they allow the determination of the magnitude of both horizontal principal stresses (experiments to 3 km in the KTB pilot hole) and at great depth the determination of the magnitude of the least horizontal principal stress S_h (modified experiments at 6 and 9 km depth in the KTB main hole). The estimations of the magnitude of the greatest horizontal principal stress by means of breakout analysis and analysis of drilling-induced tensile wall-fractures are dependent on the knowledge of the magnitude of S_h and thus, on the success of hydraulic fracturing experiments.

For the planning of the hydraulic fracturing experiments at 6 km and 9 km depth, the downhole temperature and the breakdown pressure had to be estimated to insure that the technical equipment could withstand the downhole conditions and to operate the required downhole pressure.

In mid-December, 1994, a combined hydraulic fracturing / induced seismicity experiment was carried out in the openhole section of the KTB main hole between 9030 m and 9101 m depth to investigate the hydraulic properties of the rock and to determine the recent tectonic stresses at this depth. The first part of the experiment was a modified hydraulic fracturing test conceptually very similar to the experiment run at 6 km depth, whereas the second part had the aim to induce seismicity by injection of a relatively large volume of fluid (200m^3) into the formation.

In conclusion, the various hydraulic fracturing experiments conducted in the KTB boreholes allow to constrain the magnitude of S_h to the final depth of 9 km. The classical hydraulic fracturing tests performed in the KTB pilot hole to about 3 km depth allow a discrete determination of the magnitude of S_h whereas the two modified experiments at 6 km and 9 km depth only allow to constrain the S_h magnitude by a lower limit.

In section 5.4.3 it is demonstrated that the magnitude of S_h is quite close to the lower bound resulting from the hydraulic fracturing tests at 6 km and 9 km depth. This allows to use the lower bound magnitude of S_h for the estimation of the magnitude of S_H without introducing a major error.

- Combined Stress Estimation

Two methods are used to estimate the magnitude of the greatest horizontal principal stress S_H from the occurrence of breakouts and drilling-induced fractures. Both methods are calibrated in the KTB pilot hole where independent control of the magnitude of the horizontal principal stresses is given by hydraulic fracturing measurements and are found to be capable to derive reliable estimates of the greatest horizontal principal stress S_H for the case that the least horizontal principal stress S_h is known.

Breakouts and drilling-induced fractures occur throughout the depth interval from 3000 m to 6800 m. This fact is used for the estimation of the magnitude of S_H as the actual magnitude of S_H has to be consistent with the occurrence of both types of failure. This means, the true magnitude of S_H has to fulfil both the conditions for breakout initiation and for initiation of drilling-induced tensile fractures.

While the breakout-based estimation of S_H is quite stable above 6 km depth, it significantly scatters below 6 km which is due to large changes of the breakout opening angle with depth. Below 6.8 km breakouts are still occurring as known from four-arm caliper measurements but due to the lack of BHTV measurements no reliable breakout opening angles could be determined. Therefore, the estimation of the S_H magnitude below 6.8 km is solely based on the analysis of drilling-induced fractures observed at two depth sections around 7 km and 7.7 km depth. Thus, 7.7 km depth is also the maximum depth the magnitude of S_H can be estimated from borehole failure.

Plotting the results from 3 km, 6 km and 7.7 km depth as Mohr circles demonstrates that the estimated state of stress is consistent with a frictional equilibrium on pre-existing faults optimally oriented with respect to the stress orientation and with a coefficient of friction of m between 0.6 and 0.7.

Finally, a comparison of the derived differential stresses S_1 - S_3 to the theoretically expected differential stress is presented. The strength profile in the upper crust is calculated for the case of a strike slip stress regime, a coefficient of friction m between 0.6 and 0.7 and hydrostatic pore pressure (all these assumptions are confirmed for the KTB site by stress and pore pressure measurements). To assess the entire crustal strength the ductile creep strength for lower crustal rocks with very low and very high strength is calculated, using the creep properties of Adirondack and Pikwitonei granulite as examples. For the calculation of this strength profile temperatures in the lower crust and upper mantle are estimated from a conductive thermal model incorporating the observed geotherm and the relatively high heat flow (~74 mW/m^2) at KTB and in this part of Central Europe. To obtain an upper limit for the strength a high strain rate of 10^{-16} s^{-1} is assumed which is an upper bound for the strain rate in plate interiors.

The crustal strength in the brittle part of the crust, as calculated here, is confirmed by the hydraulic fracturing experiments in the pilot well and by the results of the combined stress estimation discussed in this thesis to a depth of 7.7 km. The stress determinations presented here, clearly show that the crust has at least to 7.7 km depth considerable strength. It is capable of transmitting appreciable amounts of force, comparable in magnitude to the force exerted by e.g. ridge push (Zoback et al., 1993). The apparent strength in midcrustal regions is on the order of hundreds of megapascals. In regions with a heat flow comparable to the one used in the above calculations the strength of the upper mantle is quite low and the brittle crust acts as a 'stress guide'. This steady state failure equilibrium of the brittle upper crust is reflected by the widespread seismicity in Central Europe. The situation is supposed to change markedly in areas with a lower thermal gradient like shield areas, where the upper mantle due to relatively low temperatures is assumed to have appreciable strength. No lithospheric deformation is expected to occur in such regions as the upper mantle is capable of supporting great parts of the total force available (Zoback et al., 1993).

Chapter 6 - Further Aspects of the State of Stress at the KTB

- Stress Perturbation Associated with the SE1 Reflector

The SE1 reflector is the most prominent seismic reflector revealed at the KTB site in the detailed 3-dimensional seismic reflection survey (Hirschmann, 1993, 1994) and is also clearly identifiable by borehole logging and geological indicators (de Wall et al., 1994). Geologically, it corresponds to the fault associated with the Franconian Lineament, which separates the Permo-Carboniferous sediments to the SW from the metamorphic units to the NE (see section 1.1). The analysis of borehole failure indicates that this fault probably influences the stress field in its close surrounding. Breakout investigations reveal a stress orientation which is remarkably constant along the major part of the borehole (N150°-N170°), but just below the depth section where the SE1 is intersected by the borehole the breakout orientation changes significantly over a depth interval of about 300 m. Stress orientation directly below the SE1 reflector is found to be approximately N200° and turns back to about N160° with depth.

Comparing the strike of the SE1 reflector to the mean S_H orientation and to the orientation of S_H directly below the reflector gives a first clue what could be the reason for the observed change in stress orientation. As the SE1 reflector is striking about N130°E the mean S_H orientation (N160°) is at an angle to the reflector which induces high shear stresses on it. The stress orientation just below it is about perpendicular to the reflector which means that it is a plane of vanishing shear stress, a principal plane of the stress tensor. Assuming total stress drop during a former seismic event the SE1 plane would have become a plane free of shear stress, a principal plane. This could cause a stress orientation as it is seen just below the SE1 reflector.

- Preliminary Interpretation of the Main Induced Seismic Event

The strongest of the more than 300 events (M_L 1.2) induced during the fluid injection experiment in the KTB main hole at 9 km depth occurred at the begin of the main injection phase at an approximate depth of 8600 m. The fault plane solution is gained from first motion analysis (Harjes and Zoback, in prep.) and indicates reverse faulting with some strike-slip component along a plane striking N89° and dipping 59° towards south (plane 1), or a strike-slip movement with a reverse component along a plane striking N207° and dipping 52° towards NW (plane 2).

It is investigated if this fault plane solution is consistent with an extrapolation of the state of stress as it is derived in Chapter 5 by the combined analysis of breakouts and drilling-induced fractures to a depth of 7.7 km. Two conditions have to be satisfied in order for the earthquake to be consistent with the given stress tensor and one of the fault planes. First, the ratio of shear stress to effective normal stress on the plane has to reach values comparable to coefficients of friction known from laboratory tests (Byerlee, 1978) and second, the calculated rake should match the observed rake. While the ratio of shear to effective normal stress on plane 2 is quite high and thus favours slip on this plane the calculated rake does not match the observed rake. For plane 1 the rakes match very well but the stress ratio reaches only a value of 0.51. Despite this low stress ratio plane 1 is thought to be the true fault plane. This analysis demonstrates that the main induced seismic event can be explained by an extrapolation of the stress field determined to 7.7 km depth.

References

Barton, C. and M.D. Zoback, *Stress perturbations associated with active faults penetrated by boreholes: Possible evidence for near-complete stress drop and a new technique for stress magnitude measurement*, J. Geophys. Res., 99(B5), p. 9373-9390, 1994.

Barton, C.A., M.D. Zoback, and K.L. Burns, *In-situ stress orientation and magnitude at the Fenton Hill Geothermal site, New Mexico, determined from wellbore breakouts*, Geophys. Res. Lett., 15(5), p. 467-470, 1988.

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

Brace, W.F. and D.L. Kohlstedt, *Limits on lithospheric stress imposed by laboratory experiments*, J. Geophys. Res., 85(B11), p. 6248-6252, 1980.

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, ed. Bram, K. and J.K. Draxler, p. 281-300, Hannover: NLfB-KTB, 1993b.

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

Carter, N.L. and M. Tsenn, *Flow properties of continental lithosphere*, Tectonophysics, 136, p. 27-63, 1987.

de Wall, H., J. Duyster, G. Hirschmann, A. Kontny, S. Lich, and E. Spangenberg, *Die Störungszone in 7 km Tiefe - Ursachen eines seismischen Reflektors*, In: KTB Report 94-3, ed. Hirschmann, G. and U. Harms, p. 83-96, Hannover: NLfB-KTB, 1994.

Hickman, S., D. Moos, C. Barton, and B. Khakaev, *In-situ stress and borehole breakouts in the Tyrnauz well, Caucasus Mountains, USSR (abs)*, In AGU Fall Meeting in San Francisco, EOS Trans., 511, 1991.

Hirschmann, G., *Zur Geologie der KTB-Lokation Oberpfalz*, Zeit. geol. Wiss., 21(1/2), p. 105-116, 1993.

Hirschmann, G., *The KTB location and models of the crustal structure*, In: KTB Report 94-2, ed. Emmermann, R., P. Giese, J. Lauterjung, and T. Umsonst, p. A35-A44, Hannover: NLfB-KTB, 1994.

Müller, B., M.L. Zoback, K. Fuchs, L. Mastin, S. Gregersen, N. Pavoni, O. Stephansson, and C. Ljunggren, *Regional patterns of tectonic stress in Europe*, J. Geophys. Res., 97(B8), p. 11783-11803, 1992.

Rummel, F. and R.B. Winter, *Fracture mechanics as applied to hydraulic fracturing stress measurements*, Earthq. Predict. Res., 2, p. 33-45, 1983.

Shamir, G. and M.D. Zoback, *Stress orientation profile to 3.5 km depth near the San Andreas Fault at Cajon Pass, California*, J. Geophys. Res., 97(B4), p. 5059-5080, 1992.

Vernik, L., M.D. Zoback, and M. Brudy, *Methodology and application of the wellbore breakout analysis in estimating the maximum horizontal stress magnitude in the KTB pilot hole*, Sci. Drill., 3, p. 161-169, 1992b.

Winter, R.-B., *Bruchmechanische Gesteinsuntersuchungen mit dem Bezug zu hydraulischen Frac-Versuchen in Tiefbohrungen*, Ph.D., Ruhr-Universität Bochum, 1983.

Zoback, M.D., R. Apel, J. Baumgärtner, M. Brudy, R. Emmermann, B. Engeser, W. Kessels, K. Fuchs, H. Rischmüller, F. Rummel, and L. Vernik, *Upper-crustal strength inferred from stress measurements to 6 km depth in the KTB borehole*, Nature, 365, p. 633-635, 1993.

Zoback, M.D. and J.H. Healy, *Friction, faulting and in-situ stress*, Ann. Geophys., 2(6), p. 689-698, 1984.