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HYDRAULIC INVESTIGATIONS AND STRESS EVALUATIONS AT THE HDR TEST SITE URACH III, GERMANY

Barbara B. Heinemann (1), Bernd Troschke (1) and Helmut Tenzer (2)

(1) GTC Kappelmeyer GmbH, Technologie-Fabrik, Karlsruhe, Germany
(2) Stadtwerke Bad Urach, Germany

ABSTRACT

Bad Urach, located at the center of the positive geothermal anomaly on the Swabian Alb, has been selected to be 'The German HDR Project Site'. Hydraulic properties of the open hole section are of large interest for HDR research. Hydraulic tests resulted in pressure dependant transmissivities and showed up a possible relation to stress magnitudes. Latest investigations on tectonic stresses will be discussed. Based on breakout directions the maximum horizontal stress orientation is determined to be N172°E. More accurate information on stress values could be achieved by further hydrofrac measurements and detailed analysis of borehole cross sections.

INTRODUCTION

Areas of positive geothermal anomaly are the most favourable for exploiting geothermal energy. In Germany it has been known that subsurface temperatures are anomalously high in the area of Urach on the Swabian Alb and within the Upper Rhine Graben.

The Urach geothermal anomaly has been the subject of systematic investigations in a research program supported by a number of institutions. In addition to extensive geological and geophysical investigations a borehole (Urach III) was drilled through the sedimentary cover and about 1700 m into the basement down to 3334 m depth in 1978 (phase 1). This borehole provided an opportunity to study hot water extraction from the sedimentary cover (natural thermal water sources) and to carry out experiments on the use of Hot Dry Rock techniques in the basement rocks.

The geothermal anomaly implied detailed temperature investigations. Three-dimensional temperature distributions were evaluated according to temperature logs, heat conductivities, heat flow densities etc. (ZOTH, 1982). Temperature logs during hydraulic injection tests provided information on permeable zones. Hydraulic tests were performed to study hydraulic behavior of the sedimentary cover as well as of the basement rock (14 m of open hole). Important investigations concerned the mineralogy and essentially chemical reaction of the basement rock with water. These are of essential interest for HDR purposes: sealing, scaling and dissolution effects. furthermore physical and mechanical rock properties were studied to conclude among others on the mechanical behavior of the basement rock during HDR heat extraction.

The favourable results of geoscientific investigations (edited by HAENEL, 1982), the extended infrastructure, the nearby industries as heat (energy) consumer, the less active geological structure of the basement of the Swabian Alb relative to the huge amount of active natural faults within the Upper Rhine Graben, etc. facilitated after all the selection of Bad Urach as 'The German HDR Project Site'.

Further deepening of the well has been accomplished in 1983 down to 3488 m depth (phase 2) lengthening the open hole section from 14 m to 168 m. A bottom hole temperature of 147°C was measured. Besides other geoscientific investigations the hydraulic properties of the open hole section were of special interest for HDR research. This paper will therefore focus on the results of hydraulic tests, i.e. the transmissivity of the basement rock, by comparing all tests (slug and injection tests etc.) described and interpreted by different authors. This study yield the final and up dated result for hydraulic transmissivities in the well Urach III.

In addition, we report on the knowledge of the tectonic stresses in the area of Bad Urach. Only in 1991 stress measurements, i.e. hydraulic fracturing experiments, were performed in Urach III. By that time, the only information on the tectonic stress was its direction, obtained from borehole breakout analysis (caliper data) and fault plane solutions. All stress information has been gathered in attempt to evaluate stress magnitudes. Thus, latest information of the stress situation at Bad Urach will be given in this paper.

HYDRAULIC TRANSMISSIVITIES

Hydraulic tests were performed all the years through, starting with pump tests in 1978, continuing with injection tests (Leak-off tests, Frac-tests, etc.), interpreted by SCHÄDEL & STOBER (1984), STOBER (1987) and JUNG (1987), and slug tests (last slug test performed in 1990). An important result - pressure dependant transmissivity of the rock - has been deduced from these after that several tests were reinterpreted by GTC Passau in 1990 (GTC, 1992).

Slug tests consists in filling up the well to the top and observing the descending water level as a function of time. No head pressure builds up. The measurements of water levels versus time permits the interpretation of hydraulic parameters like transmissivity, coefficient of storage and skin factor.

During injection tests fluid at constant flow rate is injected into a packer interval of the well. Thus, head pressures will increase with time. Stopping the injection will result in a pressure decrease. The interpretation of the measurements of head pressures and injection rates versus time yield hydraulic parameters for the rock within each packer interval. Additional models of hydraulic conditions, e.g. fracture geometries, within the tested depth interval can be deduced from the registrations. Three models are presented:

- GRINGARTEN et al. (1974) considers a vertical fracture at defined length and with infinite permeability. The interpretation of the measurements yield information on the fracture geometry and on the transmissivity of the rock adjacent to the fracture.
- CINCO et al. (1978) takes an vertical fracture with defined permeability into account. The data evaluation results in a transmissivity of the fracture as well as of the rock and in the fracture geometry.
- With the approach of ARGAWAL et al. (1979) it is possible to interpret measurements affected by borehole storage and skin factors. The resulting aquifer parameters (transmissivity, coefficient of storage) represent a combination of

fracture and rock characteristic values.

These models were applied to study hydraulic transmissivities essentially of the open hole Urach III (diatexite), where temperature logs and structural data indicated fractured zones (3325 m depth), and secondary of the rock behind cased borehole sections, where fractures (Frac-Tests) were induced through Perforations (P1: 3259-3264 m, P2: 3271-3274 m, P3: 3293-3298 m, P4: 3290-3300 m (1983)).

During slug tests in Urach III (undisturbed water level at 80 - 90 m depth) a maximum volume of 2.5 m^3 water flowed into the rock. Thus, the tests affected the basement rock volume in nearest vicinity of the borehole (about 10 cm in radius) along the open hole section. Slug tests were performed in 1982, 1984 and 1990. The average transmissivity derived from these tests was of $1.5*10^{-6}$ m^2/s. No significant change in transmissivity has been observed with time as well as with deepening of the well.

On the other side, during each injection test more than 100 m^3 of water have been pressurized through the well into the rock and head pressures built up. Thus, a volume of rock of some meters to some ten meters in radius around the borehole was affected by those tests. Clear differences in transmissivities deduced from tests with head pressures less and more than 170 bar were observed (Fig.1). The transmissivities increased abruptly from $0.35*10^{-6}$ m^2/s to $3*10^{-6}$ m^2/s respectively. The observation showed that 170 bar head pressure is a critical pressure value: for head pressures larger than 170 bar joints open and the rock dilates and for head pressures less than 170 bar joints close again, i.e. the rock behaves elastically. This ovservation might imply that the minimum principal stress is reached at about 170 bar (equivalent to 17 MPa) head pressure, i.e. 49.5 MPa to 51.2 MPa downhole pressure, within the open hole section.

Transmissivities resulting from injection tests at low head pressures (head pressures less than 170 bar for 100 m^3 injected volume) and transmissivities resulting from slug tests (2.5 m^3 injected without head pressure) were expected to nearly equal each other. An explanation for the inconsistency of these values is that the rock in the nearest vicinity of the borehole wall is more transmissive (drilling induced fractures etc.) than a large rock volume around the borehole affected by injection tests.

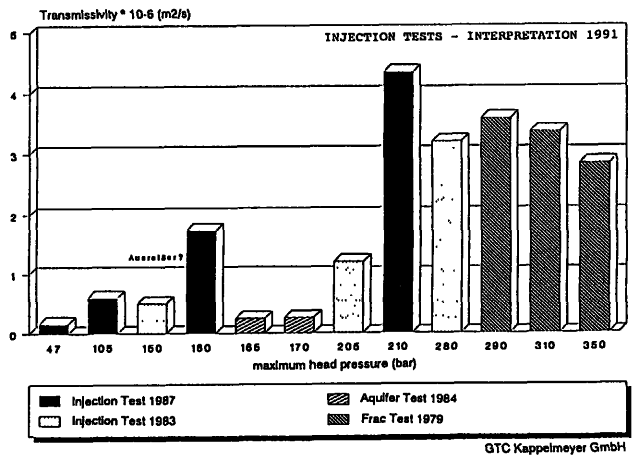

Fig.1: Interpretation of transmissivities of the basement rock at Urach III, determined with the straight line method.

Further hydraulic investigations concerned circulation tests. The lack of a second HDR well at Bad Urach resulted in one borehole circulation test: huff puff experiment. The injection occured through the annulus and the perforations P1 - P3 while extraction took place through the tubing. Huff puff experiments were performed in 1979 (bottom hole at 3334 m depth) (DIETRICH, 1983) and in 1983 (bottom hole at 3488 m depth) (DIETRICH & NETH, 1987).

12 circulation tests were performed in 1979 and three huff puff experiments were completed after deepening of the borehole in 1983. Tracer tests confirmed the hydraulic contact between the perforation interval and the open hole. While 74% of the injected fluid could be recovered during circulation test 11 in 1979, only 23% were regained in 1983. Two explanations for this reduction in extraction were given:

- Secondary stresses built up which had to be surmounted additionnally,
- Flow paths were closed by scaling effects.

However, the injection tests of 1983 do not show any worsening of the transmissivity of the whole permeable borehole section. While mineralogical and chemical reactions of rock from Urach III in contact with water (ALTHAUS, 1982) were already analysed, we lack on detailed information on tectonic stresses at Urach to understand and simulate a complete HDR circulation system. The following chapter Focuses on investigations and informations on the stress field in the area of Bad Urach and present future studies for the determination of tectonic stresses based on the analysis of borehole geometry data and performance of hydraulic fracturing stress measurements.

EVALUATION ON STRESS

The analysis of the borehole geometry of the well Urach III reveals that breakouts exist below 1900 m depth (BLÜMLING, 1986). The orientations of breakouts are very consistent within the depth interval 1900 m to 3334 m (N83°E as deduced from caliper data). In addition to the analysis of caliper data, Borehole Televiewer (BHTV) data were available for evaluation in the deepened well, down to 3488 m. The borehole breakouts at these depths were as consistent in direction as the above ones (GTC, 1992) and are equally oriented (N82°E) (Fig.2). No vertical fractures were observed in the whole borehole down to 3488 m depth.

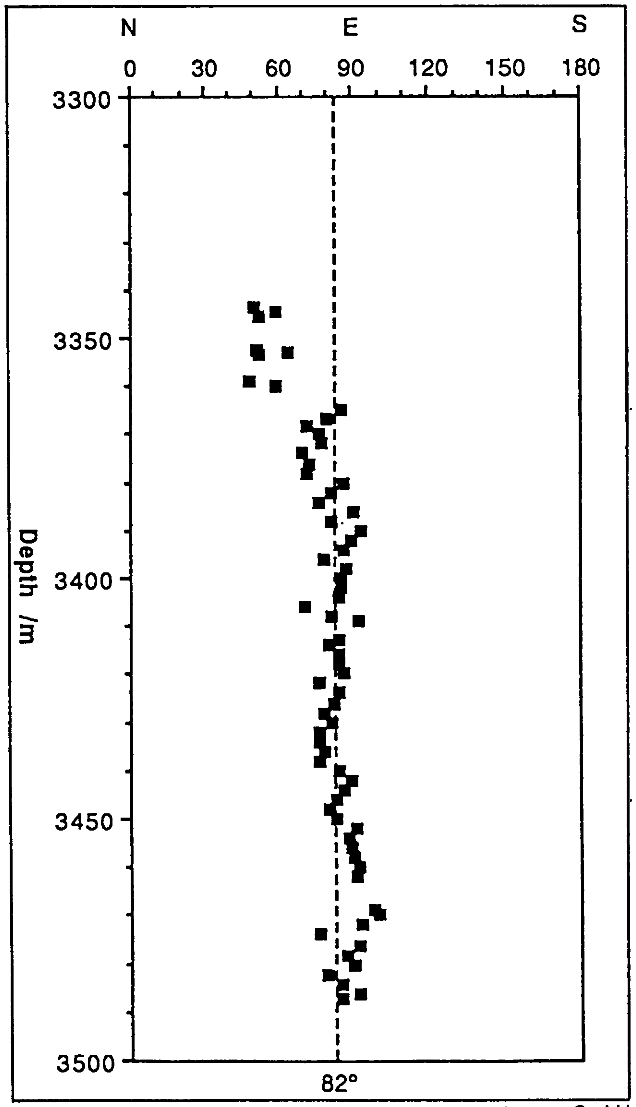

Fig.2: Breakout direction with depth, borehole Urach III

The constant breakout directions with depth suggest that the elongations of the borehole cross sections were stress induced. As known from geological description of core samples (DIETRICH, 1983*) and rock mechanical laboratory tests (RUMMEL et al., 1983), the basement of the site of Urach consists of nearly isotropic and homogeneous paragneis and diatexite. These results are important to conclude from breakout orientations to stress directions. Breakouts occuring in a well vertically drilled into homogeneous and isotropic rock are interpreted to develop in the direction perpendicular to the maximum principal horizontal stress (the vertical borehole axis being another principal stress direction with the overburden as magnitude) (BELL & GOUGH, 1979). Thus, the maximum horizontal stress direction at Urach is of N172°E (Fig.3).

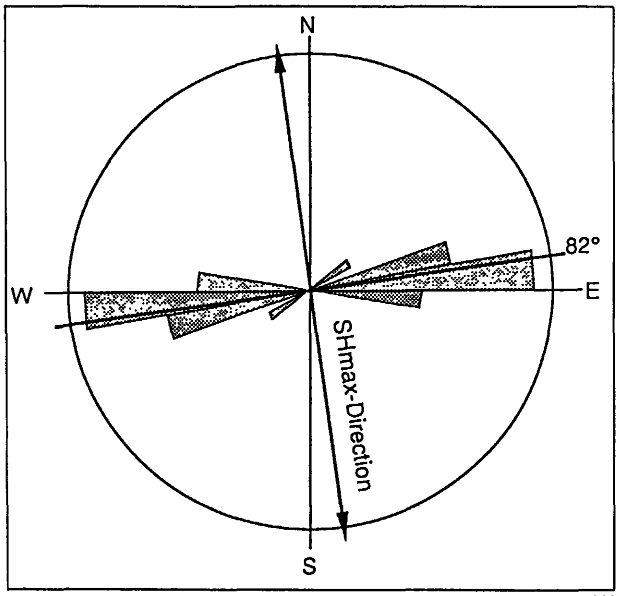

Fig.3: Breakout Orientation from BHTV data (3334-3488 m depth) with interpretec direction of max. horiz. stress SHmax

This direction resulted as well from interpretations of focal mechanisms (TURNOVSKY & SCHNEIDER, 1982). Fault plane solutions from seismic events on the Swabian Alb in vicinity of Urach, within a radius of 50 km, reveal a pure strike slip tectonic regime in this area (TURNOVSKY, 1981; LANGER, 1986). It follows that the relation between the magnitudes of the three principal stresses is:

$Sh \leq Sv \leq SH$ (with Sv the vertical overburden, Sh and SH the minimum and maximum horizontal stress respectively).

To obtain some reliable values on stress, evaluations of hydraulic fracturing stress measurements (hydrofracs) are efficient to define the least horizontal stress magnitude (Sh). In the well Urach III, the evaluation of a single hydrofrac experiment at 3350 m depth determined the minimum horizontal stress to be of the order of 40 - 50 MPa (MeSy, 1991). This value is surprisingly consistent with the pressure at which transmissivities rise abruptly (see above). Based on the knowledge of the minimum horizontal stress, evaluations on the maximum horizontal stress magnitude (SH) are possible. But essential difficulties exist in defining in situ pore pressure and breakout widths at Urach III. Thus, evaluation on the larger stress value range from about equal or slightly smaller than the calculated overburden pressure (Sv = ca. 88 MPa) (MeSy, 1991) to more than 100 MPa.

In any case, a value of SH larger than the overburden is in agreement with the investigation on the stress regime based on fault plane solutions.

Currently, the most common technique of measuring deep in situ stresses is hydraulic fracturing. An additional method may be provided by the phenomenon of borehole breakouts where it occurs (HAIMSON & HERRICK, 1986). If a correlation could be determined to exist between breakout dimensions and principal stress magnitudes, a potentially powerful technique of estimating in situ stresses could evolve. Studies on the evaluation technique of tectonic stresses and the determination of the stress field is the aim of stress investigations at Urach III.

For this analysis, the least principal stress should be known, i.e. some more (in the order of 10) reliable hydraulic fracturing stress measurement at Urach III have to be performed. Analysing borehole cross sections by recording breakout width and breakout depth, and applying the observations to analytical solutions for the stress distribution around a hole intersecting an isotropic and homogeneous medium, future studies will result in the most accurate evaluation on the maximum horizontal stress and finally the three dimensional stress distribution.

CONCLUSION

Tectonic stress orientations in the area of Bad Urach were interpreted from borehole geometry data and fault plane solutions. The direction of the maximum horizontal stress has been determined to be N172°E.

Poor information exists on tectonic stress magnitudes. Interpretation of hydraulic transmissivities (abrupt increase in transmissivity from $0.35*10^{-6}$ m^2/s to $3*10^{-6}$ m^2/s at 170 bar head pressure) and hydraulic fracturing stress measurements provide nearly the same conclusion on the minimum horizontal stress magnitude at about 3350 m depth: Sh is about 50 MPa. For the reliable determination of stress distribution with depth, the single hydrofrac stress measurement is obviously insufficient. More stress measurements will be completed after deepening the borehole Urach III once more to 4500 m in 1992 (more than 1000 m open hole section). Additionnally, detailed analyses on borehole geometry data will be realized. Thus, the deepening of the well provides the unique opportunity of an accurate evaluation on tectonic stresses at Urach. Future results will show the consistency with stress values we know today.

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