GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 7, PAGES 1045-1048, APRIL 1, 2000

Fracture permeability and in situ stress to 7 km depth in the KTB Scientific Drillhole

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Abstract. To better understand the mechanisms that control fluid flow and hydraulic conductivity at significant depth in the brittle crust, we have examined the relationship between fracture permeability and in situ stress in the German continental deep drillhole (the KTB main hole) through analysis of high resolution temperature profiles. Our analysis shows that over the entire 3 - 7 km depth range studied, permeable fractures and faults (i.e., those associated with distinct thermal anomalies) lie close to the Coulomb failure line for a coefficient of friction of about 0.6. This indicates that critically-stressed faults in the crust are also the most permeable faults. This includes a major Mesozoic thrust fault at 7.1 km that is being reactivated as a strike-slip fault in the current stress field. Conversely, non-critically stressed fractures and faults do not appear to be permeable as they are not associated with identifiable thermal anomalies.

1. Introduction

It is generally accepted that fractures provide important pathways for fluid flow in the earth's crust [see review by Hickman et al., 1995]. Fluid-filled fractures can exist even at mid-crustal depth as has been shown by the detection of large flows of hot brine at depths to greater than 9 km in the deep wellbore of the Kola Peninsula [Kozlovsky, 1984]. However, it is not well understood how such high-permeability of fractures at the mid-crustal depth can persist under a confining stress of several hundreds of Megapascals and severe hydrothermal conditions expected to cause fracture closure and healing. To better understand the mechanisms that control hydraulic conductivity at depth in the mid crust, we analyze the fractures observed in the German Continental Deep Drilling Program (KTB) main drillhole. In the present analysis, we use data collected from 3 -7 km depth in the main hole to examine the relationship among fracture permeability, fracture orientation and in situ stress.

2. Procedure

The KTB site is located in the Oberpfalz region in northeastern Bavaria at the western end of the Bohemian massif. The KTB main hole penetrated a repeated sequence of folded and faulted gneisses and amphibolites [Wagner et al., 1997] and reached a final depth of 9.1 km at the end of 1994. A wide variety of downhole measurements were made in the KTB main hole were conducted. For an overview of the KTB project, see Emmerman and Lauterjung [1997]. In this study, we analyzed data collected from 3 - 7 km depth where data quality was uniformly high. First we used precise temperature measurements to detect localized thermal anomalies. The thermal anomalies are associated with fluid flow in and out of the wellbore along relatively permeable fractures [Drury and Jessop, 1982; Hess, 1986; Cornet, 1989]. Fractures that correlated in depth with the thermal anomalies were considered to be hydraulically conductive. The depth, strike and dip of fractures were detected by FMS/FMI measurements [Hirschmann and Lapp, 1994].

To identify thermal anomalies associated with localized fluid flows in and out of the borehole, differential temperature ΔT vs. depth was obtained from temperature profiles, where ΔT is the difference between the measured temperature and the average temperature within a moving window (see Fig. 1). A 100 m window size was chosen to highlight localized temperature perturbations. We identified peaks (or troughs) with the amplitude of ΔT more than ± 0.5 °C. Fractures at the depths of thermal anomalies are assumed to be responsible for the inferred fluid flow. Taking into account the possible depth mismatch between FMS/FMI imaging and temperature logging runs, fractures detected by FMS/FMI measurements within ± 5 m of a thermal anomaly were assumed to be permeable. Conversely, fractures located more than 5 m from thermal anomalies were assumed to be non-permeable.

To examine the relationship among fracture permeability, fracture orientation and the state of in situ stress, we evaluated shear and normal stresses on each fracture and compared them with the Coulomb criterion for frictional sliding of fractures. In earlier works [Barton et al. 1995, Hickman et al., 1997], it has been shown that the permeability of fractures critically stressed for frictional shear failure is much higher than that of fractures not critically stressed in the current stress field. This has been demonstrated for the fractures in relatively shallow wellbores drilled less than 3.5 km. The Coulomb criterion is represented as

$$\tau = \mu\left(S_n - P_p\right) \tag{1}$$

where μ is the coefficient of friction along a fracture plane and P_p is local pore pressure. Frictional sliding will occur on a fracture plane with a ratio of shear to normal effective stress of $\geq \mu$. Generally, μ is thought to be in the range of μ = 0.6 - 1.0 [Byerlee, 1978]. τ and S_n are shear and normal stresses on a fracture which are given as a function of the three principal stresses S_i (i = 1, 2, 3) as follows. Direction cosines between the normal to the fracture plane and axes of S_1, S_2 and S_3 are defined as L, M and N respectively. Stress vector (resultant stress) acting on the fracture plane is denoted as $\boldsymbol{p}$ which has components p_i (i = 1, 2, 3) for the principal stress axes. Taking account of Cauchy's formula, the magnitude p of $\boldsymbol{p}$ is given by

$$p^2 = p_1^2 + p_2^2 + p_3^2 = L^2S_1^2 + M^2S_2^2 + N^2S_3^2 \tag{2}$$

$\boldsymbol{p}$ is also resolved into τ and S_n so that

$$p^2 = \tau^2 + S_n^2 \tag{3}$$

The normal stress S_n is

$$S_n = Lp_1 + Mp_2 + Np_3 = L^2S_1 + M^2S_2 + N^2S_3 \tag{4}$$

Paper number 1999GL011068.
0094-8276/00/1999GL011068$05.00

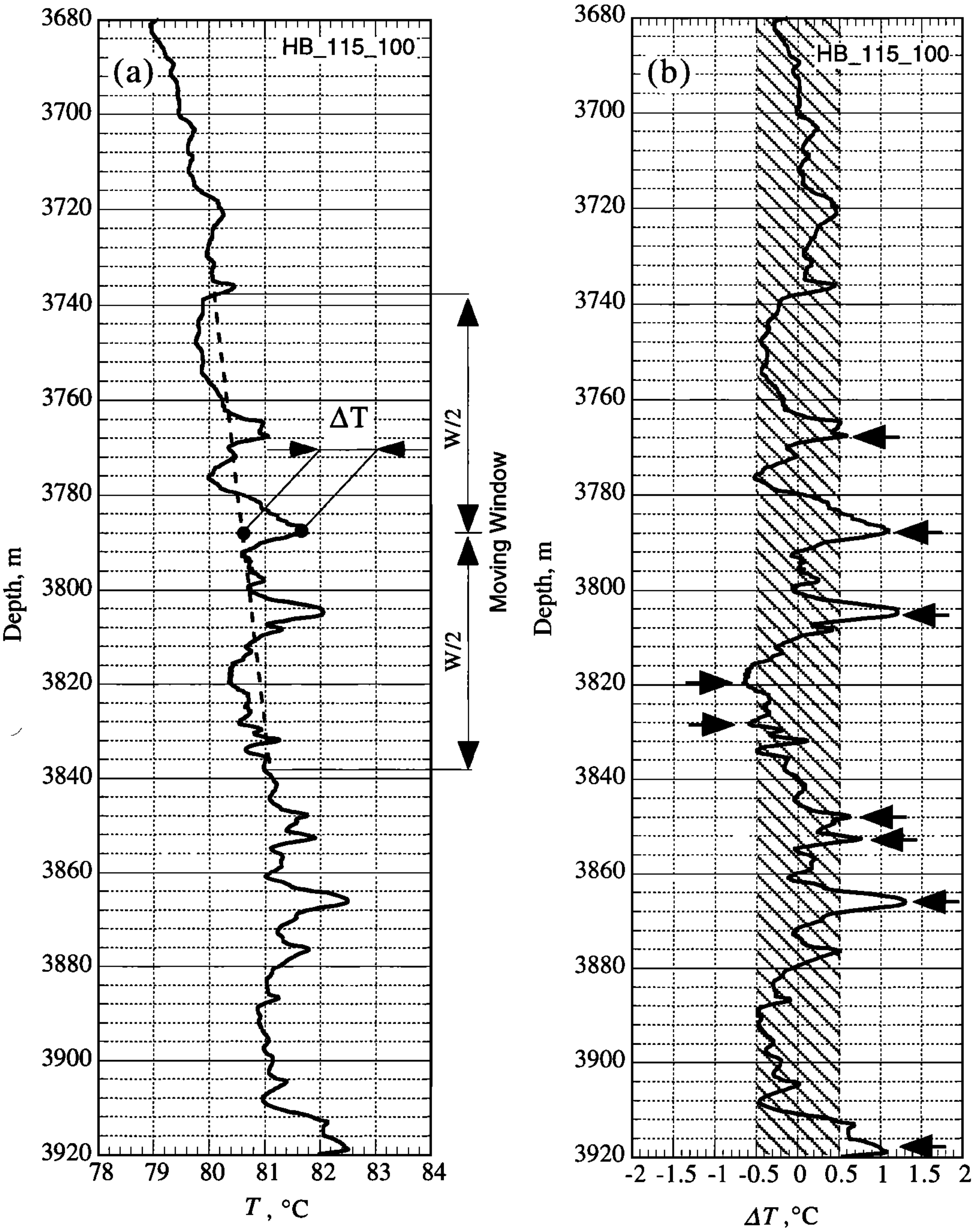

Figure 1. (a) An example of temperature profile and (b) the de-trended temperature data utilizing a moving window as described in the text. In (a) T is temperature and in (b) ΔT is the difference between the measured temperature and the average temperature to enhance thermal anomalies. We identified thermal anomalies (denoted by arrows in Fig. (b)) which exceeded a cutoff value of $\Delta T = \pm 0.5$ °C.

Substituting Eqs. (2) and (4) into Eq. (3) gives

$$\tau = \left[L^2 M^2 (S_1 - S_2)^2 + M^2 N^2 (S_2 - S_3)^2 + N^2 L^2 (S_3 - S_1)^2 \right]^{\frac{1}{2}} \qquad (5)$$

In the KTB borehole, a continuous profile of the magnitudes and orientation of S_H, S_h and S_v was estimated to the depth of 8.6 km [Brudy et al., 1997], where S_H and S_h are the principal stresses in a horizontal plane ($S_H > S_h$) and S_v is the vertical principal stress. This was achieved utilizing an "integrated stress measurement strategy" (ISMS) which combines various methods such as hydraulic fracturing tests and analysis of compressional (breakout) and tensile (drilling-induced tensile wall fractures) failures of the wellbore wall. Although uncertainties for the estimated stress magnitudes were presented in Brudy et al's results, we simplified the results by assuming linear stress profiles for the depth range of 3 - 7 km as follows:

$$S_H = 0.045d, \quad S_h = 0.02d, \quad S_v = 0.028d \qquad (6)$$

where the stresses are in MPa and depth (d) is in meters. These data indicate that the KTB site is currently in a strike-slip faulting stress regime and stress magnitudes are sufficiently high that well-oriented fractures and faults are critically-stressed (i.e., on the verge of frictional failure) in the current stress field [Brudy et al., 1997; Zoback and Harjes, 1997]. The orientation of S_H was found to be uniform with depth with an orientation of N160°E. Huenges et al. [1997] report both direct and indirect estimates of the pore pressure P_p in the KTB drillhole that indicate an essentially hydrostatic gradient to 9.1 km depth.

3. Results

The shear stress τ and the effective normal stress S_n- P_p acting upon fractures were computed and plotted in 3D Mohr diagrams. The results for fractures found in the entire depth range of 3 - 7 km are shown in Fig. 2. The results show that the great majority of permeable fractures (i.e., those associated with thermal anomalies) lie close to the Coulomb failure line for $\mu \sim 0.6$. Conversely, extremely few of the non-critically stressed fractures appear to be permeable as they are not associated with identifiable thermal anomalies.

In addition to the numerous relatively small-scale fractures and faults intersected by the borehole, a major Mesozoic age thrust fault was penetrated by the KTB main hole at 7.1 - 7.2 km [Wagner et al., 1997]. That fault is associated with a pronounced seismic reflector termed "SE1" in the 3-D seismic reflection data obtained at the site [Harjes, et al., 1997]. Importantly, there is an extremely large temperature perturbation of more than 5 °C associated with this "SE1" fault. An open square in Fig. 2 represents the shear and effective normal stresses on the SE1 reflector. The SE1 reflector also lies close to the Coulomb failure line. It is noteworthy that this Mesozoic age thrust fault is being reactivated as a strike-slip fault in the current stress field.

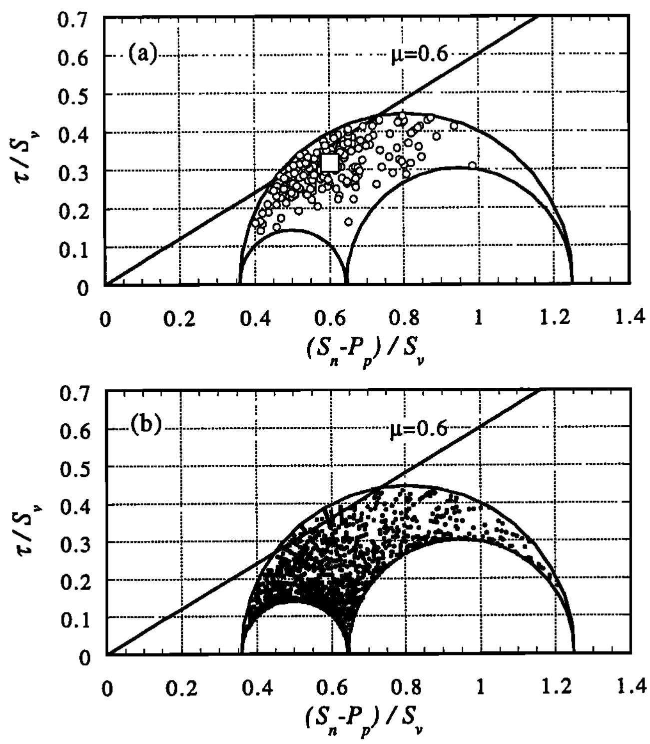

Figure 2. Shear stress versus effective normal stress, normalized by the vertical stress S_v at each fracture depth, for (a) hydraulically conductive and (b) non-conductive fractures in the KTB main hole for the depth range of 3 -7 km. The open square in Fig. (a) represents the shear and normal stresses for the major Mesozoic age thrust fault associated with the SE1 reflector (see text).

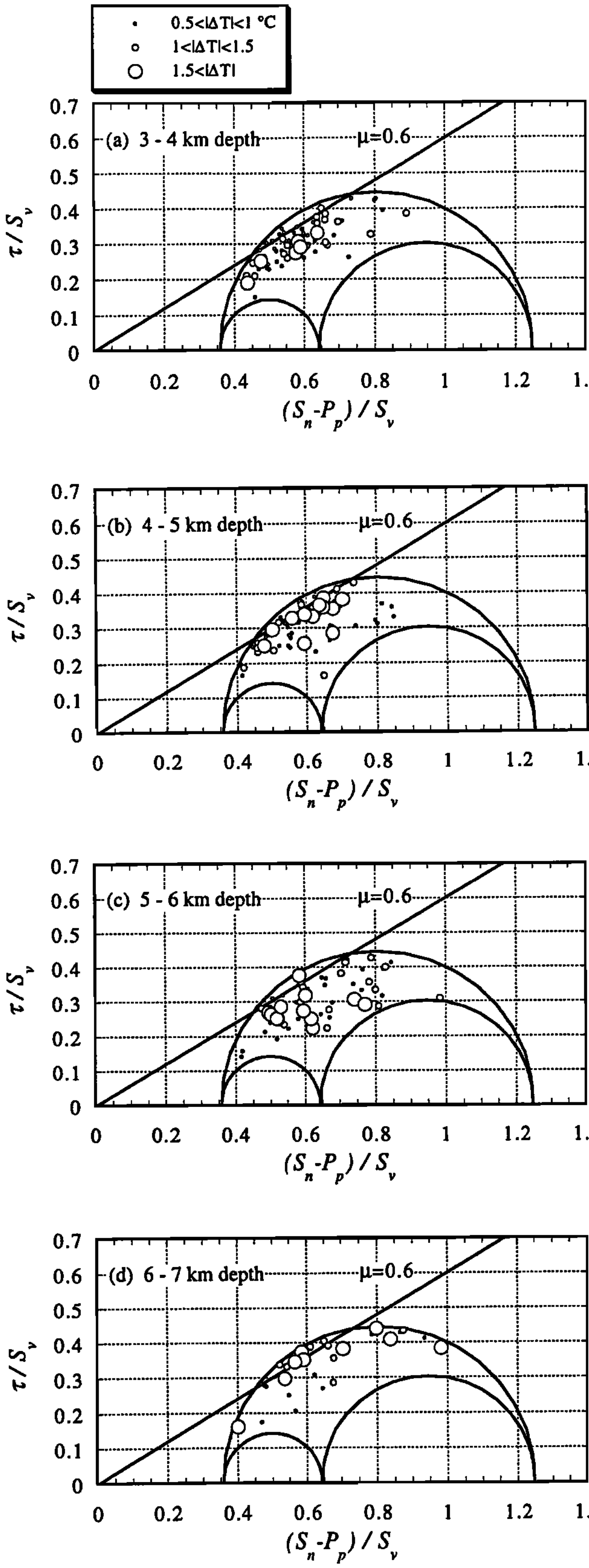

Figure 3. Shear stress versus effective normal stress, normalized by the vertical stress S_v at each fracture depth, for hydraulically conductive fractures found in the depth ranges of (a) 3 - 4 km, (b) 4 - 5 km, (c) 5 - 6 km and (d) 6 - 7 km. The stresses are represented by using open circles with three different sizes depending on the amplitude of the thermal anomaly associated with each fracture.

This result provides additional evidence of a correlation between critically-stressed fractures and faults and permeable fractures and faults at great depth in the brittle crust.

In Fig. 3, the data presented in Fig. 2 are sub-divided into 1 km depth ranges and the amplitude of the thermal anomalies is classified into three levels. Except for Fig. 3c, Figs. 3a,b,d show that the fractures associated with the larger thermal anomaly tend to lie closer to the Coulomb failure line. As more fluid flow in or out of the wellbore is likely to cause a larger thermal anomaly, there appears to be a more quantitative correlation between stress and apparent fracture permeability (fracture aperture). Fig. 3c shows that there is not a particularly good correlation between critically-stressed fractures and permeable fractures in the depth range of 5 - 6 km. The reason for this is not clear. Relatively few fractures and fault are present in this depth interval [Wagner et al., 1997] which is composed almost entirely of amphibolite. However, there are no indications of an anomalous stress magnitudes or orientations at these depths [Brudy et al., 1997].

4. Conclusions

The results of our investigation demonstrate that bulk permeability at great depth in the brittle crust (3 - 7 km depth) appears to be controlled by critically-stressed fractures and faults as previously reported by Barton et al. [1995] at much shallower depths.

Most fractures may be permeable right after their formation. However, over time, hydrothermal conditions cause healing and sealing of the fractures due to water/rock chemical reactions which will significantly reduce fracture-induced permeability. If shear slip occurs on a critically-stressed fracture, it raises the permeability of the fracture through several mechanisms. Brecciation and increases in porosity are expected to occur along the shear plane due to shear slip and there will also be an increase in the permeability due to increases of the surface roughness of the fracture plane [e.g., Brown, 1987, Yeo et al., 1998] as well as the breakdown of seals in fractures [Olsen et al., 1998]. Such mechanisms are capable of playing an important role in sustaining permeability of fractures and faults at appreciable depth and temperature over the course of geologic time.

Acknowledgments. This work was financially supported by the National Science Foundation, EAR 96-14267.

References

Barton, C. A., M. D. Zoback, and D. Moos, Fluid flow along potentially active faults in crystalline rock, *Geology*, 23(8), 683-686, 1995.

Brown, S. R., Fluid flow through rock joints, The effect of surface roughness, *J. Geophys. Res.*, 92, 1337-1347, 1987.

Brudy, M., M. D. Zoback, K. Fuchs, F. Rummel, and J. Baumgärtner, Estimation of the complete stress tensor to 8 km depth in the KTB scientific drill holes: Implications for crustal strength, *J. Geophyhs. Res.*, 102(B8), 18453-18475, 1997.

Byerlee, J., Friction of rocks, Pageoph, 116, 615-626, 1978.

Cornet, F. H., Survey by various logging techniques of natural fractures intersecting a borehole, *Proc. Int. Symp. Borehole Geophysics and Mining, Geotechnical and Groundwater Applications*, 3rd, II, 559-569, 1989.

Drury, M. J., and A. M. Jessop, The effect of a fluid-filled fracture on the temperature profile in a borehole, *Geothermics*, 11(3), 145-152, 1982.

Emmermann, R., and J. Lauterjung, The German Continental Deep Drilling Program KTB: Overview and major results, *J. Geophys. Res.*, 102(B8), 18179-18201, 1997.

Harjes, H.-P., and 12 others, Origin and nature of crustal reflections: Results from integrated seismic measurements at the KTB superdeep drilling site, *J. Geophys. Res.*, 102(B8), 18267-18288, 1997.

Hess, A. E., Identifying hydraulically-conductive fractures with low-velocity flow meter, *Canadian Geotechnical J.*, 23, 69-78, 1986.

Hickman, S., R. Sibson, and R. Bruhn, Introduction to special section: Mechanical involvement of fluids in faulting, *J. Geophys. Res.*, 100(B7), 12831-12840, 1995.

Hickman, S., C. B. Barton, M. Zoback, R. Morin, J. Sass, and R. Benoit, In-situ stress and fracture permeability in a fault-hosted geothermal reservoir at Dixie Valley, Nevada, *Geoth. Res. Coun. Trans.*, 21, 181-189, 1997.

Hirschmann, G., and M. Lapp, Evaluation of the structual geology of the KTB Hauptbohrung (KTB-Oberpfalz HB), *KTB Rep.* 94-1, 285-308, 1994.

Huenges, E., J. Erzinger, J. Kück, B. Engeser, and W. Kessels, The permeable crust: Geohydraulic properties down to 9101 m depth, *J. Geophys. Res.*, 102(B8), 18255-18265, 1997.

Kozlovsky, Y. A., The world's deepest well, *Scientific American*, December, 98-104, 1984.

Olsen, M. P., C. H. Scholz, and A. Léger, Healing and sealing of a simulated fault gouge under hydrothermal conditions: Implications for fault healing, *J. Geophys. Res.*, 103(B4), 7421-7430, 1998.

Yeo, I. W., M. H. De Freitas, and R. W. Zimmerman, Effect of shear displacement on the aperture and permebility of a rock fracture, *Int. J. Rock. Mech. Min Sci.*, 35(8), 1051-1070, 1998.

Wagner, G. A., and 17 others, Post-Variscan thermal and tectonic evolution of the KTB site and its surroundings, *J. Geophys. Res.*, 102(B8), 18221-18232, 1997.

Zoback, M. D., and H. P. Harjes, Injection-induced earthquakes and crustal stress at 9 km depth at the KTB deep drilling site, Germany, *J. Geophys. Res.*, 102(B8), 18477-18491, 1997.

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(Received September 23, 1999; revised January 21, 2000; accepted February 10, 2000.)