In Situ Permeability Measurements in the KTB Pilot Hole VB
Using a Wireline-Operated
Hydraulic Fracturing Straddle Packer Assembly

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Abstract

A series of hydraulic fracturing stress measurements within the KTB project was conducted in the pilot hole VB during February 1990. At two test zones (2010 m, 1270 m) pressure pulse test (test period 5 - 6 minutes) were performed to obtain an estimate of the in situ wall-rock permeability. These experiments were conducted using a wireline operated hydrofrac straddle packer assembly (pack-off length about 1 m). The wireline hydrofrac system is well suited for such tests because it can be considered a stiff hydraulic system due to the very small pressurized fluid volume. Permeability values can be estimated from pressure pulse tests by comparing the measured pressure decay with theoretically derived pressure decay curves. A careful data analysis shows that permeabilities values as derived from these 'short-time' experiments are very low ranging from 2 - 4 µDarcy at 2010 m to 4 - 6 µDarcy at a depth of about 1270 m.

Zusammenfassung

Im Februar 1990 wurden in der KTB Vorbohrung VB eine Reihe von Hydraulic Fracturing Spannungsmessungen durchgeführt. Dabei erfolgte in zwei Testzonen (2010 m, 1270 m) eine Abschätzung der Permeabilität des Gesteins an der Bohrlochwandung über so genannte 'Druckstoßversuche'. Bei diesen Experimenten kam eine Hydrofrac-Sonde zum Einsatz, die an einem Bohrloechskabel in die Bohrung abgelassen wird. Dieses Verfahren zeichnet sich durch sein geringes Systemvolumen und die damit verbundene hohe Systemsteifigkeit aus und ist daher auch für Permeabilitätsmessungen gut geeignet. Die Länge der Testabschnitte betrug etwa 1 m. Die Versuche erstreckten sich jeweils über einen Zeitraum von etwa 5 - 6 Minuten. Die Permeabilitätsverhältnisse können über einen Vergleich der im in situ beobachteten mit theoretisch ermittelten Druckabfallkurven bestimmt werden. Hierbei ergeben sich Permeabilitätsverhältnisse, die zwischen 2 - 4 µDarcy bei 2010 m und 4 - 6 µDarcy bei ca. 1270 m streuen.

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1. Introduction

Fluid transport properties of the Earth's crust are critical for the understanding of a wide range of phenomena such as the migration of crustal fluids, de-gassing of the mantle or deep hydrothermal circulation related to ore genesis. In situ measurements of rock mass permeability in deep boreholes are an indispensable tool gathering the data base necessary for the development of appropriate models of fluid transport in the lower crust. The hydraulic fracturing technique for stress measurements offers a unique possibility to collect permeability data from definite, carefully packed-off test zones at no additional costs. However, permeability measurements require a testing apparatus capable of recording even very small fluid exchanges between the hydraulic test system and the rock mass. This goal can be achieved through a very stiff hydraulic test system. At the KTB site permeability measurements were performed using a wireline operated hydraulic fracturing system. Thin flexible steel tubing injection lines (I.D. 6mm) plus the fairly short test section of about 1 m guarantee in this construction a very stiff hydraulic system, even at great depths. Unfortunately, wireline hydrofrac testing had to be given up after the wireline tool got stuck in the hole due to a damaged packer element. The test program was then continued using a conventional string operated straddle packer assembly. Permeability tests remained limited to the wireline test period because a suitable downhole shut-in valve was not available. Such a valve is required in a conventional tubing operated hydrofrac system to achieve the system stiffness necessary for permeability measurements.

2. Apparatus and Testing Procedure

To conduct permeability and stress measurements in boreholes the Institute of Geophysics at the Ruhr-University in Bochum began in 1973 the development of a wireline hydrofracturing packer assembly which should render fast and relatively inexpensive borehole measurements without the need for standby of a drill rig [1]. Since 1985, the further development and implementation of this concept for deep boreholes was carried out by MeSy GmbH in Bochum. For the hot dry rock research at Soultz sous Forets a wireline-based system for measurements down to 5000 m was developed.
The main components of this system are shown in Fig. 1. It can be seen that the straddle packer unit is tripped into the borehole on a seven conductor logging cable. The packer elements and the test chamber are pressurized via a flexible steel tubing (I.D. 6 mm) which is clamped to the logging cable at 30 m intervals. The straddle packer assembly consists mainly of two about 1 m long inflatable packer elements with an injection adaptor piece in between. A precision push-pull valve mounted on top of the straddle packer assembly allows to switch from packer pressurization to injection into the test interval, and the reverse, by simply releasing or pulling the logging cable. For the tests at the KTB site a test section of about 1 m length was prepared. The fluid volume incorporated in the hydraulic system described here is less than 30 liters per 1000 m depth. The injection fluid used during wireline testing was water mixed with antifreeze to prevent freezing in the pressure lines on surface. A remote controlled hydraulic driven URACA plunger pump system was installed on surface which could yield injection pressures of up to 50 MPa at a maximum injection rate of 9 l/min. Integrated amplifier pressure gages are mounted downhole on top of the straddle packer assembly inside a transducer housing with a dewar bottle and two heat sinks. Surface and downhole pressures, pumping rate and back flow from the test zone are recorded on a strip chart recorder and are digitally stored (2 Hz per channel) on a hard disk.

The testing procedure for permeability measurements begins immediately after packers are set by rapidly pressurizing the test interval to about 3 - 6 MPa above hydrostatic. After the pump has been shut-off, the following pressure drop in the closed system is recorded over a period of about 5 - 6 minutes. Then, before hydrofracturing starts, the hydraulic systems is completely vented.

3. Permeability Data Analysis

The analysis of the observed pressure decay curves follows the theoretical treatment suggested by Cooper et al. [2] for slug tests. The procedure is described in detail by Heuser [3]. For easier analysis Rummel et al. [4] have presented a collection of theoretical pressure decay curves adapted for the typical wireline hydrofrac set up and computed for a variety of parameter sets which for instance include system stiffness, storage
coefficient, pressure level and rock permeability. Permeability values can now be determined by simply comparing the observed pressure decay curve with different model curves.

It should be noted here, that due to the fact that the analysis described above is based on the equation of diffusion for an isotropic and homogeneous material,

\[
\frac{\partial^2 p}{\partial r^2} + \frac{1}{r} \frac{\partial p}{\partial r} - \frac{1}{\kappa} \frac{\partial p}{\partial t} = 0
\]

\( p \): fluid pressure within the pore volume (function of distance \( r \) and time \( t \))

\( \kappa \): diffusivity

the rock present in the selected test interval is simplified as a uniformly permeable rock mass - although in reality the fluid leak-off in crystalline rocks occurs along distinct cracks in the rock mass.

4. Results

As already mentioned above, only two permeability measurements could be performed in the VB borehole because wireline hydrofrac testing had to be given up after the wireline tool got stuck in the hole due to a damaged packer element. The recorded pressure decay curves are shown in Fig. 2 a,b. The test depths as measured during wireline hydrofrac testing are 1270 m and 2010 m (center of test interval). A post-hydrofrac FMS log showed that the test called 1270 m was probably performed a bit deeper, around 1277 m (the FMS log also showed some depth uncertainty !). A depth measuring error in our system may have encountered while the already damaged packer was dragged up-hole from 2010 m. Therefore, the test at 1270 m / 1277 m was performed in amphibolite while the test at 2010m was conducted in gneiss. The results of the permeability analyses are summarized below in Tab. 1. It can be seen that the test at about 1270 m shows a somewhat lower system stiffness compared to the test at 2010 m. This is probably caused by a small amount of air trapped in the hydraulic
system. The permeability values derived are extremely low and demonstrate that basically no difference exists between amphibolite and gneiss in our test zones.

**Tab. 1:** Results of permeability measurements in the KTB-VB borehole using a wireline hydrofrac straddle packer assembly

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>$\Delta V/\Delta P$ (cm³/MPa)</th>
<th>$\alpha$ (sec.)</th>
<th>$T_m$ (sec.)</th>
<th>$\kappa$ (μDarcy)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>~ 1270</td>
<td>60</td>
<td>90</td>
<td>3000</td>
<td>4 - 6</td>
<td>hydr. tensile strength</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~ 5000</td>
<td></td>
<td>about 3.4 MPa</td>
</tr>
<tr>
<td>2010</td>
<td>40</td>
<td>90</td>
<td>3000</td>
<td>2 - 4</td>
<td>hydr. tensile strength</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>in the order of 20 MPa</td>
</tr>
</tbody>
</table>

**Symbols:**

- $\kappa$: permeability
- $\Delta V/\Delta P$: inverse system stiffness
- $\alpha$: storage coefficient
- $T_m$: time factor, necessary for the comparison of standardized pressure decay curves

5 **Acknowledgement**

The proposal of hydrofrac permeability and stress measurements was always strongly supported by the KTB working group "Stress and Borehole Stability". Great interest in the proposal was shown by the project coordinators, particularly by R. Emmermann and P. Giese. Encouragement for the conduction of our work came also from the KTB project management in Hannover, particularly from J.K. Draxler, B. Engesser, W. Klessels, and from I. Rischmüller.

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The Ruhr-University in Bochum provided all the infrastructure for the preparation, conducton and data evaluation of the permeability and stress measurements.

6 Literature


Fig. 1: Set up for wireline hydrofrac and permeability measurements at the KTB - VB borehole
Fig. 2a: KTB - VB  
1270 m wireline

Fig. 2b: KTB - VB  
2010 m wireline

Fig. 2: Pressure decay curves recorded at 2010 m and at 1270 m depth in the KTB - VB borehole