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In situ stress in the German KTB pilot hole deduced from differential strain analysis

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Summary. Differential Strain Analysis is used for the investigation of oriented core samples from the German Continental Deep Drilling Project (KTB) at Windischeschenbach (Oberpfalz/Bavaria). The analysis is modified by using crack closure pressure instead of crack closure strain for determination of the amount and orientation of principal in situ stress. A stress profile as a function of the depth is given and a mean principal stress orientation is calculated. Another result of our work is that in situ stress does not only increase with depth but that the geological structures and the physical properties of rocks are major causes for the local modification of regional in situ stress.

Introduction

Stress measurements in boreholes involve sophisticated techniques, especially in deep ones. There is no measuring technique which is best suited for both shallow and deep boreholes, enabling the calculation of a stress tensor. Each method has its special advantage and disadvantage. The Differential Strain Analysis (DSA) we use in our work is not depth restricted and only core samples of 30 x 30 x 30 [mm] are needed. If principal strain or stress orientations with respect to geographic north are needed, the samples have to be cut from oriented cores. The traditional DSA (Simmons et al. 1974, Ren and Rogiers 1983) is not well suited for foliated or magmatic rocks. Our aim is to correlate the crack closure pressure tensor with the in situ stress tensor. Justification for this attempt is given below.

Sample preparation and measuring technique

First, the core sample is diamond cut and then handpolished to avoid surface damage. Three Hottinger Baldwin Meßtechnik strain gauges (RY93 10/120) are glued on (arranged as in figure 1), and the specimen is vacuum dried and nitrogen vented. A coating of acrylic lacquer prevents the sample from being penetrated by the hydraulic fluid when pressurized. A quartz glass strain compensation cell (Homosil = stress free Optosil) is used. The autoclave can be pressurized up to 600 MPa by a usable length of 120 mm and an internal diameter of 60 mm. The 225 kHz test amplifier is a UPM 40A (Hottinger Baldwin) with a serial interface connected to a computer.

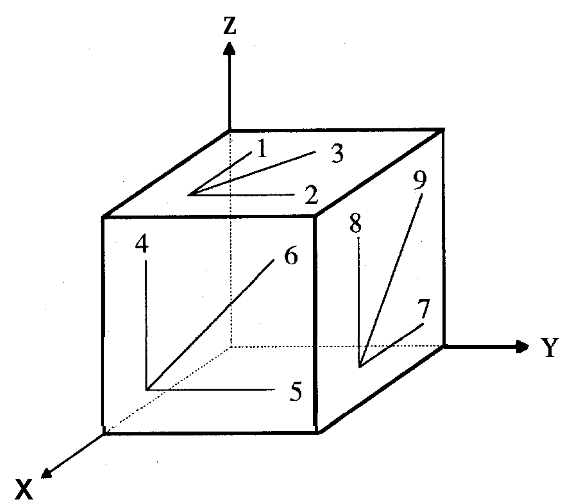

Fig. 1. Orientation of the nine strain gauges (3 strain rosettes) on a core sample for DSA

The hydrostatic pressure in the vessel is increased stepwise (2 MPa per step), and the associated sample strains are recorded. For each measuring direction these strains can be divided into a part due to closure of microcracks and a part caused by the elastic deformation of the core sample. The particular pressure value where all microcracks are closed (the point where the strain curve starts with its linear section) is considered as the total crack closure pressure for the corresponding direction and thus a component of the crack closure pressure tensor. The associated crack closure strains are components of the crack closure strain tensor.

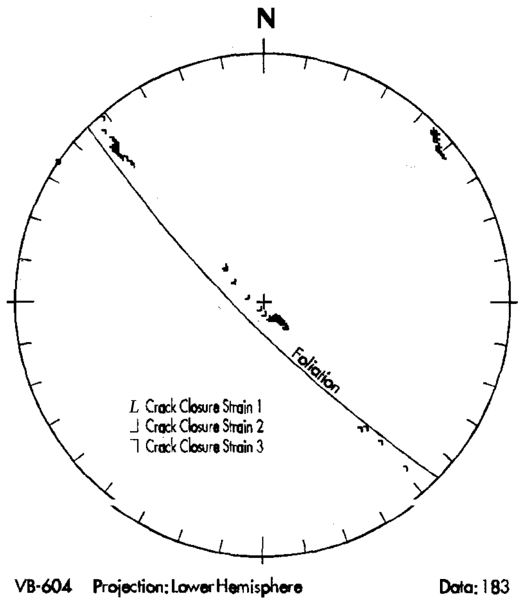

Fig. 2. Dependence of principal crack closure strains orientation on the foliation of rock (garnet amphibole biotite gneiss, 2481 m)

Data processing

According to Siegfried (1977), the strain pressure curves are interpreted as differential strain (sample strain minus strain of the quartz glass), crack closure strain, and crack spectrum.

An example for the orientation of the principal axes of the differential strain tensor is given in figure 2. The orientations are calculated for 61 pressure steps. The correlation between the principal closure strains and the foliation of the rock is obvious. In all tested samples the greatest principal closure strain is oriented normal to the foliation of the rock, and the other two principal closure strains are located in the foliation plane. Usually, the principal values of the crack closure strains are correlated to in situ rock stresses. No such correlation is possible for foliated rock samples but an empirical dependence was found between crack closure pressure and depth. It is possible to identify a distinct crack closure pressure for each strain measuring direction. The obtained pressure values are thought to be components of a crack closure pressure tensor (CCPT). A proof for the assumption that CCPT is linked to the stress tensor is obtained by vertical stress. Vertical stress calculated by rock densities and by CCPT does not differ by more than ± 10 % (fig. 3).

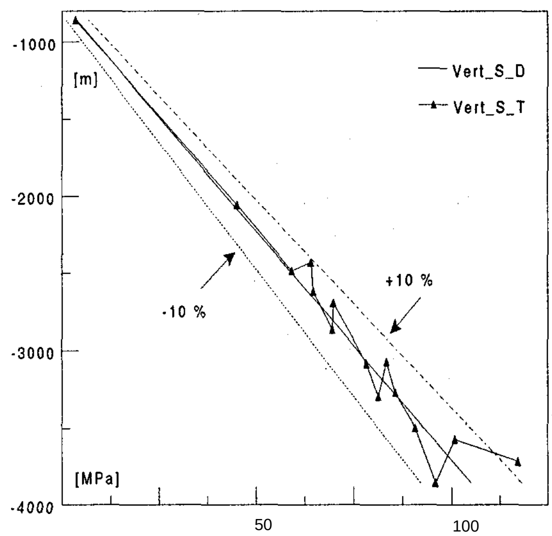

Fig. 3. Diagram showing vertical stresses for the KTB-pilot hole calculated with a density of 2.75 g/cm3 (Vert_S_D) compared with the calculated vertical stresses by crack closure pressure tensor

For six independent directions the components for the crack closure pressure tensor are derived from 3 x 9 different curves (9 x differential strain curve, 9 x crack closure strain curve and 9 x crack spectrum). For three measuring directions we get a second data set and are therefore able to compute nine tensors. The principal values are averaged. The mean values for the corresponding principal directions are obtained by computing three centers of gravity:

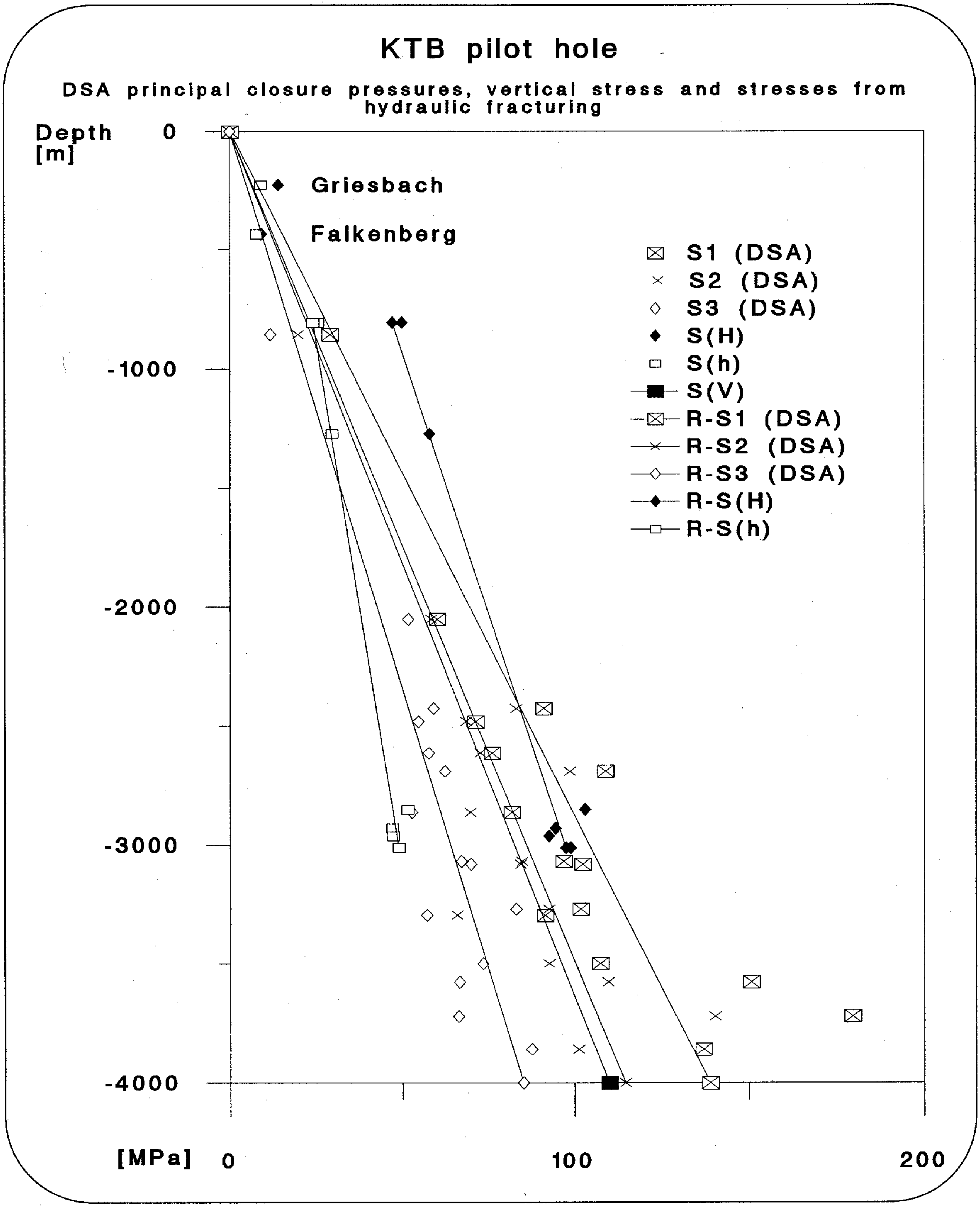

Fig. 4. S1, S2, S3: greatest, intermediate, least principal in situ stress obtained by DS
S(H), S(h): greatest, least principal stress by hydraulic fracturin
S(V): vertical stress calculated by rock density of 2.75 g/cm^3
R-S1, R-S2, R-S3: regression lines of S1, S2, S3
R-S(H), R-S(h): regression lines of S(H), S(h)
Griesbach and **Falkenberg** are sites of hydraulic fracturing in former times

Table 1. DSA - results of cores from the german KTB-pilot-borehole. Principal crack closure pressures (σ_1, σ_2, σ_3) and directions are interpreted as in situ rock stresses

Lithology:

I	sillimanite-biotite-gneiss	VI	biotite-amphibole-gneiss
II	garnet-biotite-gneiss	VII	lamprophyre
III	garnet-sillimanite-biotite-gneiss	VIII	meta-ultramafitite
IV	garnet-sillimanite-muscovite-biotite-gneiss	IX	amphibolite
V	garnet-amphibole-biotite-gneiss	()	orientation opposite core reference line

core-sample	Depth [m]	Lithology	Foliation	σ-1 [MPa]	σ-2 [MPa]	σ-3 [MPa]	dip of σ-1	dip of σ-2	dip of σ-3
191	855	III	45°, 226°	28.9	19.7	11.7	44°, 358°	17°, 106°	40°, 212°
468	2051	VII	-----------	60.0	58.2	51.7	06°, 252°	56°, 153°	33°, 345°
588	2426	III	70°, 036°	91.0	83.0	59.0	35°, 188°	06°, 093°	54°, 355°
604	2481	V	80°, 225°	71.2	68.5	54.6	16°, 153°	65°, 023°	18°, 248°
632	2614	II	50°, 230°	76.0	72.6	57.6	35°, 101°	45°, 325°	24°, 209°
638	2690	VI	70°, 245°	108.9	98.6	62.2	28°, 314°	00°, 224°	62°, 134°
699	2863	III	45°, 230°	81.8	69.7	52.7	56°, 055°	19°, 175°	27°, 275°
751	3068	IV	~horizontal	96.8	84.9	67.1	52°, 177°	00°, 267°	38°, 357°
753	3080	IV	35°, 054°	102.4	84.5	69.9	07°, 006°	64°, 110°	25°, 273°
797	3269	IV	?	101.8	92.5	83.0	07°, 187°	48°, 090°	41°, 283°
802	3295	IV	~horizontal	91.5	65.9	57.0	58°, 225°	30°, 066°	09°, 331°
815	3349	VII	-------------	-----	-----	-----	15°, 043° ?	70°, 148° ?	20°, 308° ?
855	3497	I	?	107.4	92.7	73.4	00°, 045°	86°, 133°	04°, 315°
874	3574	II	80°, 350°	150.7	109.8	66.5	07°, 172°	57°, 071°	32°, 267°
911	3719	VIII	-------------	179.5	140.3	66.2	19°, 258°	37°, 152°	46°, 009°
944	3858	IX	(55°, 240°)	137.0	101.2	87.6	(07°, 060°)	(49°, 322°)	(40°, 156°)

(1) unit vector for each direction:

$$\vec{v_i} = \pm \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix}$$

(2) summation vector:

$$\overrightarrow{|R|} = \left| \sum_{i=1}^{n} \vec{v_i} \right|$$

(3) center of gravity:

$$\vec{S} = \frac{\vec{R}}{|\vec{R}|}$$

In table 1 this vector (3) is given for the directions of the principal crack closure pressures σ_1, σ_2 and σ_3.

Results

Recently, a connection between crack closure pressure and in situ rock stress was reported from other test sites as well. Meglis et al. (1991) report (drillholes of Kent Cliffs (New York) and Moodus (Connecticut)) that the greatest crack closure pressure is approximately equal to the greatest in situ stress. In figure 6 of their article, it can be seen that the pressure steps for the DSA are big (10 MPa) and that it is therefore not possible to estimate the principal crack closure pressures with the necessary precision. In our experiments we increased pressure in steps of only 2 MPa, and are therefore able to calculate principal stresses as described above.

We examined core samples between 855 m and 3858 m depth. All samples, except for 944, are oriented against geographic north. Results are presented in table 1 and figure 4. With these data it is possible to calculate a regression of principal stress magnitudes ($\sigma_{1R} > \sigma_{2R} > \sigma_{3R}$) versus depth:

$$\sigma_{1R} = 0.158 \text{ MPa} + 0.0347 \text{ MPa/m}$$

$$\sigma_{2R} = 0.008 \text{ MPa} + 0.0287 \text{ MPa/m}$$

$$\sigma_{3R} = 0.000 \text{ MPa} + 0.0213 \text{ MPa/m}$$

$$\sigma_{1R} : \sigma_{2R} : \sigma_{3R} = 1 : 0.82 : 0.61$$

The calculation of mean principal stress directions of all samples is not as simple (because of the scattering directions) as it is of one sample as described above. We therefore made a contour plot of the principal stress directions (fig. 5) and calculated a center of gravity with an opening angle of 30° for the highest counter level. The mean directions gained this way are:

σ_1 (direction) = 11°/177°

σ_2 (direction) = 66°/110°

σ_3 (direction) = 29°/280°

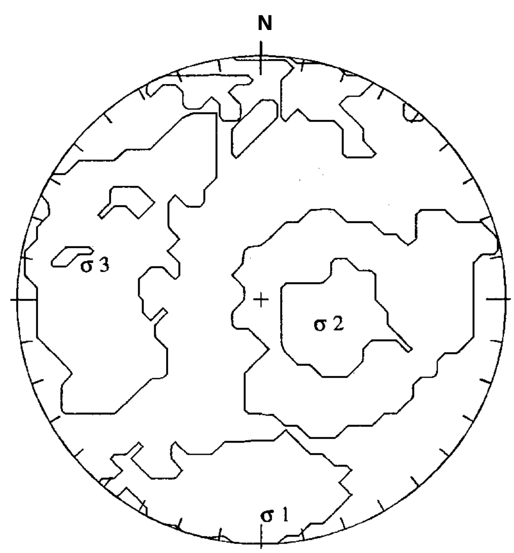

Fig. 5. Mean principle stress directions estimated by contour plot and corresponding centers of gravity

The tectonic regime indicated by the DSA is that of dip slip (fig. 6) at least for the depth range from 800 m to 4000 m. No nearby change of tectonics is indicated by fig. 4. The potential shear planes are oriented SW-NE and NW-SE by a steep dip (this interpretation ignores that angles between conjugate shear planes are smaller than 90°). Nevertheless, proposed tectonic movements are in agreement with the youngest tectonics in the Thuringian Forest where karst caves are affected by dip slip movements, too (Franzke and Rauche 1991).

The interpretation of crack closure pressures as in situ stresses is done first in our research in the KTB-pilot-drillhole, and, fortunately, we are able to compare our results with those obtained by hydraulic fracturing, borehole breakouts, core disking and others.

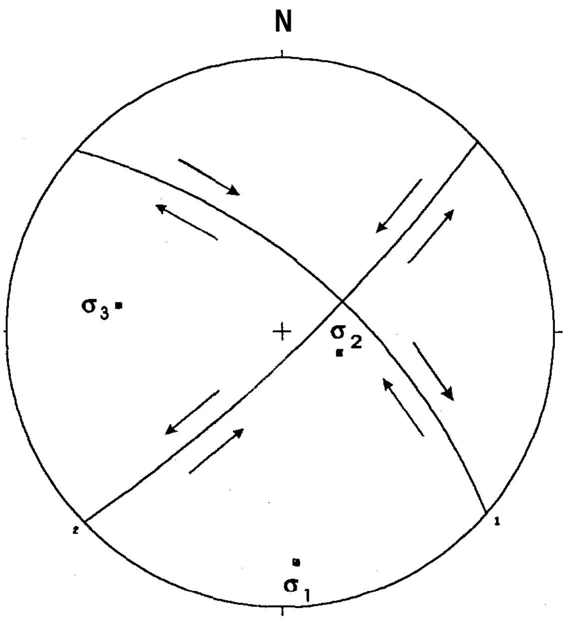

Fig. 6. In situ tectonic principal stresses derived from DSA and the resulting tectonics for the KTB-borehole

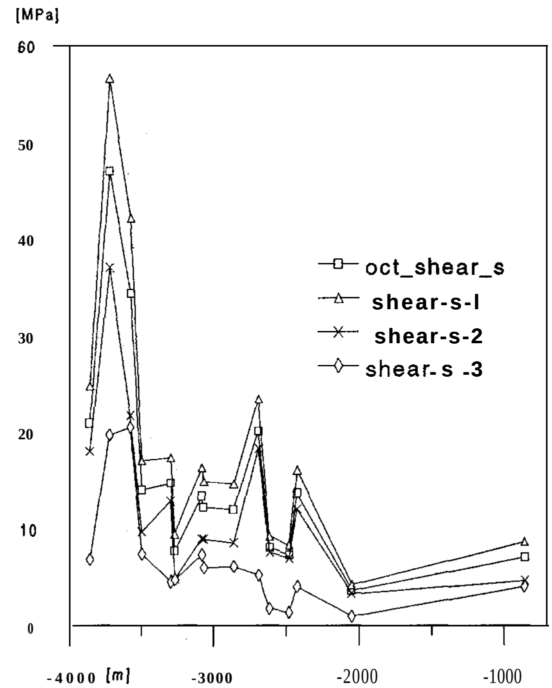

Fig. 7. Shear stress increases below -2600 m and below -3500 m as well as the corresponding principal stresses. The increase in stress is probably caused by changes in the physical properties of rock

Interpretation of the DSA stresses and checking with other data obtained in the KTB pilot drillhole

It is usually assumed in the DSA literature that differential strain and crack porosity are increasing with depth. Our data shows that this is not true for the KTB pilot borehole. Crack porosity depends primarily on petrology and not on depth (Baumann 1991). Kern et al. (1991), fig. 9, published densities of KTB rocks obtained by compressional and shear wave velocities. Data scatters and below 1400 m no dependence of crack porosity on depth is to be seen. Furthermore, the difference between surface and in situ crack porosity is in the range of < 0.1 % and 0.7 %. The comparable DSA crack porosities are between 0.01 % and 0.5 %.

A simple method to estimate crack closure pressure by differential strain or ultrasonic wave velocity pressure response curves is to calculate the point of intersection of the two nearly linear parts of this curve. Kern et al. (1991) showed in their fig. 6 p-velocity pressure response curves for three orthogonal directions of the KTB pilot borehole, depth -2840 m. For these directions we calculated three orthogonal crack closure pressures (58 MPa, 67 MPa, 83 MPa; system of coordinates chosen in respect to petrographic fabric), and the first stress invariant I1 = 208 MPa with the above described method. For depth 2863 m, the stress data from DSA are 53 MPa, 70 MPa, 82 MPa; (system of coordinates chosen to geographic north and downhole) and invariant of stress, I1 = 205 MPa. The magnitude of horizontal principal stresses calculated with the hydraulic fracturing data (Baumgartner et al. 1990) for the corresponding depth are: 47 MPa and 94 MPa (I1 = 222 MPa). I believe these data fit very well and constitute a further proof that crack closure pressures are connected linearly with in situ stresses.

Principal stresses and shear stresses (from DSA) show two prominent peaks below 2600 m and below 3500 m depth (fig. 4, 7). For this local increase in stress two causes may be acting. Firstly, the geological structure of the recumbent double fold described by Röhr et al. (1990), and secondly, the change in rock composition corresponds to changes in physical properties. Between 2470 m and 2690 m, intercalations of amphibolites, biotite-gneiss and amphibolite-gneisses are observed (Lauterjung and Emmermann 1990) and below 3575 m, amphibolites, that means more competent rocks.

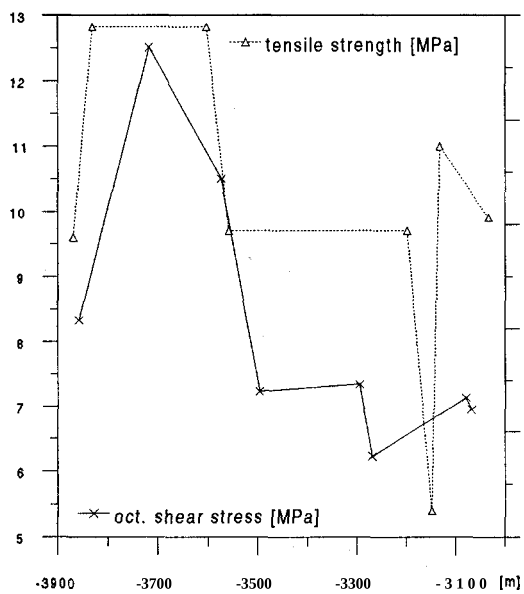

Fig. 8. The magnitude of in situ stress in the KTB-pilot-hole depends on physical properties of rock. Shown are tensile rock strength (Brazilian test) and octahedral shear stress (DSA)

The change of stress recorded by DSA is accompanied by several other changes of physical rock properties, like rock density (Stroh et al. 1990; Bücker et al. 1990), susceptibility (Bücker et al. 1990), and tensile strength of rock. For the depth of maximum increase of stress we compared octahedral shear stresses with tensile strength obtained by Brazilian tests of core samples in the KTB-Feldlabor (Röckel and Natau 1990). These data (fig. 8) substantiate the connection of local in situ stress and physical rock properties.

The implication of our stress data and its interpretation is to look thoroughly at the stress changes with depth and to interpret these in connection with geological structure and physical properties of rocks. Calculating a mean stress gradient is only a useful and common simplification.

Stress orientations obtained by DSA are spatial data, and not plane data as all other stress measurements done in the KTB pilot drill hole. The direction of σ_1 (DSA) is comparable to the maximum horizontal principal stress directions (σ_H) calculated by the other stress measurements. The mean directions of DSA: σ_1 = 177°, breakouts: σ_H = 161° ± 14° (Mastin et al. 1991), core discing: σ_H = 163° ± 22° (Wolter et al. 1990), core retardation: σ_H = 168° ± 25° (Zang et al. 1990) and hydraulic fracturing: σ_H = 149° ± 15° (Baumgärtner et al. 1990) differ significantly from the regional Western European stressfield with σ_H = 146° ± 14° (Baumann and Illies 1983). Fore these mean directions we have to take into account that directions may change with depth as a consequence of the geological structure and changes in petrology. The KTB-project with its interdisciplinary research is a chance for a better understanding of these interactions between in situ stress and the geological structure.

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