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DEVELOPMENT AND CHARACTERIZATION OF A HDR HEAT EXCHANGER AT THE HDR TEST SITE AT SOULTZ-SOUS-FORÊTS: FLOW LOGS, JOINT SYSTEMS AND HYDRAULIC ACTIVE FRACTURES

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ABSTRACT

In addition to previous work of fracture evaluation of Ultrasonic Borehole Imager (UBI) logs (in cooperation with BRGM, Orléans) a more detailed evaluation of fracture orientation was carried out. During reprocessing procedure, the distribution of fracture network versus depth and the distribution of different classes of apparent apertures of fractures were amended. A total number of 1827 natural fractures and 872 stress induced en-echelon type fractures were individually evaluated from UBI-logs within the depth interval from 1400 m to 3800 m. The frequency distribution of strike orientation were evaluated by plotting data into rose diagrams. In the granitic section of GPK2, highly dipping natural fractures mainly strike approximately N-S. The orientation of the major horizontal stress field direction can be deducted from strike direction of stress related vertical or subvertical induced fractures and en-echelon type structures. As a whole the very small and small en-echelon type fractures are organized in a principal fracture set striking mainly NNW-SSE. Large apparent aperture fracture classes strike predominantly NNW-SSE, whereas small apparent apertures strike N-S. In the hydraulic active part of the lower bore hole section of GPK2, seven joints show a hydraulic active behaviour at depths between 3244 m and 3562 m with a strike orientation between N 120° E and N 198° E.

Flow logs in GPK1 during the hydraulic tests in 1997, show water flow in different joints below casing shoe. The flow regime shows significant changes during various test conditions and flow rates in GPK1. The orientation and the apparent aperture of hydraulic active joints were determined. Totally 14 different hydraulic active joints with mainly medium to large apparent aperture size could be detected between 2866 m and 3497 m depth. The major strike direction of medium size apparent aperture is NNW-SSE and large size aperture NNE-SSW. Hydraulic active fractures determined on FMI-logs dip in general steep and few moderately steep. In combination with results of seismic investigations and the orientation of horizontal stress direction flow paths were estimated.

1. REPROCESSING OF FRACTURE ORIENTATION

1.1 Distribution of Fracture Network versus Depth and Evaluation of Orientation of Apparent Fracture Aperture

Prior to the discussion of production logs reprocessed, analysis of fracture orientation will be presented. In addition to previous work of fracture evaluation of UBI logs (Genter & Tenzer 1995), a more detailed evaluation of fracture orientation was carried out. During reprocessing procedure, the distribution of fracture network versus depth and the distribution of different classes of apparent apertures of fractures were amended. A total number of 1827 natural fractures and 872 stress induced en-echelon type fractures were individually evaluated from UBI-logs within depth interval from 1400 m to 3800 m.

Furthermore, a more detailed analysis of natural fracture orientation within depth intervals of 50 m sections were carried out. In these 50 m sections, the strike and dip directions of joints were evaluated. The frequency distribution of strike orientation were evaluated by rose diagrams. The frequency of various dip directions was evaluated by histograms.

Overall, natural fracture dip direction have a maximum in Southwest direction (8.7%) and a submaximum (6.7%) towards Northeast. In the granitic section of GPK2, highly dipping natural fractures therefore mainly strike N 184°E (15%) and to a minor extent N 174° E (14%), N 164° E (12%) and N 154°E (11%).

1.2 Major Horizontal Stress Direction

The orientation of the main stress field direction can be deducted from strike direction of stress related vertical or subvertical induced fractures and en-echelon type structures. As a whole the very small (435) and small (391) en-echelon type fractures are organised in a principal fracture set striking N 164° E (23%) and three minor fracture sets striking N 174° E (18%), N 155° E (16%) and N 184° E (13%). The dip direction is mainly Northeast (12.7%) with a submaximum (10.1%) towards Southwest. Additionally a number of 40 medium size and 6 large size of apparent aperture induced fractures were determined.

1.3 Orientation of Different Apparent Apertures of Joints

Totally a number of 210 natural fractures of medium sized aperture were determined. This fracture class is mainly striking N 184° E (21%) with two submaxima towards N 174° E (14%) and N 163° E (13%). Their principal dip direction tends towards West (11.9%) and to a lesser extent to the East (9.5%).

Large aperture fracture classes in principle strike N 164° E (22%). Altogether a number of 58 fractures of this type were evaluated. Their principal dip direction is Southwest (15.5%). Further orientational submaxima are the strike directions N 174° E (17%) and N 153° E (12%) as well as the dip direction Northeast.

Finally very large aperture fracture classes exhibit two strike maxima towards N 154° E and N 177° E (each 25% of a number of 12) and two submaxima striking N 144° E and N 163° E (each 17%). Their principal dip direction is Northeast (25%) and to a lesser extent westward orientated (8%).

2. CIRCULATION TESTS 1996/1997 EVALUATION OF PRODUCTION LOGGING DATA IN DRILL HOLES GPK1 AND GPK2

2.1 Introduction and Working Programme

During the time period from August 1996 until October 1996 extended hydraulic tests were performed within the drill holes GPK1 and GPK2 at Soultz sous Forêts under the leadership of BGR. The objectives of the test can be summarized as follows:

- Propagation of the fracture system in the open hole section of GPK2
- Determination of hydraulic parameters, especially the injectivity of GPK2 after stimulation
- Observation of flow and pressure response in GPK1, EPS1, and peripheral wells
- Determination of productivity of GPK2 and injectivity of GPK1
- Determination of salinity of the produced zones in GPK2
- Preparation of diagrams for the periodic report

In a co-operation between J. Nicholls, Logging Service Camborne and Stadtwerke Bad Urach (SWBU), the Logging Programme and evaluation of data were carried out: Temperature and flow logs were recorded during the stimulation and stepped injection tests in GPK2 and the production test from GPK2 between August and October 1996 as well as in GPK1 during longterm circulation test between July and November 1997.

2.2 Methods of Processing and Presentation

Processing of flow logs comprised depth correction, caliper-correction, normalisation and subsequent smoothing of measured data (according to the method after Evans et al. 1996). Preliminary depth corrections of flow logs with constant shift values applied to the whole depth section revealed non-linear effects especially in deeper parts of the flow-logs. Therefore flow logs were divided into discrete intervals and depth correction was individually preferred for each depth interval by correlating distinctive peaks of caliper cross sectional area log with corresponding characteristic minima of flow logs (presented in Figs. 1 & 2).
Subsequent caliper correction was done applying the ratio of the actual caliper cross section referred to the cross section of the borehole casing to measured flow values. Average caliper was extracted from Western Atlas Sonic logs in conjunction with UBI logs from Schlumberger.
For normalisation of flow logs so far corrected data were referred to actual flow input. Normalised flow curves were smoothed applying a Fourier Transform filter that removes
Fourier components with frequencies higher than 1/n Δz (n: number of considered data points per meter, Δz: spacing between adjacent data points). Alternatively a running average was tested but FFT-Filtering was preferred because of it's enhanced smoothing effect to small and sharp peaks.

Data sets of temperature logs, caliper logs and flow logs were processed and illustrated in different diagrams. Combining normalized flow logs with temperature logs and horizontal cross-sectional area of caliper, improves interpretational capabilities. Normalization of flow-logs visualises even slight differences in depth dependence of individual flows. To enhance fractured and hydrothermally altered zones, caliper is shown in terms of cross-sectional area. Flow-logs of hydraulic tests in GPK2 were combined in such a way, that possible changes with increasing flow input could be seen.
In the following section, discussion starts with individual flow-logs and continues with a comparison of different normalized flow profiles correlated with temperature logs and cross sectional area.

2.3 Orientation of Hydraulic Active Joints in Drill Hole GPK2

For correlation of characteristic rises in production flow with possible hydraulically active fractures in Schlumberger UBI-log, a depth correction had to be applied to the Schlumberger UBI-log. This was done by relating specific peaks in Western Atlas Caliper-log to corresponding deviations in measured Schlumberger UBI borehole-radius. UBI-log typically had a shift of plus 3.7 m versus depth scale of Western Atlas Caliper-log.

The hydraulic active joints in GPK2 are presented in Table 1. Principal strike direction is North-Northwest to South-Southeast, thus confirming their orientational relation to the main stress field. The depth, orientation and size are described below.
The upper section above 3250 m on the flow-log shows a corresponding joint system on the Schlumberger UBI-log. Two distinct fractures of small and medium size aperture are visible in the UBI-log. The first at a depth of 3247,50 m has a strike direction of N 150° E (dip direction: N 60° E) and a dip of 57°. Second at a depth of 3248,15 m striking N 120° E and dipping 65° (dip direction N 30° E).
Next strong hydraulic response above 3348 m correlates with a smaller peak in Caliper Cross Sectional Area (CSA) log and is probably caused by a large aperture fracture at 3347.35 m. It strikes N 141° E and dips very steep (87°). Another very wide one is located at 3371,83 m which presumably gives rise to slowly increased flow of production-log in Fig. 1 (curve I) at depth 3368,13 m. It's oriented N 148° E and dips 73°.
Highest hydraulic activity occurs slightly above 3468.5 m on the flow-log where the CSA-log only shows insignificant peaks. This strong increase of production flow is probably caused by an almost vertically dipping fracture of medium sized aperture located at about 3473,50 m. The fracture strikes approximately North-South (N 175° E).
The temperature decrease at 3504 m on flow-log correlates with flow leaving a very small fracture at 3508.40 m that strikes N 198° E and dips 82°.
Finally a small aperture fracture at 3566,20 m presumably causes the rise of flow, which is apparent in the production log. It strikes N 158° E and dips 81°.
The flow-log in Figure 1 displays four significant flow peaks. The first at a depth of about 3220 m where about 25-30% intake of water into the surrounding rock is registered. From depth 3250 m to about 3350 m a gradually loss of about 40-60% is notable whereas from 3250 m to about 3470 m flow stagnation of about 60-65% is recognisable. A last strong loss of water up to 80% occurs from 3470 m and continues gradually diminishing with depth to nearly 100% (about 3600m).

2.4 Orientation of Hydraulic Active Joints in Drill Hole GPK1

Important hydraulic active joints in GPK1 could be detected in Flow- and FMI-logs during the long-term circulation test 1997 at depths from about 2866 m to 3497 m. Fourteen different hydraulic active fractures were detected on the FMI-log which include small, medium and large size apparent apertures (Table 2).

The first remarkable large size fracture occurs at a depth of 2866,60 m on the FMI-log. It strikes N 20° E (dip direction: N 290° W) and dips 78°. Three very near spaced fractures of medium size aperture occur at a depth of 2954,50 m, 2956,75 m and 2959,50 m. The first one differs from the other two in its dip direction (N 63° E), dipping 80° and striking N 153° E. The second strikes N 167° E and dips 82° in N 257° W direction, while the third strikes N 174° E and dips 83° to the West.

Moving further down to about 3092 m, two closely spaced steeply dipping medium and large size joints are recognisable. One is situated at 3092,50 m striking N 27° E and the other at 3102 m striking N 17° E.

The next two fractures located at 3234,30 m and 3235,60 m are of large size aperture and strike N 45° E respectively N 60° E and dip 78° and 75°. A single medium size aperture is visible at 3337,50 m striking N 164 E, dipping 73° to the East.

Finally two large size fractures at 3490,10 m and 3496,10 m strike N 27° E and N 12° E but dip to the West, similar to the first ones described above. The dip direction is N 297° W and dip value 74°; the direction of the second is N 282° W, 76° dip.

At depths of 2962,70 m, 2965,30 m and 2967,10 m data were measured during the first flow-log measurement of the long-term circulation test 1997 in September 29 th. (Table 2). During the following later circulation test measurements, no hydraulic active behaviour was registered at these depths. However the first medium size aperture at 2962,70 m strikes N 179° E, dips 74° to the West. The second at 2965,30 m strikes N 7° E dips 64° and the third at 2967,10 m strikes N 15° E and dips likewise 72°.

The flow-log in Figure 2 exhibits several significant flow behaviours below casing shoe. A first flow fluctuation occurs at 2860 m where a loss of about 55% can be registered direct below casing shoe (2850 m). Moving deeper to about 2950 m, a gradual increase of water loss up to about 70% into the surrounding rock is visible. A further flow fluctuation occurs at 3225 m, where about 90% water vanishes into the fractured rock. With increasing depth the flow value remains nearly constant while reaching the depth of about above 3500 m the total amount of water disappears which correlates positive to a strong Caliper-log peak.

3. GEOLOGICAL MONOTORING OF EXTENSION DRILL HOLE GPK2 FROM 3880 TO 5093 m DEPTH

3.1 Lithology

The general objective of this research consists of the geological characterisation of the deep granite massive dedicated to HDR experiments. The initial target of GPK2 well was to reach 4500-5000 m depth with an anticipated temperature of 195°C+5°C. The drilling rig was supplied by ENEL. SOCOMINE assisted by Southern International Incorporated acted as the operator for the drilling operations. Drillhole GPK-2 was drilled in 8-1/2” diameter between 3880 and 5057 m. A core was taken between 5057 and 5060 m depth. A pilot hole of 6 ½” for stress measurements was then drilled to final depth. Due to borehole conditions (temperature, deviation, caves), the well logging operations were conducted at different times (10/4/99, 13/4/99, 12/5/99) in the deeper part of GPK-2 well. As the well is slightly deviated in the deeper part, the actual vertical depth after the trajectory correction is 5024 m (ground reference).

Cuttings collected from GPK-2 are fine-grained, ranging between 0,1 and 1 mm averaging at about 0,5 mm. The following petrographic types were encountered in GPK-2 between 3880 m and 5093 m depth: (a) standard porphyritic granite, (b) biotite-rich granite, (c) light colored biotite-poor granite, (d) granite rich in xenolith, (e) granite with 2 micas, (f) K-feldspar depleted granite, (g) altered porphyritic granite related to fractured zones and divided into four alteration grades (low, moderate, high and very high).

From a general point of view, the geological profile of well GPK-2 could be summerized as follow:

- between 3900 and 4540 m, the well penetrated an unaltered granite section with a few hydrothermally altered and fractured zones, namely 4040, 4200-4220, 4260, 4325, 4370, 4430, 4440, 4460 m.
- between 4540 m and 4820 m, the well penetrated several fractured and altered zones with the major features located between 4580 m and 4600 m and about 4775 m.
- from 4820 m to the bottom depth, strong petrographical variations are evidenced and a few fractured zones are present.

3.2 Borehole Logging

Various standard open-hole well logs (caliper, resistivity and gamma ray logs) were performed in the well in order to determine the main distribution of the petrographic facies in terms of facies variations, standard granite and hydrothermally altered and fractured zones. For a better understanding of the existing fracture network, Ultrasonic Borehole Imager (UBI) was run between 3200 m and 3900 m depth.

The caliper data indicate two kinds of different behaviours: (1) some values which are close to nominal borehole diameter induced by standard unaltered granite or magmatic heterogeneities, (2) some values which are higher than borehole size and which could be related to the occurrence of cavities induced by hydrothermally altered and fractured granite.

Due to the occurrences of large caves at about 3900 m and technical problems with the device, it was impossible to log deeper with the UBI tool. In order to get minimum structural information about fracture location at depth in the deeper part of GPK-2 well, the Azimuthal Resistivity Imager (ARI) was run between 3500 m and 4500 m depth. This oriented tool has a coaser resolution than classical borehole imagery (BHTV, FMI, UBI). However, this electrical tool is able to detect preferentially the most conductive fracture network that intersects the well. Then, it must provide the location as well as the geometry of the major structural features encountered at depth.

Data from UBI and ARI-logs were evaluated. UBI-log of the

zone of previous hydraulic stimulation between 3200 m and 3500 m depth show clearly artificial hydraulic fractures orientated around N 170° E. Additionally UBI test log between 4284 and 4437 m shows between 4304 and 4309 m a vertical hydraulic fracture which strikes between N 158° E - N 185° E. Breakout in this section are orientated N 60° E and N 250° E respectively. This indicates that the horizontal stress direction is N 170° E.
Data from ARI-log enables us to verify hydrothermal altered zones. The strike direction of a major part of joints is around NNW-SSE.

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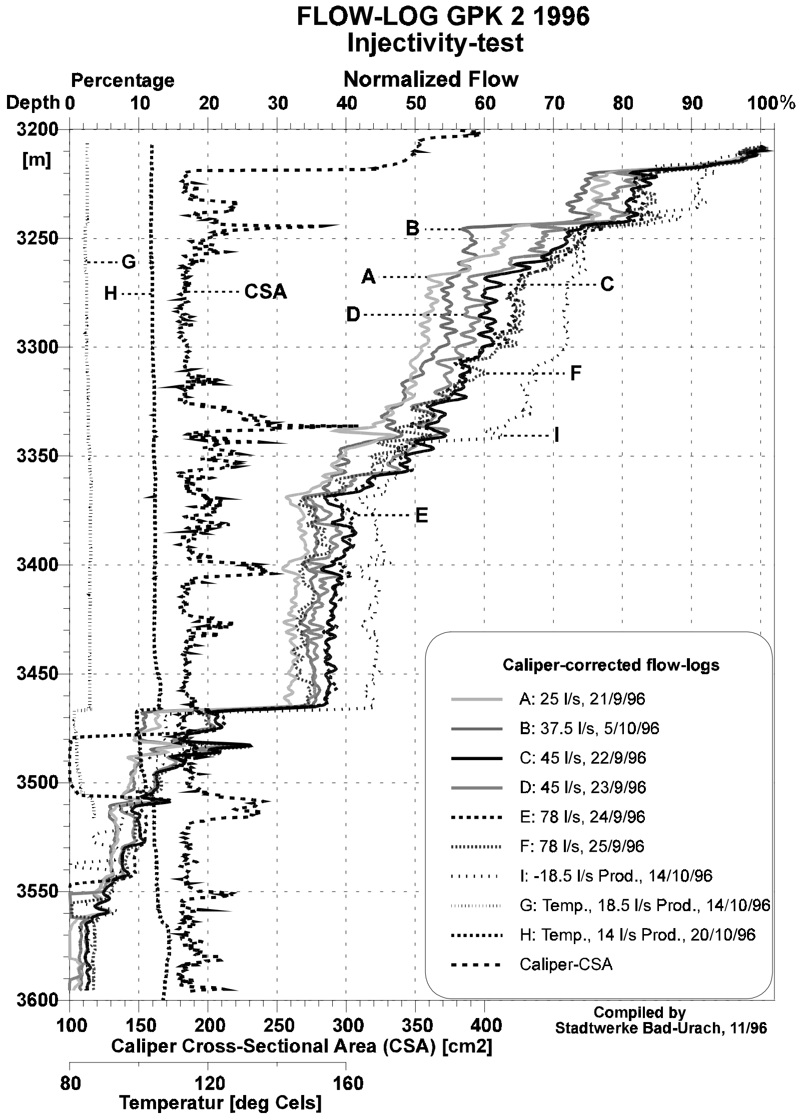

Fig. 1

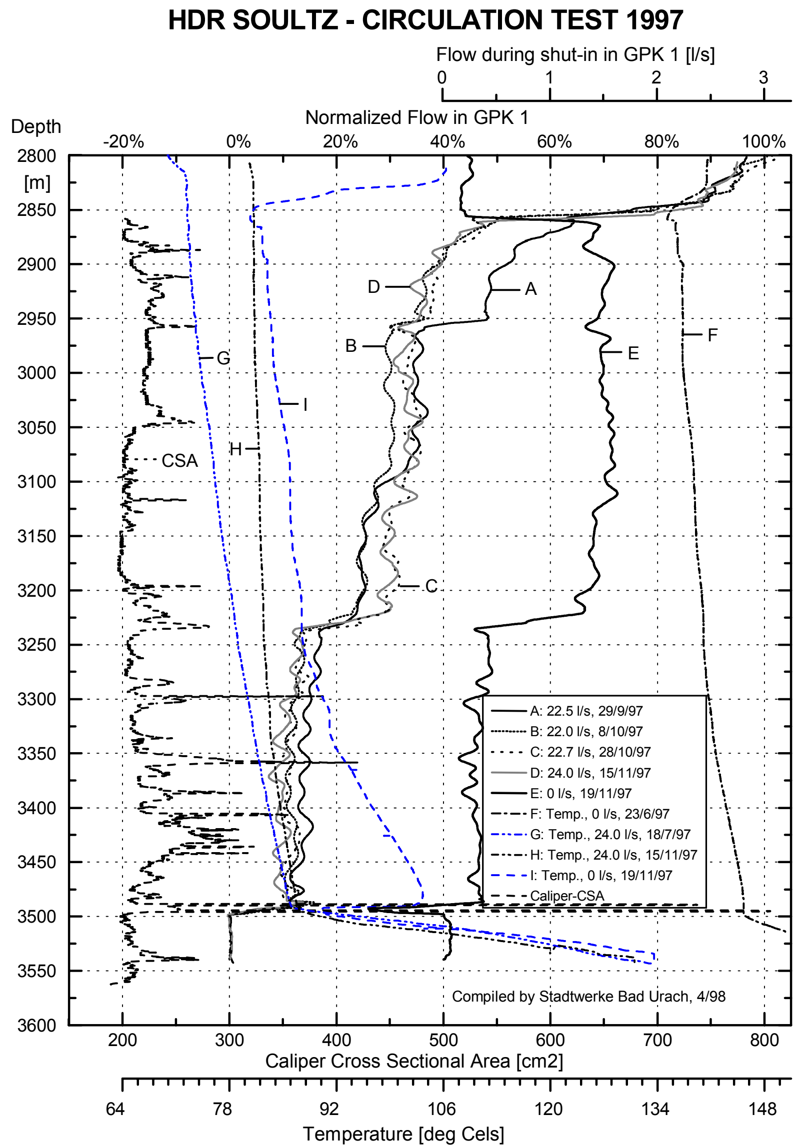

Fig. 2

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Table 1

Hydraulic active fractures in GPK2

Depth correlation Flow-Log caliper (m)	Depth of joints UBI-Log (m)	Strike direction	Azimuth	Dip	Apparent aperture size
3244,31	3247,50	N 150° E	N 60° E	57°	small
3244,93	3248,15	N 120° E	N 30° E	65°	medium
3343,50	3347,35	N 141° E	N 231° W	87°	large
3368,13	3371,83	N 148° E	N 238° W	73°	large
3469,80	3473,50	N 175° E	N 265° W	89°	medium
3504,80	3508,40	N 198° E	N 288° W	82°	small
3562,35	3566,20	N 158° E	N 68° E	81°	small

Table 2

Hydraulic active fractures in GPK1

Depth correlation Flow-Log caliper (m)	Caliper FMI (m)	Depth of joints UBI-Log (m)	Strike direction	Azimuth	Dip	Apparent Aperture size
2863,80		2866,70	N 20° E	N 290° W	78°	large
		2954,50	N 153° E	N 63° E	80°	medium
2956,90	2957,60	2956,75	N 167° E	N 257° W	82°	medium
		2959,50	N 174° E	N 264° W	83°	medium
3045,80	3045,80	(Caliper-Log only for depth correlation)				
3090,30	3090,00	3092,50	N 27° E	N 117° E	88°	medium
3100,00		3102,00	N 17° E	N 107° E	87°	large
3233,30	3233,80	3234,30	N 45° E	N 135° E	78°	large
	3235,50	3235,60	N 60° E	N 150° E	75°	large
		3337,50	N 164° E	N 74° E	73°	medium
3494,40	3489,80	3490,10	N 27° E	N 297° W	74°	large
	3494,80	3496,10	N 12° E	N 282° W	76°	large
Flow measured in Sept. 29. 1997 (no hydraulic active behaviour in later measurements)		2962,70	N 179° E	N 269° W	74°	medium
		2965,30	N 7° E	N 277° W	64°	small
		2967,10	N 15° E	N 285° W	72°	small