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Development and characterisation 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 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 hctures and 872 stress induced en-echelon type fractures were individually evaluated from UBI-logs within depth interval fiom 1400 m to 3800 m. The frequency distribution of strike orientation were evaluated by rose diagrams. In the granitic section of GPK2 highly dipping natural fractures mainly strike approximately N-S. The orientation of major horizontal stress field direction can be deducted fiom 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 organised 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 and 3562 m with a strike orientation between N 120"E and N 198"E.

Flow logs in GPKl 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 GPKl. 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.

KEYWORDS

Flow log, horizontal stress direction, Hot Dry Rock, hydraulic active fractures, joint system, UBI-log.

Reprocessing of fracture orientation

Distribution of fracture network versus depth and evaluation of orientation of apparent fracture aperture

Prior to discussion of production logs reprocessed analysis of fracture orientation will be presented. In addition 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 sections were carried out. In this 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 were evaluated by histograms.

Overall natural fracture dip direction have a maximum in Southwest direction (8.7%) and a submaximum (6.7%) to Northeast (table 1A). In the granitic section of GPK2 highly dipping natural fractures therefore mainly striking N 184°E (15%) and to a minor extend N 174" E (14%), N 164" E (12%) and N 154°E (11%).

Major horizontal stress direction

The orientation of 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 hctures 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.

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 is west (11.9%) and to a lesser extend 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 orientation 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 extend westward orientated (8%).

Circulation test 1996. Evaluation of production logging data in drill holes GPK1 and GPK2

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 summarised 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 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 long-term circulation test between July and November 1997.

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 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 figures 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 which removes Fourier components with frequencies higher than 1/n Az (n: number of considered data points/m, Az: 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 normalised flow logs with temperature logs and horizontal cross-sectional area of caliper improves interpretation capabilities. Normalisation 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 can be seen.

In the following section, discussion starts with individual flow-logs and continues with a comparison of different normalised flow profiles correlating them with temperature logs and cross sectional area.

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 1A. Principal strike direction is North-Northwest to South thus confirming their orientation 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 in correlates with a smaller peak in CSA-log and is probably caused by a large aperture hcture 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 figure 1 (curve I) at depth 3368,13 m. It's oriented N 148" E and dips 73°.

Table 1A: 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

Highest hydraulic activity occurs slightly above 3468.5 m on Flow-log where 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).

Orientation of hydraulic active joints in drill hole GPKl

Important hydraulic active joints in GPKl 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 1B).

The first remarkable large size hcture 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 hctures of medium size aperture occur at a depth of 2954,50 m, 2956,75 m and 2959,50m. 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 3102,00 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.

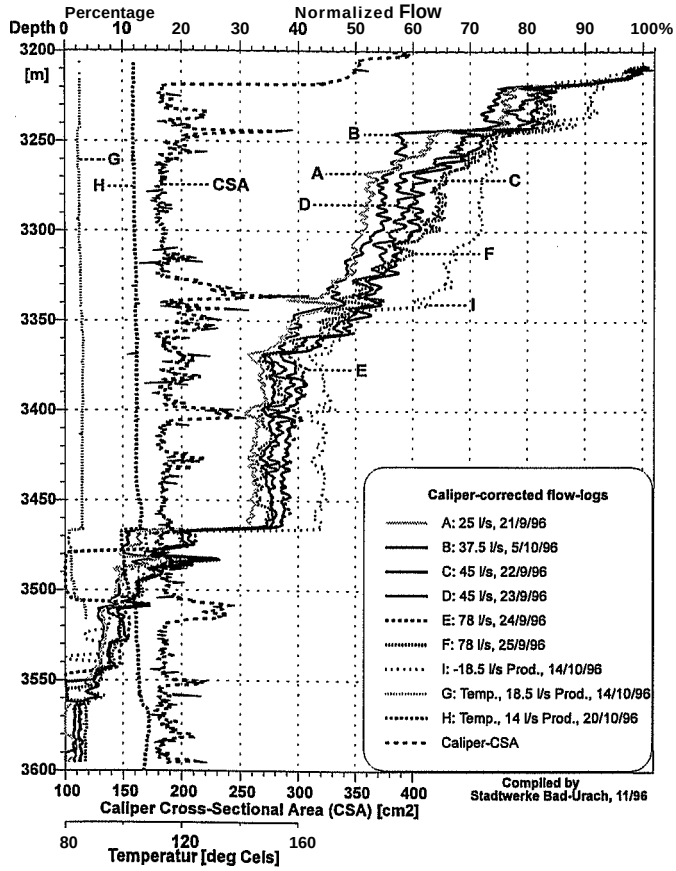


Figure 1: Flow-log in GPK2 during the injectivity test of 1996

The following three established data's at depths 2962,70 m, 2965,30 m and 2967,10 m were measured during the first Flow-log measurement of the long-term circulation test 1997 in September 29th (table 1B). The following later circulation test measurements did not register any hydraulic active behaviour 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 below casing shoe several significant flow behaviour. **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.

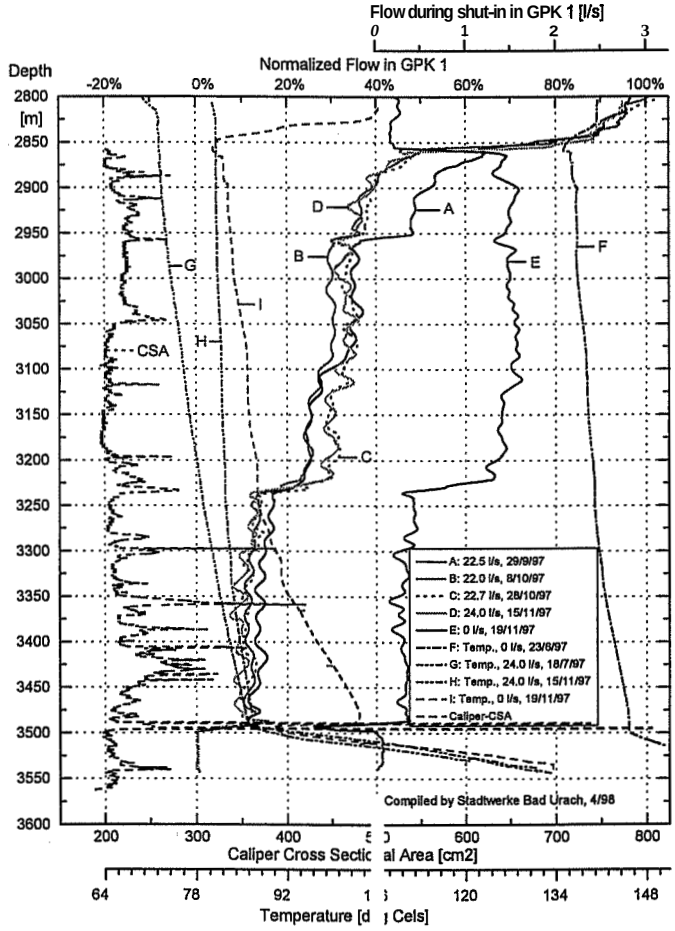


Figure 2: Flow-log in GPKl during the circulation test of 1997

Table 1B: Hydraulic active fractures in GPK2

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					
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
		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

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