HYDRAULIC FRACTURING STRESS MEASUREMENTS IN THE GPK1 BOREHOLE, SOULTZ SOUS FORETS

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During late 1988, eight hydrofrac or injection tests were carried out within the crystalline granitic section (1376 to 2000 m) of borehole GPK1 to both investigate the hydraulics of the rock and to determine the state of stress at depth. Although various problems were encountered due to high temperature, gas content and salinity of the borehole fluid, sufficient pressure data and fracture orientations could be sampled during the tests and subsequent BHTV logging to enable us to conduct an inversion type stress analysis. The computations yields the following principle stress profiles for the granitic basement between 1450 and 2000 m:

\[ S_v, \text{MPa} = 0.024^*z, m \]
\[ S_h, \text{MPa} = 15.0 + 0.0179 \cdot (z, m - 1450) \]
\[ S_H, \text{MPa} = 24.6 + 0.0198 \cdot (z, m - 1450) \]

According to the computation, the direction \( \theta \) of maximum horizontal compression \( S_H \) is \( N 155^\circ \pm 3^\circ \). Taking into account an error in depth measurement by 0.5 m yields a direction of \( \theta = N 176^\circ \pm 6^\circ \). Both directions can be accepted with respect to existing data for Central Europe. The stress profiles obtained characterize normal faulting typical for graben tectonics. It should be mentioned, however, that the present data base is extremely limited, and further tests are required to allow a reliable stress estimate at greater depth.

*Keywords: geothermal energy, hydraulic fracturing, stress analysis, stress field, Hot Dry Rock*

INTRODUCTION

The concept of HDR geothermal energy extraction requires water circulation between two boreholes through artificially induced hydraulic fractures or/and through the pre-existing joint system in the rock at depth. In the long term operation of an HDR-system, thermally induced fractures may also contribute to the heat exchange area.

Efficient heat exchange between the circulating water and the rock for an economic operation of the system strongly depends upon the hydraulic impedance of the flow path. This is controlled by the nature of the fracture and joint pattern (roughness of their surfaces, fillings or proppings within the joint space, their geometrical dimensions, etc.), chemical reactions between the circulating fluid and the rock (dissolution/deposition), the mechanical properties of the rock (strength, frictional
resistance), but mainly on the magnitude and orientation of the in-situ stresses and the pore pressure in the reservoir rock. Depending on the stress regime, some discontinuities may easily open (mode I) or shear (mode II) by forced fluid circulation and may yield permanently enhanced flow paths, while others remain inefficient for hydraulic flow. This results in hydraulic anisotropy and influences the design of an HDR-system.

The tectonic stress field also affects the stress concentration in the close vicinity of the borehole, and therefore determines borehole stability in open hole sections (break-outs, closure) and the hydraulic impedance at the borehole-fracture intersection.

Due to the existence of faults and rock mass anisotropy and heterogeneity, stresses may vary considerably with depth. This makes extrapolation of shallow stress data to depth questionable. Therefore, for HDR site selection and the design of an HDR-heat exchanger system, a systematic stress evaluation to full depth is indispensable.

This paper presents a stress analysis derived from preliminary hydraulic injection test carried out in the granitic section of borehole GPK1 at Soultz sous Forets. The paper also describes some of the difficulties of hydraulic testing in a hot, gassy and geochemically aggressive downhole environment.

TEKTONIC SETTING AND DOWNHOLE CONDITIONS

Borehole GPK1 (48.56°N, 7.53°E) is located near the western edge of the Rhinegraben. The graben tectonics of the area is illustrated by N–S normal faults dipping either to west or to east, as shown by seismic profiles and geologists from numerous oil wells in the close vicinity of GPK1 (Cautru 1989). Fracture analysis of an oriented granite core (K19, GPK1) yields two directional families, one of them N–S dipping west, in accordance with the orientation of the Oligocene faults (Genter 1989). Analysis of FMS (Formation Microscanner logging device) and BHTV (Borehole Televiewer logging device) data from GPK1 again show a dominating orientation of $N 170^\circ E$ for most planar discontinuities dipping either $70^\circ W$ or $80^\circ E$ (Genter 1989 and Tenzer 1989). Some distinct vertical BHTV features in GPK1, probably drilling-induced hydrofractures, are oriented $N 169^\circ E \pm 12^\circ$ (Mastin and Heinemann, 1989).

No direct data from in-situ stress measurements exist in the immediate vicinity of the drill site. However, both borehole breakout and hydrofrac data from boreholes in the central part of the Upper Rhinegraben and in the Black Forest indicate an average direction of $N 145^\circ E \pm 10^\circ$ for the regional orientation of the maximum horizontal stress $S_H$ (Blümling 1986, Schneider et al. 1986, Rummel & Baumgärtner 1986). Although this direction corresponds to most stress field data for central and western Europe, there are clear exceptions such as the stress direction derived from borehole Urach III which suggest a more N–S direction of $S_H$ (Blümling, 1986).

An estimate of the anisotropy and the magnitude of the principal stresses can only be inferred from direct stress measurements in deep boreholes. Based on a world-wide hydrofrac data base for continental areas, Rummel (1986) suggests an average
normalized stress-depth relation

\[ \frac{S_h}{S_v} = 0.15/z + 0.65 \]
\[ \frac{S_H}{S_v} = 0.25/z + 0.98 \]

where \( z \) is the depth in km. At a depth of a few kilometers, this could relate to both normal or strike-slip faulting if one considers the significant deviations from such a general relation.

**HYDRAULIC INJECTION TESTS IN GPK1**

The hydrofrac stress measurements were part of a hydraulic injection test series carried out in collaboration with the HDR research teams from BGR (see paper by R. Jung, this volume), from NLfB (see paper by Schellschmidt and Schulz, this volume), and from BRGM during September to December 1988. The tests were conducted using inflatable double packer tools (Figure 1) equipped with either 5.5 inches O.D. TAM standard (320 bars/110°C) and high temperature (320 bars/177°C) packer elements or with Lynes SCI-type packer elements. The injection interval between the packers was either 2.5 or 3.6 m long. The packer tools were run in the borehole via a 60 mm O.D. steel tubing string which also served as the hydraulic injection line. Packer pressurization was achieved via a 6.3 mm O.D. flexible stainless steel coil tubing (4 mm I.D.) clamped to the carrier tubing at 30 m intervals. The carrier tubing was centralized by MeSy centralizers at 30 m intervals to prevent damage of the tubing at the joints due to friction on the borehole wall. After damage of one Lynes heavy duty packer element during a down-trip, an additional centralizer was installed below the straddle packer tool.

The first three tests were conducted with injection rates of about 9 liters per minute; during later tests, the injection rates were stepwise increased to a maximum of 72 and 192 liters per minute, respectively. Prior to each test, the borehole brine was displaced from the injection interval by fresh water circulation. Pressure and flow rate of each test was monitored at the well-head by analog and digital recording systems. Most tests were performed on pre-existing fractures with known orientation, determined by acoustic televiewer logging.

A total of eight injection tests initially considered useful for a stress evaluation were conducted (Table I). Three of the tests were carried out near the top of the granite (1450 to 1500 m), the rest near the bottom of the borehole from 1946 to 2000 m. The latter included two single packer tests at bottom hole (1968 to 2000 m).

During testing, the teams faced with a number of technical problems due to temperature (120° to 140°C), high salinity (total mineralization 100 g/l with HCO\(_3^\), SO\(_4^{2-}\), CL\(^-\), F\(^-\), and Br\(^-\) anions) and the high gas content of the borehole fluid (20% by volume, mostly CO\(_2\), N\(_2\), CH\(_4\) and He). Examples of these problems are listed below:

— The first problem was to correlate measured tubing depth with BHTV-cable depth (WBK) and temperature-sonde-cable depth (NLfB) in order to select certain pre-existing joints identified by BHTV for the hydraulic tests. By setting an impression
Figure 1 Schematic drawing of the straddle packer system used at Soultz.

Packer via the tubing in an interval with several identified distinct joints, the corresponding cable depth of the temperature-probe was measured by lowering the probe through the tubing to the hydrofrac tool. This depth calibration was not fully successful since the packer impressions could not be unambiguously correlated with the BHTV-Log.

During initial tests, the lower 500 m of the steel-reinforced rubber pressure hose for packer pressurization were damaged over the entire length, probably because of
Table I
Hydraulic tests carried out in GPK1 Soultz sous Forets during preliminary testing in late 1988.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Date</th>
<th>Depth/m</th>
<th>Injected volume/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>88 Oct 05</td>
<td>1457.3–1459.7 m</td>
<td>0.07</td>
</tr>
<tr>
<td>Test 2</td>
<td>88 Oct 07</td>
<td>1494.5–1496.9 m</td>
<td>0.1</td>
</tr>
<tr>
<td>Test 3</td>
<td>88 Oct 07</td>
<td>1500.0–1502.4 m</td>
<td>0.05</td>
</tr>
<tr>
<td>Test 4</td>
<td>88 Nov 30</td>
<td>1945.7–1949.3 m</td>
<td>4</td>
</tr>
<tr>
<td>Test 5</td>
<td>88 Dec 02</td>
<td>1968.4–1972.0 m</td>
<td>19</td>
</tr>
<tr>
<td>Test 6</td>
<td>88 Dec 04</td>
<td>1969.4–1973.0 m</td>
<td>58</td>
</tr>
<tr>
<td>Test 7</td>
<td>88 Dec 12</td>
<td>1968.4–2000.0 m</td>
<td>42</td>
</tr>
<tr>
<td>Test 8</td>
<td>88 Dec 13</td>
<td>1968.4–2000.0 m</td>
<td>524</td>
</tr>
</tbody>
</table>

fluid deficiency in the hose. The problem is not fully understood yet. The rubber hose was replaced by a stainless steel coil tubing.

—None of the packers used as sealing elements was operable more than 2 tests or a testing period of more than 2 to 5 days in the hostile downhole environment. Packer failure resulted from mechanical damages during down-tripping, temperature-induced hardening of the fluorine/carbon or nitrile based rubber composition, gas diffusion from the borehole fluid into the pores of the rubber elements and resulting gas-fracturing of the rubber.

—The downhole pressure/temperature transducers failed due to isolation resistance failure or high temperature failure of the downhole electronics.

Certainly, presently available packers are the weakest part in deep hydrofrac testing in downhole hostile environment. This urgently calls for new packer developments.

STRESS ANALYSIS TECHNIQUE

The fact that the stress measurements in GPK1 were conducted in conjunction with the conventional hydrological tests reduced the technological efforts and thus was cost efficient. However, this excluded the possibility of artificially inducing new fractures. Instead, stress data had to be derived from pump tests on pre-existing fractures and joints with various orientations.

Solutions for this problem have been introduced by Cornet and Valette (1984) and Baumgärtnert (1987). The solution consists of measuring the normal stresses acting across fractures or joints during the shut-in-phases of pumping cycles. These shut-in pressure values are assumed to be directly equal to the normal stresses. In cases where the instantaneous shut-in pressure is not well defined, pump tests with controlled low injection and pressurization rates can be performed to get an estimate of the normal stress component. In cases where the stress gradient within a limited
depth range can be assumed to be linear, then the normal stress component $S_n$ is given by:

$$S_n(z_i) = \rho g z_i \cos^2 \alpha_i + 1/2 \sin^2 \alpha_i \left\{ G1 + G2 + (\delta 1 + \delta 2)z_i \right\}$$

$$- (G1 - G2) \cos 2 (\theta'_i - \theta'') - (\delta 1 - \delta 2)z_i \cos 2 [\theta'_i - (\theta'' + \eta)]$$

(1)

In equation (1) $G1$, $G2$ describe the horizontal stress components at the upper boundary of the depth range considered for stress computations, $\delta 1$, $\delta 2$, are the respective stress gradients and $\theta$ and $\alpha$ are the strike and dip angle of the fracture observed at the borehole wall. $Z_i$ is the depth measured from the upper end of the depth interval selected for stress computations. Equation (1) assumes that the overburden stress $S_o$ is a principal stress but it does not require that the borehole is aligned with $S_o$.

The angle $\eta$ in (1) allows in the most general case consideration of the rotation of the horizontal stress components with depth. This is reasonable if very long depth ranges are studied. Usually the depth ranges for stress computations with the simplified assumption of a linear stress gradient are carefully selected, based on the available geological and geophysical information.

To calculate the stress tensor from a set of such fractures from pressurization tests, an inversion technique is used which minimizes the difference between the measured stress components and theoretical normal stress values derived from constantly re-sampled model stress fields (Baumgärtner, 1987).

THE STRESS FIELD AT SOULTZ—DATA EVALUATION AND DISCUSSION

The depths, the dates of test performance as well as the injected volumes of the 8 tests originally designated for stress measurements are listed in Table I. It can be seen that the depth range between 1968.4 m and 2000.0 (single packer test) has been tested twice at considerably different injective volumes. For this depth, mainly the large volume injection test was examined for the stress analysis.

The pressure records of the injection tests on which our stress analysis is based are given in Appendix A. From these the characteristic pressure values, the fracture re-opening $P_r$, the opening pressure $P_{op}$ (necessary to keep the fracture merely dynamically open), and the instantaneous shut-in pressure $P_{si}$ can be obtained using established interpretation techniques (Baumgärtner 1987).

The spatial orientations of the hydraulically activated fractures were derived from acoustic teviewer logs. However, the strike and dip data of the features found in the respective depth range are uncertain to some extent. This is due to the problem of correlating depth data from teviewer logs with tubing depths from hydraulic testing, as well as the fact that more than one fracture or joint appears on the teviewer image in some of the test intervals. In view of such uncertainties, two of the tests listed in Table I had to be disregarded for the stress evaluations (nos. 5 and 6 in Table I). This reduced the available data base to five tests, an absolute minimum for the stress evaluation technique presented here.
The acoustic borehole teviewer images of the remaining 5 test intervals are shown in Appendix B. It can be easily seen that even for the remaining test zones the identification of the hydraulically activated fractures is still ambiguous, especially if depth uncertainties of the order of 1 m are taken into consideration. Therefore, "second choice" fractures are marked in four test zones and listed in brackets in addition to the selected feature.

The results of the analysis of the pressure records as well as all observed fracture orientations from teviewer logs are summarized in Table II. For the test at 1458 m, two possible shut-in pressure values are listed, both of which were included in the stress evaluation. The various computations performed on the data base of Table II also considered the "second choice" fractures. However, it can be shown that nearly all fracture/shut-in combinations led to very similar stress regimes because the fracture or joint orientations are very similar.

In general we obtain a stress regime with very low horizontal stress magnitudes ($S_h \leq S_{\|} < S_v$), typical for the normal faulting tectonic graben situation in the Soultz area. Some solutions even show $S_h$ magnitudes which are smaller than the hydrostatic pressure at the depth, an unlikely scenario which is most probably related to the limited data base.

The preferred direction of $S_{\|}$ as derived from the majority of data combinations is well defined at N $155^\circ \pm 3^\circ$. The difference between observed and theoretically computed normal stress components becomes as small as 0.2 MPa. The only parameter combination which seriously affects this result is associated with the test at 1495 m. If during this test the depth measurement were too shallow by 0.5 m, the fracture observed at the very top of the test zone would have to be replaced by a N $166^\circ/70^\circ$ oriented fracture which can be seen in Appendix B just below the marked

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Strike direction $\theta$ ($^\circ$)</th>
<th>Inclination $\alpha$ ($^\circ$)</th>
<th>Opening pressure $P_{op}$ (bar)</th>
<th>Reopening pressure $P_{r}$ (bar)</th>
<th>Shut-in pressure $P_{si}$ (bar)</th>
<th>Overburden pressure $S_v$ (bar) ($\rho = 2.44$ g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1458.0</td>
<td>54</td>
<td>77</td>
<td></td>
<td>253</td>
<td>243/232</td>
<td>349</td>
</tr>
<tr>
<td>(166)*</td>
<td></td>
<td>(90)*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1495.0</td>
<td>122</td>
<td>66</td>
<td></td>
<td>209</td>
<td>206</td>
<td>358</td>
</tr>
<tr>
<td>(162)</td>
<td></td>
<td>(70)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1501.0</td>
<td>8</td>
<td>72</td>
<td>193</td>
<td></td>
<td></td>
<td>359</td>
</tr>
<tr>
<td>(17)</td>
<td></td>
<td>(80)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1946</td>
<td>136</td>
<td>63</td>
<td></td>
<td>294</td>
<td></td>
<td>466</td>
</tr>
<tr>
<td>1989</td>
<td>165$^\circ$</td>
<td>90$^\circ$</td>
<td></td>
<td>253</td>
<td></td>
<td>476</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(150)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* If this fracture is included in the data base, no reasonable fit between measured and computed stress values can be obtained!
between 1458–2000 m:

\[ S_h = 15.1 \text{ MPa} + 0.0179 \text{ MPa/m}^*(z - 1458 \text{ m}) \]

\[ S_H = 24.8 \text{ MPa} + 0.0198 \text{ MPa/m}^*(z - 1458 \text{ m}) \]

\[ S_v = 0.024 \text{ MPa/m}^*z \]

\( \theta \) (orientation of \( S_H \), related to magnetic North): N 155° +/- 3° (respectively N 176° +/- 6° for the second group of solutions).

Considering the uncertainties of the field data base, the stress regimes obtained from the inversion of the results of the hydraulic tests are generally in good agreement
Figure 3 Average deviation AVE between (a) theoretical computed and (b) measured normal stress components as a function of the orientation of the maximum horizontal compression selected for the respective stress field model. Shown is the full range of scatter of horizontal stress orientations as it was derived using all possible combinations of fracture orientations and pressure values listed in Table II.

A second minimum is marked which is associated with the test at 1495 m. If during this test the depth measurement was erroneous by about 0.5 m, the fracture observed at the very top of the test zone has to be replaced by a N 166°/70° fracture, a feature which can be seen in Appendix B just below the test interval. With this fracture the solutions for the stress regime point towards higher magnitudes for $S_h$ and a more N/S oriented maximum horizontal stress component.

with locally observed tectonic and geological stress indicators (Genter, 1989). The same argument is valid for the computed direction of $S_H$ if one compares this orientation with the mean orientation of observed drilling-induced hydrofractures of N 169° $+/–$ 12° (Mastin and Heinemann, 1989), assuming that these hydrofractures are aligned with the principal stress $S_H$.

Due to the limited data base, it is extremely difficult to extrapolate the present stress data to greater depth with any confidence. However, extrapolation of the present data suggests that the probability of drilling-induced hydrofractures will vanish with depth and a more stable stress situation for normal faulting will be approached at greater depth. A “cross-over” of the horizontal stresses as indicated by the extension of the limits of the stress profiles in Figures 2a,b seems unlikely when the regional tectonical situation in the Upper Rhinegraben Area is considered (see Kappelmeyer et al., 1991).
ACKNOWLEDGEMENT

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LITERATURE


APPENDIX A

Pressure time records of the hydraulic tests used for stress analysis
Soultz, GPK1, test at 1457.3 m

Soultz, GPK1, test at 1494 m
Soultz, GPK1, test at 1500 m

pressure, bar

80
70
60
50
40
30
20
10
0

0 2 4 6 8 10

time, min
Soultz, GPK1, test 4 at 1945.7 to 1949.3 m, 31.11.88 (see Jung, this volume)
APPENDIX B

Fracture orientations as derived from acoustic televiwer logs (WBK Bochum)

Shown are the amplitude images
Test 1

strike: N54° (+/- 10°)
dip: 77° (+/- 3°)

average strike N166° (±10°)
Test 2

strike: N122° (+/- 10°)
dip: 66° (+/- 3°)

strike: N162° (±10°)
dip: 70° (±5°)
Test 3

Test zone

average

strike: N 08° (± 10°)
dip: 72° (± 5°)

strike: W 17° (± 10°)
dip: 80° (± 5°)
strike: N136° (+/-10°)
dip: 53° (+/-3°)

Test zone

Test 4
Test 7, 8
1968 - 2000 m
strike: N160° N180°
average
strike: N165° +/- 10°

Test 7, 8
1968-2000m
Test 7, 8
1968–2000m

average strike: N165° (+/-10°)
average
strike: N 165° (+/- 10°)

Test 7, 8
1988 – 2000 m
end of log