FRACTURE MAPPING AND DETERMINATION OF HORIZONTAL STRESS FIELD BY BOREHOLE MEASUREMENTS IN HDR DRILLHOLES SOULTZ & URACH

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ABSTRACT

Well logging with borehole imagery and sonic logs enables continuous recording of natural and artificial planar disconti-nuities. The fracture system in Soultz granite was determined to be N 170° S with submaxima at N 10°-30° E and N 90°-110° E. The orientation of the maximum horizontal stress was determined to be N 154°E and N 169° E±7°. Results of VAL and DSI logging (sonic tools) and the evaluation of Stoneley wave reflections enables the determination of hydraulically activated joints and fractures. Investigations on microcracks show an orthogonal strike direction of N 34°E and N 122° E.

Structural analysis of the joint system in drillhole Urach 3 between 4000 and 4444 m obtains a maximum strike of N 170° S Hydrofrac packer tests at 3352 m depth yield stress values of S_h=41-50 MPa and of S_H=76-102 MPa. The major horizontal stress direction was determined hy different methods to be between N 157°E±20° and N 194°E±18°. Results of ASR measurements on cores from 4424 m depth yield magnitudes of S_H between 99 and 137 MPa. Interpretation of leak-off tests obtained magnitudes of S_h around 65 MPa at 4420 m depth. The stress regime in the Urach gneiss is characterized by a nearly left lateral strike slip faulting system with the maximum principal stress having NNW-SSE direction. The classical Hot Dry Rock technology can here be followed in the wide spread tectonic, horizontal strike-slip system.

In the Soultz field the natural hydrothermal convection and the pecularities of the tension field in the expanding tectonics of the Upper Rhein Graben as well as the major fault systems must be included in any closer investigation of multiple artificial fracture system that are to be used to generate a heat exchanger.

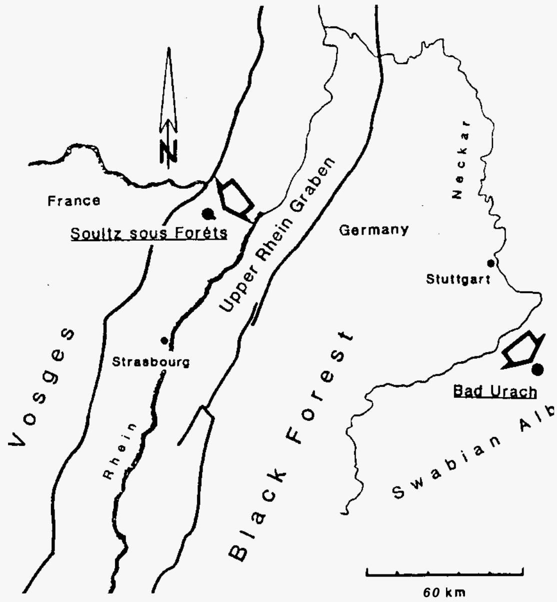

Fig 1: Location of the Hot Dry Rock Projects at Soultz sousForêts (Alsace, France) and Urach Spa (SwabianAlb, Germany)

1. INTRODUCTION

Borehole measurements with the Acoustic Borehole Televiewer and Formation Microscanner (Imager) as also the Azimuthal Resistivity Imager and borehole sonic tools enables continuous recording of natural and artificial planar discontinuities on the drillhole wall and data on the drillhole geometry to be measured.

Efforts were made to resolve the orientation and characterization of the natural joint system, the active fault pattern, the alteration zones, the orientation of microcracks and the direction of maximum horizontal stress.

The availability of structural borehole data through the results of well logging and hydraulic tests permits the determination of hydraulically activatedjoints and their relationship to the regional stress field.

With the help of specific well logs the orientation and frequency of planar discontinuities can be determined, also their apparent apertures as well as the predominant orientation of the different apertures.

2. WORKING OBJECTIVES AND RESULTS

HDR Soultz and Urach sites

Intense logging programmes and measurements were carried out in the HDR drillholes GPK1 and EPS1 (between 1000 m and 3600 m depth) in the Muschelkalk, Buntsandstein and granite at Soultz sous Forêts (Alsace, France) and the extended Urach 3 drillhole (3488 to 4444 m depth) in the gneiss formation at Urach located 35 km south east of Stuttgart in Germany (Fig. 1).

2.1. HDR Soultz site

2.1.1 Orientation of planar discontinuities

The maximum strike of the discontinuities in the Soultz granite was determined in drillhole GPK 1 to be N 170° E with subvertical dips to W and E as well as further submaxima strikes N 10-30° E dipping West and N 90-110° E, N 140° E dipping within 30° from the vertical (Fig. 2).

Three main directions of dips were identified in natural discontinuities (Fig. 3). These directions are: 1. N 270° E, 2. N 50° E and 3. N 190° E.

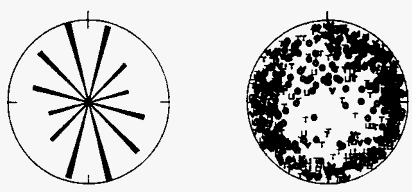

Fig. 2: Rose and Pole diagram (Schmidt net, lower hemisphere) of natural planar discontinuities between 2000 and 3574 m of depth. Main strike directions of 672 data are shown

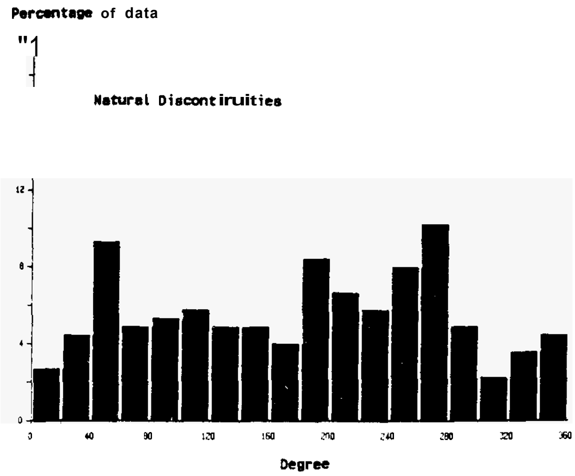

Fig. 3: Direction of dips of natural discontinuities. Three main directions of dips were identified, which are 1. N 270° E, 2. N 50" E, 3. N 190" E The main angle of dip between horizontal and direction of joint planes is 65' - 75°.

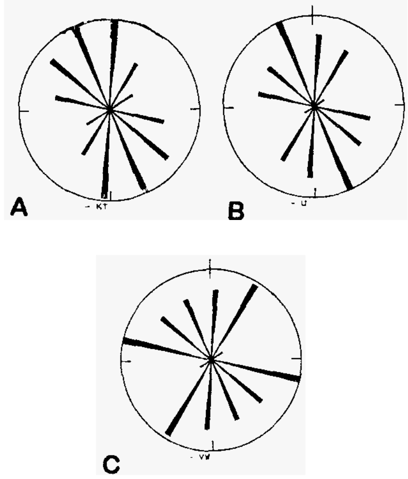

Fig. 4b...Strike directions of natural discontinuities of three classes of apparent apertures. A: very small and small size, B: medium size, C: large and very large size

The different apparent apertures of discontinuities were determined by the evaluation of imagery logs (Borehole Televiewer and Formation Microimager). Figure 4a show the orientation of five classes of different apparent apertures. The width of the apparent aperture were subdivided in: very small small, medium, wide, extremeelywide.
The orientation of small to medium size apperent apertuters of joints are related to the normal distribution of the joint system. The orientation of large and extremely large apertures changed to a prefered SSW-NEN and WNW-ESE direction (Fig. 4b).

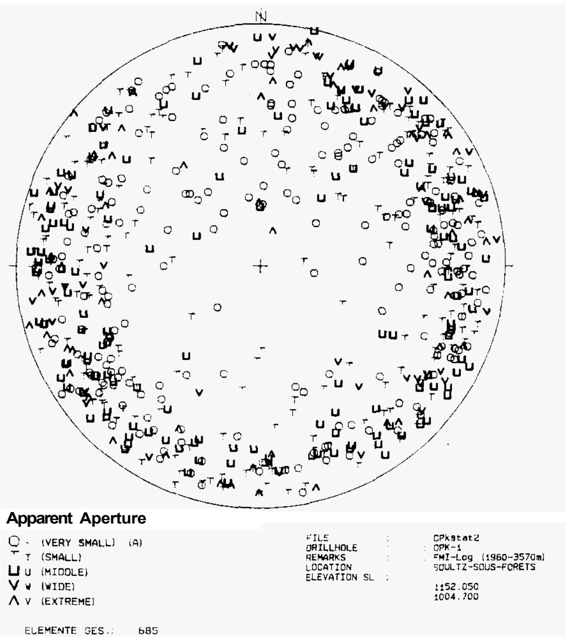

Fig. 4a: Pole diagram (lower hemisphere) of the oreintation of different apparent apertures of natural planar discontinuities of Soultz drillhole GPKI-2 (2000 - 3570 m depth). Number of data: 685 discontinuities

In the deep granite a high number of hydrothermally alterd and fractured zones to the depth of 3500 m was determined (Genter and Traineau, 1993). These alteration zones can be identified by cutting analysis and borehole measurements.

Evaluation of the borehole imagery logs of the Soultz drillholes revealed a large number of subvertical en-échelon type and vertical fractures striking around N 170°E. These structures are induced and related to the regional stress field.
Investigations on cores of GPKl (core 21, 3512,88-3516,18 m) shows that the induced fractures related to stress relaxation are the majority of structures (Genter and Traineau, 1993).

2.1.2 Principal horizontal stress direction

Evaluation of the strike of vertical fractures determined the orientation of the direction of maximum horizontal stress to be around N 170° E down to a depth of 3300 m. Between 3300 and 3570 m depth the orientation of vertical and subvertical fractures rotates to N 100°-120° E. This result corresponds to the result of a hydrofrac test at 3506 m depth where the orientation of horizontal stress rotates to W-E. This rotation may be caused by a large fault zone in the vicinity of the drillhole.

2.1.3 Orientation of drill cores

With the results derived from the logging data (mainly Borehole Televiewer of DMT), it was possible to re-orientate over 99% of the 1,300 m continuous drill cores of well EPS1.
The evaluation of orientated cores enables the determination of orientation of joints with different types of joint fillings (Genter & Traineau 1991).

2.1.4 Orientation of microcracks

Investigations on the orientation of microcracks carried out by the author and Schild (1994) show different orientations in drillholes GPKl and EPSl. In GPK1 a dominant orientation of N 175° E at a depth of 1436 m was determined. Contrary to these results, the evaluation of microcracks in drillhole EPSl shows a maximum strike at N 30°-34° E and N 115°-122° E with submaxima at N 165° S (Fig. 5).
After Adam et. al (1985) the orientation of microcracks is within 30° of the principal horizontal stress direction.
This indicates for the maximum strike in EPSl a paleo stress field whereas the submaxima of EPSl and maxima of GPKl may represent the recent regional horizontal stress direction.

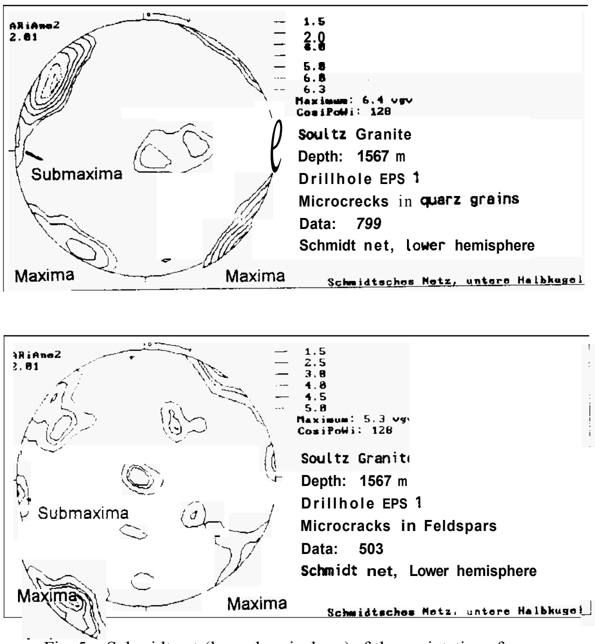

Fig. 5: Schmidt net (lower hemisphere) of the oreintation of microcracks in quarz grains and feldspars of hte Soultz granite at 1567 m depth. Data indicates an orthogonal system (N 34" E and N 122' E with a submaxima at N 165" E. This submaxima is in the direction of rescent horizontal stress direction).

2.1.5 Orientation of open joints detected by Stoneley wave reflections

Fracture localisation (after Homby et. al. 1989) was carried out by **BHTV, FMS**, FMI, ARI, UBI, DSI, and VAL logging. Furthermore the results of temperature measurements and flow logs were used.

The results of DSI logging (Digital Sonic Tool) and VAL logging (Variable Acoustic Low Frequency Tool) and the evaluation of the reflected energy of Stoneley waves as well as temperature measurements show only a small number of joints absorbing water during hydraulic tests.

The orientation of joints with respose of Stoneley wave reflections during DSI logging in GPK1 between 3190 m and 3490 m depth were evaluated with the help of FMI logs and plotted in Fig. 6.

Data shows a preferred NE-SW direction of open joints in the depth section between 3190 and 3340 m in contrary to a WNW-ESE orientation in the lower borehole section between 3340 and 3490 m depth.

This orientation of hydraulically active open joints in the lower drill hole section corresponds to the orientation of vertical induced fractures at that depth and the results of hydrofrac test at 3506 m depth.

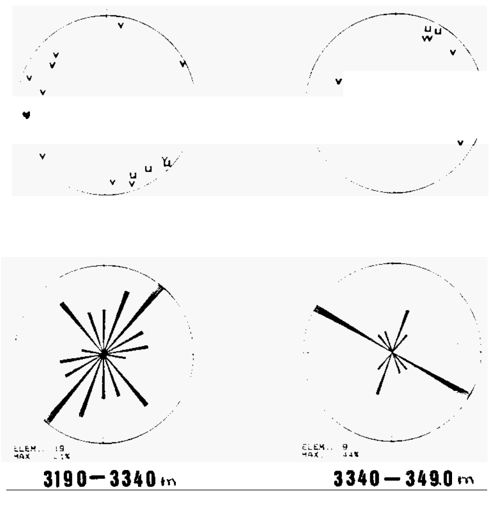

Fig 6 Pole and rose diagrams od discontinuities with response of Stoneley wave reflections between 3190 and 3490 m depth Data shows a prefered SE-NE orientation in depth section 3190-3340 m in contrast to a WNW-ESE orientation in the lower borehole section between 3340 and 3490 m depth

Further measurements are planned to extend the data base on the use of low frequency Stoneley wave reflections for the evaluation of Characteristics associated with the opening of joints during hydraulic testing.

Recent improvements on VAL equipment such as more powerful transmitters and more sensitive receivers with a broader frequency band combined with on-site QUASAR data processing (Quality Assured Sonic data Aquisition in Real-time) allows the 200 millisecond time-window for full wave form data aquisition to be fully utilized. With the QUASAR System, full wave form data of all receivers are monitored simultaneously in real time. Subsequent interactive data processing provides quick access to fracture data.

2.2. HDR Urach site

2.2.1 Temperature field

The temperature at 4394 m true vertical depth was determined around 60 hrs after ending mud circulation at 169°C. It can be proved that the temperature gradient is constant with 2,9° K/100 m versus depth. Temperatures expected at 4500 m depth are in the range of 172-175°C.

2.2.2 Lithology

Within the scope of a feasibility study the already existing drillhole Urach 3 was extended from 3488 m to 4444 m depth.

Investigations were carried out concermng the geothermal temperature field, the fracture system, the regional stress field, the lithology and basic hydraulic parameters.

The lithological profile after Polte (1992) of the extended section is show in Fig. 7.

Metamorphic gneiss rocks as were drilled through. As main lithological units biotite-gneiss, anatexite and diatexite were determined by evaluation of cuttings and drill cores.

Petrographic studies on core samples were carried out by Hottin (1993). Sillimanite occurs in metatectic gneiss, with a restitic habit; it means that these gneiss were derived from more or less siliceous shales. Anatexis produces segregation of quarzo-feldspathic leucosomes that may be mobilised as dykes crosscutting the metatexis.

The different crystalline units are affected by brittle deformation. The resulting fracture system is sealed by hydrothermal products (clays, carbonates, sulfates) related to former deep hydrothermal circulation. At the boundaries of these fractures the rocks are affected by retrograde processes.

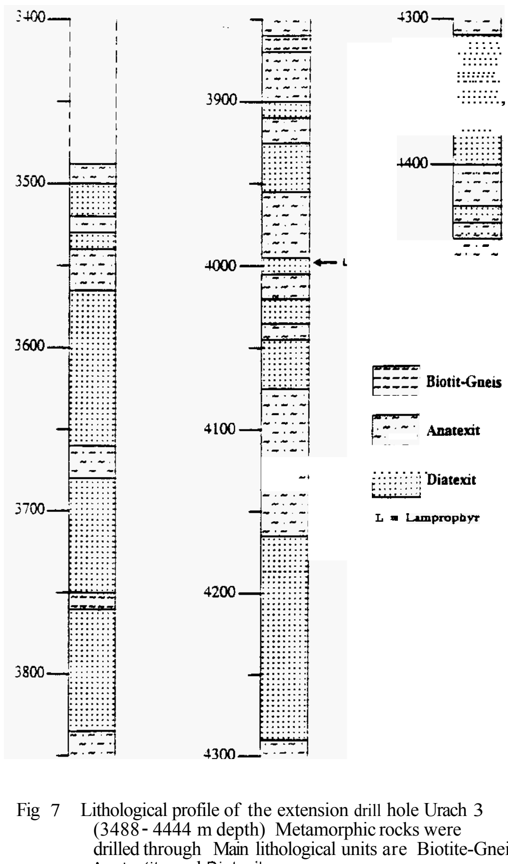

Fig 7 Lithological profile of the extension drill hole Urach 3 (3488 - 4444 m depth) Metamorphic rocks were drilled through Main lithological units are Biotite-Gneiss, Anatextite and Diatexite

2.2.3 Orientation of planar discontinuities

The structural analysis of imagery **logs** in the extended HDR drillhole Urach **3 between** 3500 m and **3750** m depth show the maximum **strike** direction of planar discontinuities is N **170° -200°** E with subvertical dips to West and East and submaxima **of** E-W **and** NE-SW strike dipping to *S* and NW. Below **3950** m depth the preferred orientation of discontinuities is within N **165°** E and N **15°** E.

These direction correspond to the direction of the principal horizontal stress. The orientation **of** the joint system in comparison with the lithology and geophysical borehole measurements between **3950** and **4100** m depth **are** represented in Fig. **8.**

2.2.4 Planar discontinuities on drill cores

The orientated drill cores were investigated by Genter **(1994).**

The azimuth **of** structures recorded on the borehole imagery was measured on the image copy with a 5° uncertainty. Azimuth of natural joints observed on the core section **(14.8** m) was determined **from** their sinusoid on a flat copy with an uncertainty of **5°** too. Finally the uncertainty on azimuth value assigned to the core section is assumed to be less than 10°.

Three main type of structures observed on core section are chronologically organised as magmatic foliation, post-magmatic vein ***sealed* by** early granitic ***dike,*** natural fracture and core-instabilities. Brittle fracture frequency **per**

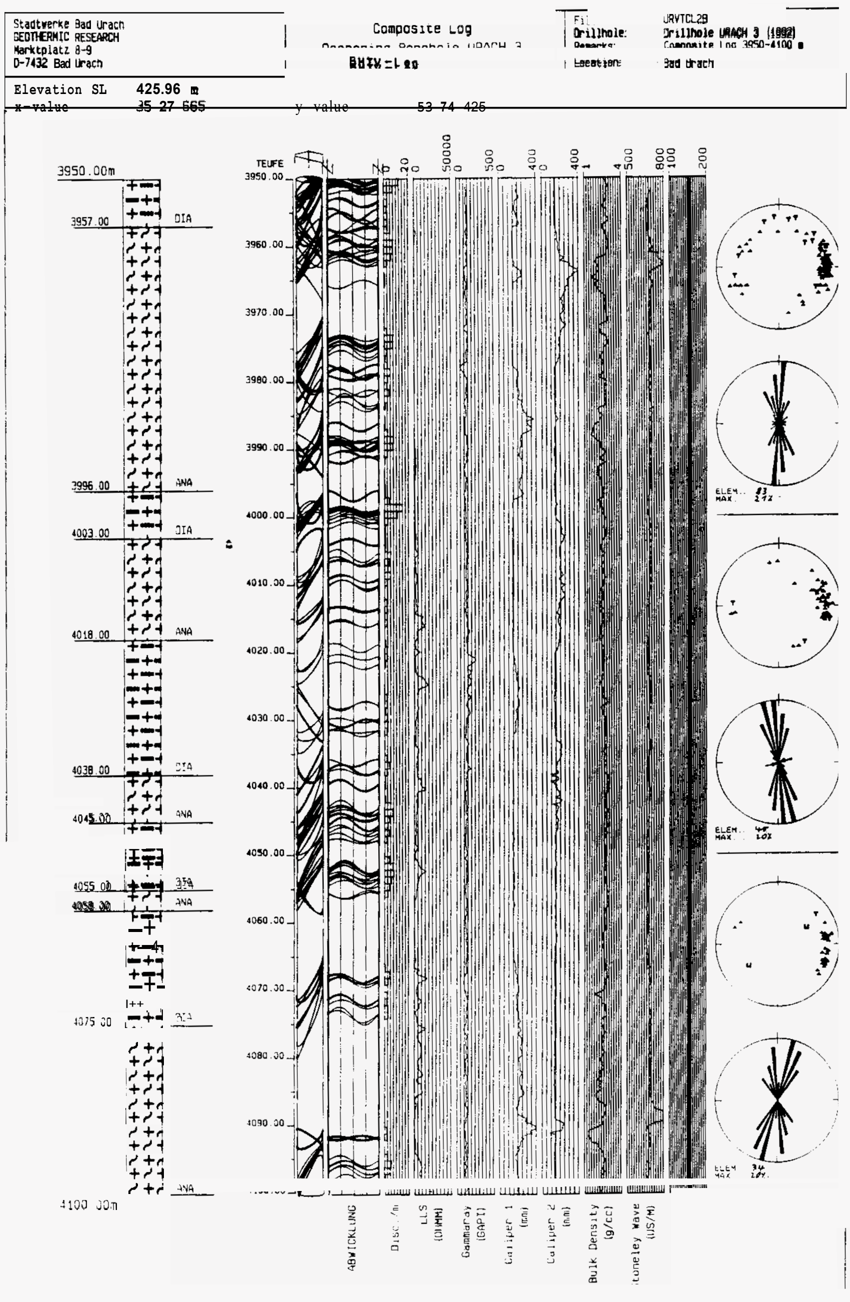

Fig 8 Composite Log of Urach 3 extension drill hole between 3950 and 4100 m depth The lithology and main geopysical borehole measurements are compared with the orientation of discontinuities The natural joint system strikes mainly in N-S and corresponds to the major horizontal stress direction

meter in core 57 (3876-3885 m) and core 59 (4420-4424 m) sections is about 2.0 and 8.0 respectively.
On core **57** subvertical sinistral strike-slip shears and faults which correspond to the most intense catalastic structures Occurring in these cores, are striking N 170° E. Features of core disking are striking N 160° E to N 170° E and N 10° E to N 20° E.
On core 59 two main orientations were determined N 100° E and N 30° E with submaxima at N 70° E and N 120° E. Core instabilities show a preferential fracture set which is *striking* N 10-20" E with a secondary fracture set striking N 120° E.

2.2.5 Stress field

By evaluation of BHTV, FMI, FMS and Caliper logs (Heinemann Troschke and Tenzer 1992, Tenzer 1993) the direction of the maximum horizontal stress was found to be in the range of N 172° E±7°.
The results of wireline hyfrofrac packer tests at 3352 m depth (Rummel, 1993) yield the stress values of S_h= 41-50 MPa and for S_H= 76-102 MPa and determined the orientation of the major horizontal stress to be N 157° E ±20°.
With Anelastic Strain Recovery (ASR) measurements on cores (Wolter, 1993) the orientation of maximum horizontal stress was determined between N 174° E±12° and N 14° E±18. The method of ASR measurements is shown in Fig. 9.

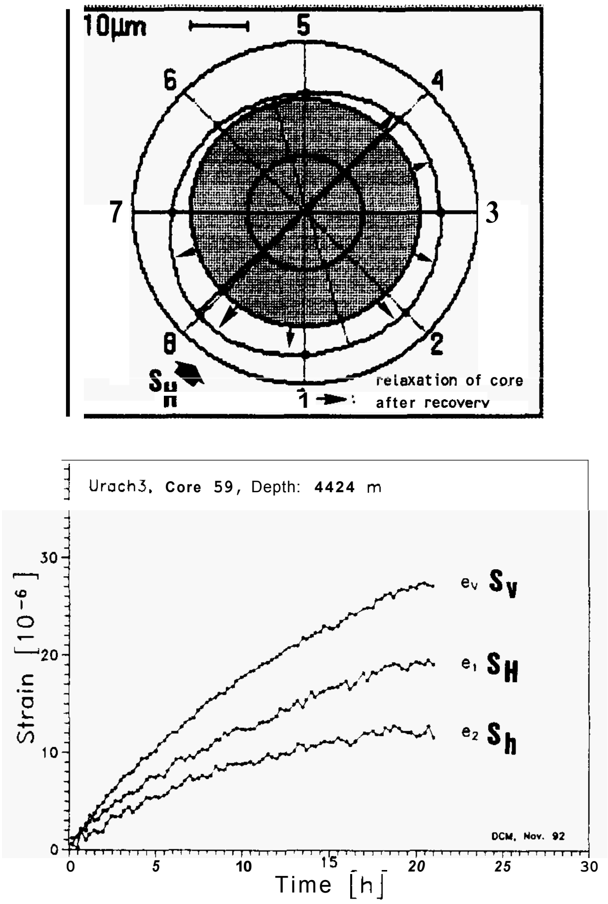

Fig. 9: Anelastic Strain Recovery Measurements (ASR) on drill cores of Urach 3. ASR measurements enables the determination of the direction of maximum horizonztal stress (SH) on orientated drill core samples. Axix 1-8: Positions of eight high resolotion sensors

A compilation of stress data obtained by various methods is represented in Fig. 10.
Stresses estimated from interpretation of leak-off and influx tests as well as obtained by core disking and centerline fractures (Roeckel 1994) and ASR measurements are compared with hydrofrac measurements. The magnitude of the minimum horizontal stress shows a good agreement between the different methods. The estimated results of ASR measurements show larger values.

Extrapolation of leak-off tests leads to an estimated minimum horizontal stresss around 65 MPa at 4420 m depth (Roeckel 1994).
Estimated stress magnitudes from ASR measurements using the Blanton formula yields values of S_H between 99 ±2 and 137±8 MPa at 4425 m depth. The overburden stress is calculated as 120 MPa.
The stress regime in the Urach gneiss formation is characterized by a nearly left lateral strike slip faulting regime with the maximum principal stress having NNW-SSE direction.

Blanton Formula

$$S_H = S_V \frac{(1 - v)\, e_1 + v\,(e_2 + e_V)}{(1 - v)\, e_V + v\,(e_1 + e_2)} \quad (1)$$

$$S_h = S_V \frac{(1 - v)\, e_2 + v\,(e_1 + e_V)}{(1 - v)\, e_V + v\,(e_2 + e_1)} \quad (2)$$

e_1: maximum radial tension
e_2: minimum radial tension
e_V: vertical tension
S_H: major horizontal stress
S_h: minimum horizontal stress
S_V: vertical stress
v: poissonratio

2.2.6 Innovative acoustic emission packer

The functionality of an innovative acoustic emission (AE) packer tool (Albrecht & Gelbke 1992) was tested at a depth of 3356 m. The events received during the setting of the packer show a prefered angle of incidence which is similar to the joint pattern at testing depth. Because of the positive result the tool promises to yield information about the seismic activity of hydraulic fracturing and the hydraulically activated joints in relationship to the regional *stress* field during a wireline hydrofrac packer test.

3. Conclusion and Scope

The result lead to new findings on HDR-relevant joint parameters such as type of discontinuity, joint aperture and joint filling. The connection of natural joint system with permeable fracture zones and faults *can* be detected from acoustic and electrical borehole logging in combination with stimulation tests and hydro-geothermic measurements. ASR measurements on orientated cores in connection with en-échelon type fractures and core disking effects enables the determination of the horizontal stress direction. Furthermore, the prediction of the probable extension of hydraulic fractures and further development of a new method for the survey of the stress field is possible. The data base for the feasibility study *can* be enlarged with new basic parameters. The results will aid the further development of the Hot Dry Rock technology.
Natural planar discontinuities and natural conduits will be included within the development of multiple fracture systems and artificial heat exchange systems in the crystalline basement.
Due to the results of the investigations it is proposed that the Urach site is suitable for a HDR demonstration project. The classical HDR-Technology *can* here be followed in the wide spread tectonic horizontztal strike-slip system in contrast to the tension system at the Soultz site. The natural hydrothermal convection and the pecularities of the tension field in the expanding tectonics of the Upper Rhine Graben as well as the major fault systems must here. be included in *any* closer examination of the system of artificial multiple fracture systems that are to be used to generate a heat exchanger.
A schematic view of a HDR system in a strike slip regime of the Urach gneiss formation is shown in Fig. 11. The separation between the drillholes should not exeed the distance of 450 m and both drillholes shold be placed in the direction of N 172° E. The heat exchanger with temperatures of 175-200°C *can* be created between 4500 and 5300 m depth.

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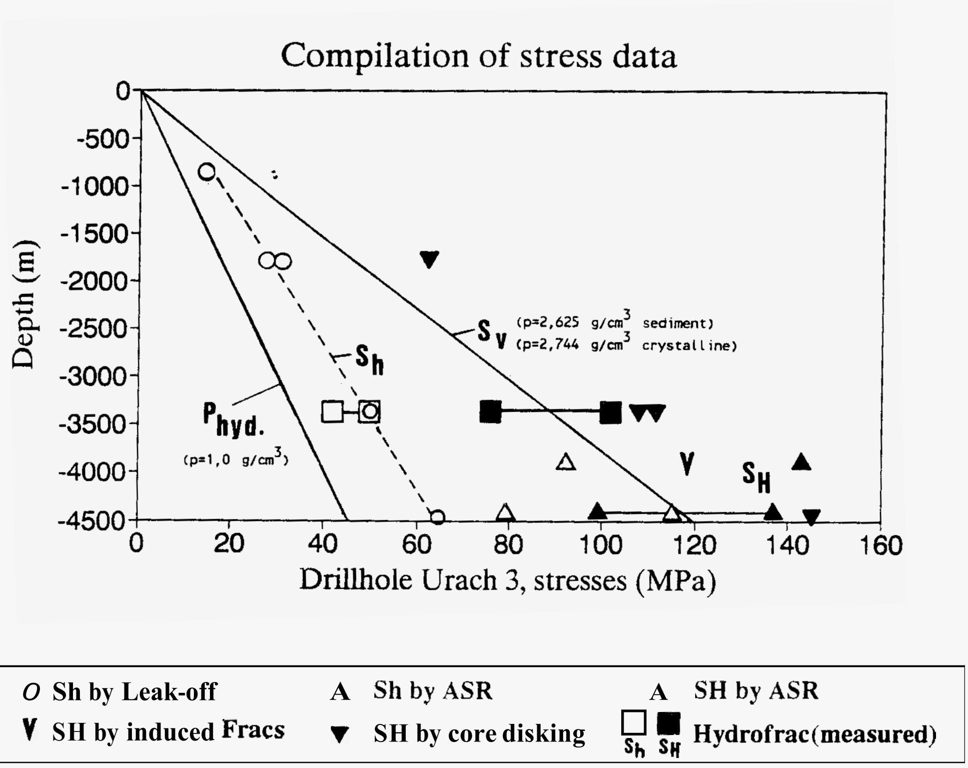

Fig. 10: Compilation of stress data of Urach 3 drill hole.
Estimated data obtained by interpretation of results of former Leak-off and influx tests and interpretation of core disking and centerline fractures as well as results of ASR measurements are compared with results of Hydrofrac tests. Data of Sh shows a close agreement between different methods.

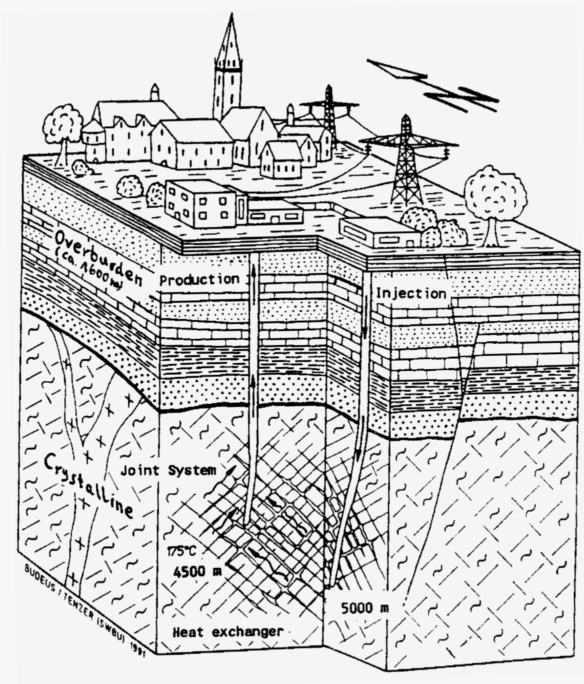

Fig. 11: Schematic view of a possible Hot Dry Rock system at the Urach site.

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