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## Fracture Network of the EGS Geothermal Reservoir at Soutz-sous-Forêts (Rhine Graben, France)

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### Keywords

*EGS, fractures, fluid flow, granite, borehole image logs, Soutz-sous-Forêts, Upper Rhine Graben, France*

### ABSTRACT

In the framework of the EGS geothermal project at Soutz-sous-Forêts, characterizing the fracture network provides a basis for understanding both the underlying mechanisms and results of hydraulic stimulation, and the fluid circulation within the underground heat exchanger.

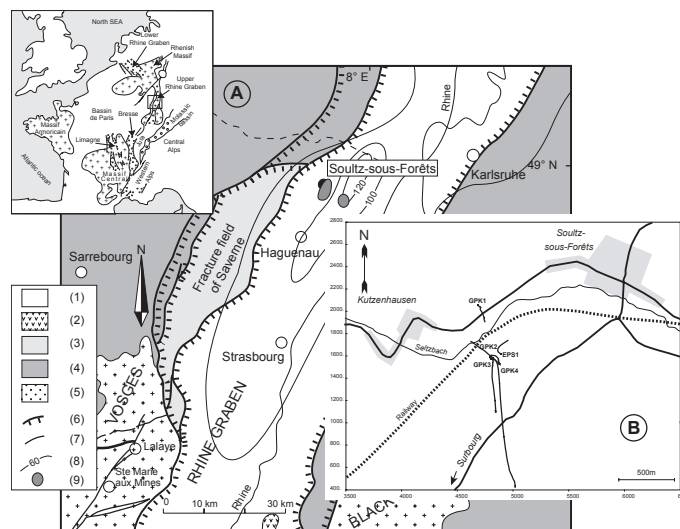
The Soutz site is located within the Rhine Graben, near its major western boundary fault. Five boreholes have been drilled since 1987: two relatively shallow exploratory wells (GPK1 and EPS1) and three for reservoir development and heat exploitation (GPK2, GPK3 and GPK4), all of which were drilled to depths of approximately 5,000 m, where temperatures reach 200°C. One of the exploration wells was cored; the others were partially or totally logged with borehole image logs (UBI or Ultrasonic Borehole Imager). Analysis of cores and downhole logs provides a basis for characterizing the fracture network at Soutz.

The reservoir is a fractured massif of granite overlain by 1,400 m of sedimentary cover. In a first step, the fracture network within the whole granite massif has been evaluated based on the analysis of the image logs. Fracture orientations are quite persistent in the entire massif: two main conjugate sets of nearly vertical fractures occur with a N170°E direction in all the wells, with dips both to the east and the west. This orientation is consistent with the regional tectonic framework, and the changes in dip direction may relate to major structures within the graben.

In a second step, we characterized the main permeable structures within the deep reservoir between 4,580 and 5,100 m. To evaluate the main features of these permeable structures in the open hole sections of GPK2 and GPK3, we simultaneously analyzed several sets of logs, including UBI and spectral gamma ray logs collected at the time of well completion, and

temperature and flow logs collected during hydraulic experiments. For the new borehole GPK4, completed in April 2004, the hydraulic tests have not yet been carried out yet and the geophysical logging data are not available.

In GPK2, we have identified seven fracture zones that appear to be participating in the fluid circulation. The most important zone is located at 4,780 m. However, the orientation of these zones could not be determined because there are no data from image logs available in this section. We analysed in detail the GPK3 well, which is fully documented, to improve our knowledge about the fracture network involved in the hydraulic experiments in the deep wells. In GPK3, UBI and spectral gamma ray logs are available for the whole borehole section. The analysis of flow and temperature logs measured during the hydraulic tests shows eight main fracture zones.



**Figure 1.** Location of the EGS Soutz site and geology of the Upper Rhine Graben. A: (1) Cenozoic sediments (2) Cenozoic volcanism (3) Jurassic (4) Trias (5) Hercynian basement (6) Boundary faults (7) Other faults (8) Temperature distribution in °C at 1500m depth (Haenel et al., 1979). (9) Local thermal anomalies (Haenel et al., 1979). B: Local map of the Soutz drill site with the well trajectories.

The most important zone is located at 4,760 m and is oriented N160°E, dipping 50°W. This large fracture zone has been probably intersected in the new borehole GPK4 at about 5,100 m depth, and appears to be a major fluid pathway of the lower reservoir at Soultz. The actively flowing fractures are mainly faulted zones associated with significant hydrothermal alteration haloes.

## Introduction

The European EGS Program aims to exploit the heat from the fractured granite basement of the Upper Rhine Graben in northeastern France, near the town of Soultz-sous-Forêts (Figure 1). Located near the western boundary fault of the Rhine Graben, the crystalline basement rocks do not outcrop but are overlain by 1,400 m of Mesozoic and Tertiary sediments (Figure 2). Heat extraction is achieved through forced circulation of fluid between wells drilled to 5,000 m depth, where the temperature reaches 200°C. Fluid circulates through the fractures of the rock massif after their permeability has been increased by hydraulic stimulation (Evans, 2000).

Since the beginning of the experiments initiated in 1997, five deep wells have been drilled into the granite basement (Figure 1). Two exploration wells, GPK 1 and EPS1, were drilled to 3,600 and 2,200 m, respectively, EPS1 being fully cored. The future exploitation triplet is formed by GPK2, GPK3 and GPK4, which were drilled to about 5,000 m from the same well pad and are slightly inclined with depth. Because the wells are deviated, the three wells are aligned at 5,000 m depth in a N165°E direction, and the horizontal distance between adjacent wells is about 600 m (Figure 2).

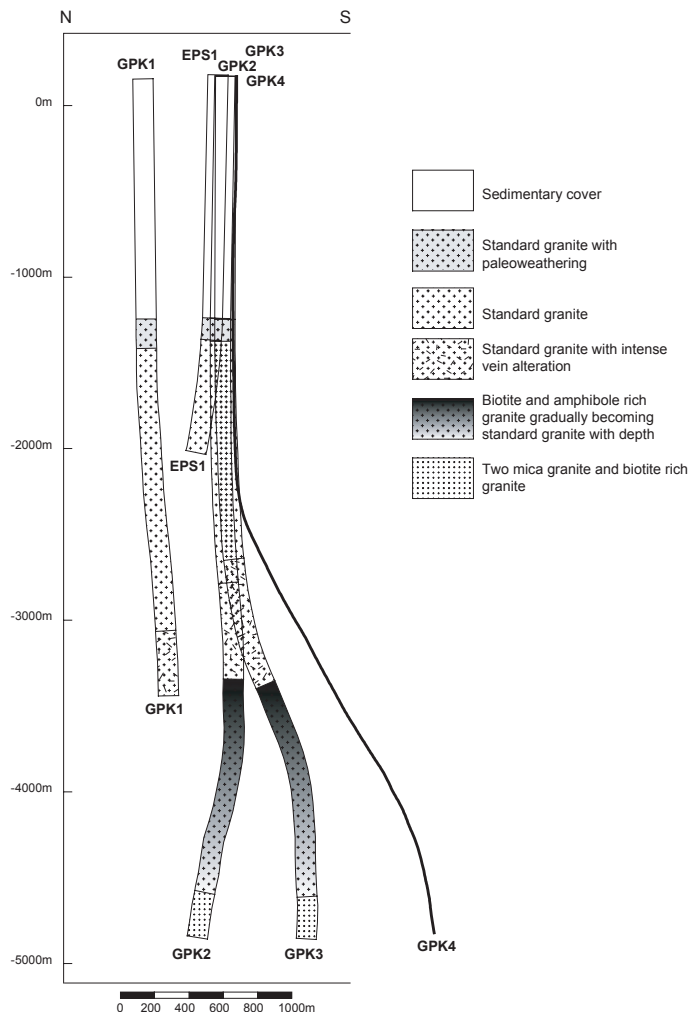
Cuttings, cores, geophysical logs and borehole image logs acquired in the granite were analyzed and interpreted to characterize the fracture network properties as well as the petrographical variations of the granite (Genter and Traineau, 1992; Genter et al., 1995; Genter et al., 1997; Genter et al., 1999; Genter et al., 2000; Dezayes et al., 2003). The deep geology of the Soultz site is mainly composed of three main granite units with depth. The upper part is referred to as the Mega K-Feldspar granite, the intermediate part is a biotite-rich granite and the lower part is a two-mica granite (Figure 2).

Based on continuous core samples available in EPS1 and borehole image logs in the other wells, the fracture network has been evaluated with a high spatial resolution. At depth within the heat exchanger (between about 4,500 and 5,000 m, several major fractures intersect all three deep wells; these form the potential fluid pathways. The hydraulic experiments conducted in the deeper part of GPK2 in 2000 (Weidler et al., 2002) as well as those done in GPK3 in 2003 (Michelet et al., 2004) showed that some localised fluid flow entries correspond closely to these large-scale fracture zones.

## Fracture network

### Data Available

Orientations and classification of several thousand fractures were collected from high-resolution acoustic image logs



**Figure 2.** Deep seated geology of the Soultz wells on a N-S cross-section.

such as BoreHole TeleViewer (BHTV) in GPK1 and EPS1, and Ultrasonic Borehole Imager (UBI) in GPK2, GPK3 and GPK4. Wells GPK1, GPK3 and GPK4 were fully logged, whereas in GPK2 the log stopped at 3,800 m and no image data were acquired in the bottom part of the well between 3,800 and 5,100 m. In total, about 10,000 m of image logs were analysed, and about 5,000 natural fractures were measured and characterized with a morphology in relation with their image signature.

In EPS1, the orientation, location and morphology of about 3,000 fractures were determined from 810 m of granite cores (Genter & Traineau, 1996). In the same interval, only 517 fractures were observed on the BHTV images. Despite the better resolution of the more recent images, the number of fractures is underestimated from the analysis of image logs; however, this does not lead to any biasing relative to the orientation of the network (Genter et al., 1997).

### Analysis of Cores and Image Logs

Between the top of the granite and 5,000 m, the distribution of the fractures versus depth shows several sections with different fracture densities. The top of the granite is highly

fractured with an average fracture density of 1 fr/m above 2,000 m. Below 2,000 m depth, the fracture density decreases to 0.4 fr/m. In the deeper part of the reservoir, the fracture density increases to 0.6 fr/m between 4,600 and 5,100 m, with several depth sections with higher value. This concentration of fractures in limited depth intervals corresponds to fracture clusters (Genter et al., 1997).

In the granite, the orientation of fractures based on cores and image logs show good agreement between all the wells. The fracture network shows two conjugate fracture sets with a N-S principal direction and high dip values (Figure 3), consistent with both the tectonic setting of the graben (Dezayes et al., 1995) and the stress field (Klee and Rummel, 1993).

The EPS1 cores show two major fracture sets: 1) a west-dipping major set that is more scattered with orientations of N175°E and N20°E with an 80° west dip (Figure 3); and 2) a second, more consistent east-dipping set, oriented N170°E with a 70° east dip. In this well, located in the north-east quadrant of the Soultz site, it appears that west-dipping fractures are more dominant. On the GPK1 BHTV logs, the fracture orientations are highly scattered (Figure 3), with a dominant N165°E trend. The fractures dip either 80° to the west or 75° to the east.

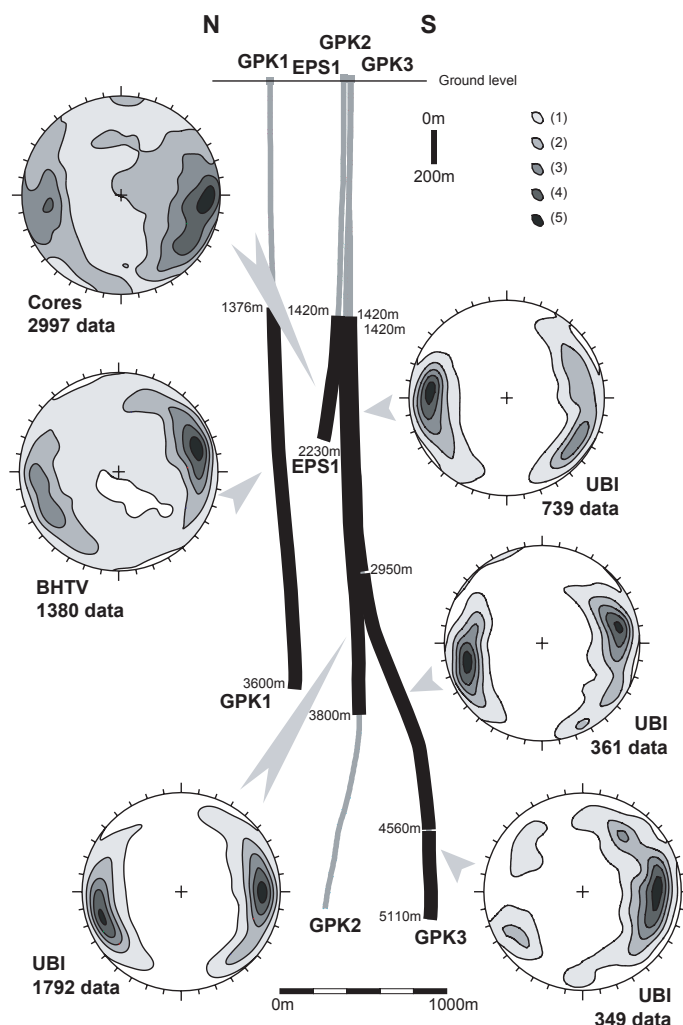
The fractures observed on UBI in the GPK2 well are gathered around two dominant sets oriented N170°E, which show the same proportion of nearly-vertical fractures. In GPK3, the fractures appear to show different orientations and dips in the three main crystalline units. In the upper part, between 1,420 and 2,950m depth, the major fracture set trends N5°E and dips 75° to the east. A second, more scattered fracture set is oriented N30°E and dips to the West. In the intermediate part, two conjugate, nearly vertical fracture sets are equally represented with a N170°E orientation. In the lower part, the fractures are scattered around a major set oriented N5°E. This dominant set is dipping 70° to the west. A secondary fracture set dipping to the east occurs. On the whole, the fractures are mainly oriented N-S and have high dips, but the dip direction is eastward in the upper part and westward in the lower part.

At Soultz, fracture data obtained using various analytical methods (cores, BHTV and UBI) show a consistency between all wells: the fractures are always highly dipping with a dominant orientation close to N-S. That geometry observed at great depth within the Rhine graben is consistent with the extensional regime, which occurred during Oligocene time (Dezayes et al., 1995).

## Characterisation of Fluid Pathways

### Hydraulic Stimulation

In wells GPK2 and GPK3, several temperature and flow logs have been acquired during hydraulic tests. Two types of hydraulic tests have been done in these wells: 1) injection tests with flow rates at about 15 l/s to determine the permeability of the fracture network; and 2) stimulation tests with higher flow rates (between 25 and 50 l/s, with some peaks at 90 l/s to increase the permeability. In GPK2, two temperature logs were acquired before and after the injection tests in February 2000



**Figure 3.** Fracture network orientation in the Soultz wells based on cores and various borehole image logs. Contour-density diagrams in Schmidt's projection, lower hemisphere: (1) 10%, (2) 30%, (3) 50%, (4) 70%, (5) 90% of the maximum frequency.

and one flow log was acquired during the stimulation tests in July 2000. In the GPK3 well, several temperature logs have been acquired after the drilling operation in December 2002, during the production tests in March 2003 and during the stimulation tests in May-June 2003. During the production and the stimulation tests, the temperature logs were associated with flow logs. These logs have been analyzed to identify flow anomalies that represent the active fractures within the rock mass.

### Fracture Zones in GPK2

The flow log acquired during the stimulation of GPK2 has not been corrected for borehole size effects because no caliper data are available from the open hole section. This complicates the precise determination of the fluid exit zones. However, a detailed analysis of temperature logs run before and after injection shows seven permeable fracture zones. As only a petrographic log is available in the open hole section, we correlated these fluid loss zones with hydrothermally altered granite zones, which is consistent with the presence of conduc-



tive fractures. In GPK2, the most important zone is a highly altered granite at 4,780 m depth, where there is a significant anomaly on both temperature and flow logs.

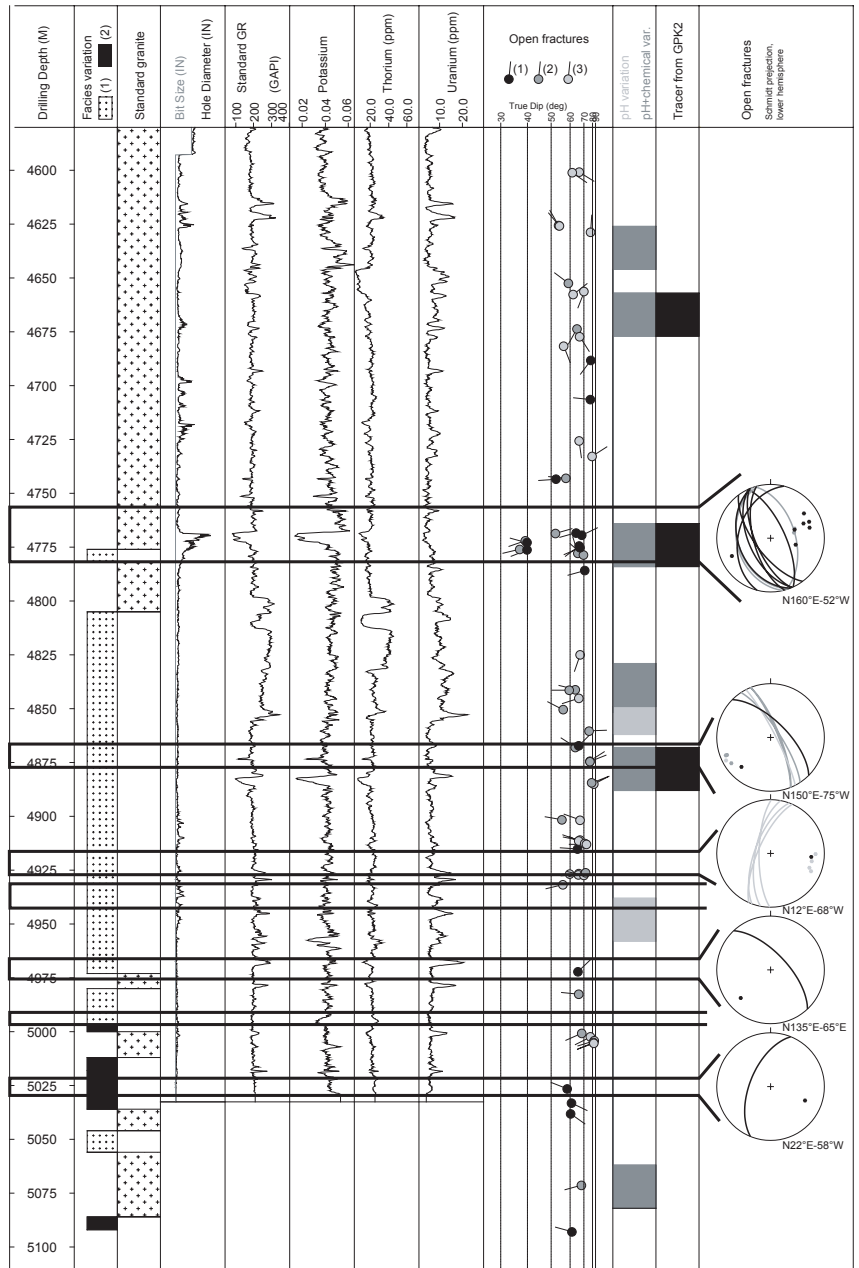
**Fracture Zones in GPK3**

In the GPK3 well, the flow logs were corrected using caliper data and were analyzed in combination with the temperature logs to permit more accurate location of fluid exit zones. Using this combination of temperature and flow logs, eight fluid exit zones were located. The first zone is located just below the casing shoe at 4,580 m. However, as no UBI data are available from this zone, its orientation was not determined. The seven other zones could be observed and measured on the UBI logs. Additional measurements, such as petrographical log, caliper log, spectral gamma ray log and chemical anomalies of the drilling fluid, were very helpful for a better characterisation of these zones (Figure 4). The chemical data correspond to variations in pH and Mg and SiO<sub>2</sub> concentrations in the drilling fluid flowing into and out of the hole. Other chemical analyses permit detection of tracers injected previously in the neighbouring well GPK2 during its hydraulic tests in 2000 (Sanjuan et al., 2004).

**Geological Characterization of Fluid Exit Zones**

The most important fracture zone in GPK3 at 4,775 m corresponds to a huge void visible on the caliper log (Figure 4). At this zone, an important negative gamma ray anomaly is spatially bounded by a significant increase of the potassium content. This potassium enrichment is correlated with the occurrence of secondary potassium-bearing hydrothermal clay minerals, namely illite (Genter et Traineau, 1996). That indicates the presence of a hydrothermally altered granite with possible occurrence of geodal quartz as it was observed in the EPS1 core sections (Traineau et al., 1991). The chemical analyses of the drilling mud point out pH and Mg and SiO<sub>2</sub> concentration variations associated with the presence of tracers. This fracture zone, which appears as the major pathway between GPK2 and GPK3, has been also intersected in the new well GPK4 at about 5100m depth.

Other permeable fracture zones also correspond to significant variations visible on the geophysical logs, but with lower amplitude. However, the occurrence of hydrothermal alteration associated with these fractures is not well constrained. Chemical variations do not always match with permeable zones (Figure 4). Moreover, the zone at 4,670 m reveals the presence of tracers, but does not seem to correspond to a fluid pathway during hydraulic testing.



**Figure 4.** Synthetic log of the open hole section of the GPK3 well showing characterization of the fluid exit fractures. Column 2. Facies variation log: (1) two mica granite, (2) biotite rich granite; Column 3 Standard granite: porphyritic MFK-rich granite; Column 9. Open fractures versus depth: grey density variation indicates the percentage of continuity of the fracture trace on UBI log: (1) 100%, (2) >50%, (3) <50%. The horizontal scale indicates the dip value of fractures. The direction of the tadpole indicated the dip direction of fractures (north is to the top, east to the right). Columns 10 and 11: Chemical anomalies detected in the drilling mud flowing into and out of the drill hole.

**Geometrical Characterization of the Fluid Exit Zones**

Analysis of UBI data permit the determination of the orientation of open fractures located at the depth of the permeable zones observed from temperature and flow logs. The orientation and nature of the fracture zones vary in an important way. The most important zone at 4,775 m, which takes 63% to 78% of fluid during the stimulation, is actually a cluster of fractures (Figure 5a). The fractures within this

cluster trend N160°E and most of them dip westward at an average angle of 52° (Figure 4).

The zone at 4,875 m consists of four fractures, one of which appears thicker on the borehole images. The average orientation is N150°E-75°E. This zone takes 2% of the fluid during the stimulation tests. Chemical variations and tracers observed from changes in the drilling fluids indicate the presence of fractures bearing flow.

The zone at 4,920 m also consists of several fractures, with one being more prominent (Figure 4). This zone did not take any fluid during the last hydraulic test, which included injection at a rate of 50 l/s after two peaks at 90 l/s. The average orientation is N12°E-68°W (Figure 4). The zone at 4,972 m shows a single open fracture without any alteration (Figure 5b). The fracture is oriented N135°E-65°E and takes approximately 4% of the fluid during all of the hydraulic tests. A deeper zone at 5,025 m also consists of a single fracture oriented N22°E-58°W (Figure 4). The fracture takes 10 to 15% of the total injection accepted by the wellbore during all the hydraulic tests.

Two zones, namely 4,940 and 4,990m, do not correspond to open fractures based on UBI image logs acquired shortly after the end of the drilling. However, these two zones appear to be hydraulically active under certain conditions. The zone at 4,940 m accepted about 2-4% of the injected fluid at an injection rate of 25 and 30 l/s, but did not accept any fluid during injection at 50 l/s and after the 90 l/s period. The zone at 4,990 m seems closed at the beginning of the stimulation (at an injection of 25 l/s), but later accepts 4% of the fluid flow. These zones may have initially been closed but later were opened during the hydraulic experiments.

## Discussion

In the deeper part of the Soultz site, the fracture system shows a dominant orientation close to N-S with high westward dips. The fracture zones at 4,775 m, 4,920 m and 5,025 m in GPK3 are the most important from a hydraulic perspective (Figures 3 and 4). The two other fracture zones located at 4,875 m and 4,972 m dip to the NE and belong to the minor fracture set (Figure 3).

In the open hole section of GPK3, the flowing fracture zones have two main organizations. The first is a cluster pattern, which corresponds to the fracture zones located at 4,775 m. This zone shows a significant hydrothermal alteration halo as identified by the geophysical well-logging data. The second is a small scale fracture network characterised by individual fractures such as those at 4,875, 4,925, 4,975 and 5,025 m, which have no significant alteration halo.

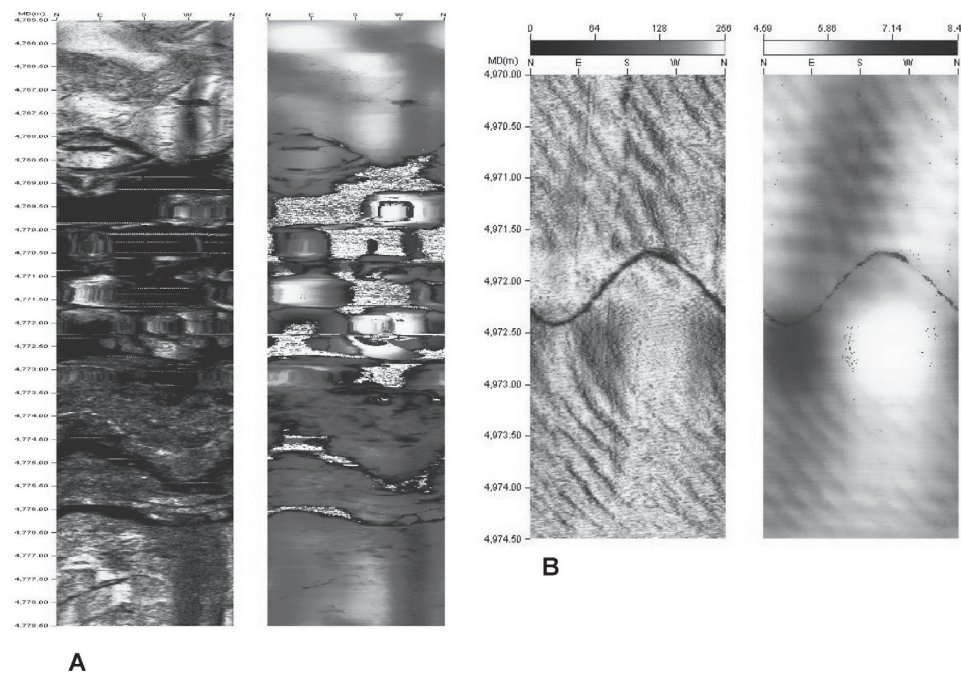
In GPK2, the major flow zone is present at 4,780 m depth and is connected to GPK3. In GPK4, we could identify this same zone at about 5,100 m. However, in GPK2 and GPK4, this zone is thinner and less permeable than in GPK3. This major flow structure is located near the transition from the M-K-Feldspar granite and the two-mica granite.

Other permeable zones are fractures that appear to be closed on the image logs run shortly after the drilling. They have been probably reactivated during the hydraulic stimulation that permits to increase the permeability of the reservoir.

## Conclusion

In the four deep wells of the EGS Soultz project, the whole fracture network has been analysed based on cores and borehole image logs. The network geometry is quite persistent for all the wells and shows two main conjugate fracture sets, both oriented N170°E and both with high dip values. The dip direction of the major fracture set alternates between eastward and westward. This orientation is clearly related to the regional extensional tectonic regime and the dip direction of the major set appears to be related to major normal fault zones developed within the granite. The new data in the most recent well GPK4 will be evaluated to assist in deciphering the relationship between large-scale faulting and the permeable fracture network.

The major fluid pathways have been identified in GPK2 and GPK3. As GPK2 is poorly documented, the fracture study was mainly concentrated on well GPK3. In this well, we identified eight zones that take fluid during the stimulation tests. These zones have been characterized in term of fracture zones, the main one being a fracture cluster oriented N160°E-52°W. Some permeable zones are single open



**Figure 5.** Two types of permeable fractures on UBI log in GPK3 well. The left part of the images corresponds to amplitude measurement and the right part corresponds to transit time measurement. A- Fracture cluster at 4,775 m which takes 63% to 78% of the fluid during hydraulic stimulation. B- Single fracture at 4,972 m which takes 4% of fluid during the hydraulic stimulation.

fractures whereas other types correspond to closed fractures that probably re-opened during the stimulation tests. The detailed study of the GPK3 well, which is fully documented, has permitted a significant improvement in the understanding of hydraulic circulation in the deep wells.

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