

Deep-Seated Geology and Fracture System of the EGS Soultz Reservoir (France) based on Recent 5km Depth Boreholes

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ABSTRACT

In the framework of the EGS (Enhanced Geothermal System) European Soultz project (France), the recent drilling of the wells (GPK2, GPK3, GPK4) at 5km depth, where the bottom hole temperature reaches 200°C, allows to revisit the deep-seated geology of the granite reservoir.

The deep geology of the reservoir was studied from cutting observation and well logging data (spectral gamma-ray, caliper, drilling parameters). By using a fine resolution image log, the Ultrasonic Borehole Imager, the fracture network was evaluated in terms of fracture density and orientation between 1500 to 5100m depth.

Comparison between the geological data has pointed out different granite intrusion, which has been differentiated and characterised within the basement. The deeper granite intrusion corresponds to a two-mica granite, being the youngest, which intrudes within the shallower porphyritic biotite granite.

The small-scale fracture direction is mainly N-S, which is roughly parallel to those of the present-stress field. At larger scale, some fractured zones develop a hydrothermally altered halo, which represent some potential candidate for fluid circulation through the granite reservoir.

Hydraulic tests, carried out in the open hole sections, confirm that some connections occur between the boreholes 600m away, at 5km depth, throughout the natural fractures of the granite basement. A updated conceptual model of both the deep geology and the fracture network of the Soultz reservoir were reexamined in the light of these recent investigations.

1. INTRODUCTION

The European EGS project, located at Soultz, aims to evaluate and exploit the heat potential of the deep fractured granite basement of the Upper Rhine Graben in northeastern France (Figure 1). In this area of extensional tectonic regime, the crystalline basement is not outcropping but is covered by about 1.4km of Cenozoic and Mesozoic sediments (Figure 2).

Heat extraction is achieved through forced circulation of a fluid between wells drilled to 5000 m depth, where the temperature reaches 200°C. Fluid circulates through the fractures of the rock massif after their permeability has been increased by the hydraulic stimulation (Evans, 2000; Baria *et al.*, 2004).

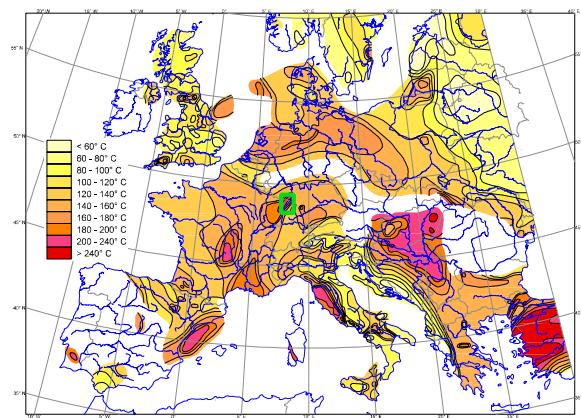


Figure 1: Map of temperature extrapolated at 5km depth in Europe (Hurtig *et al.*, 1992). The green square indicates the area of the Figure 2.

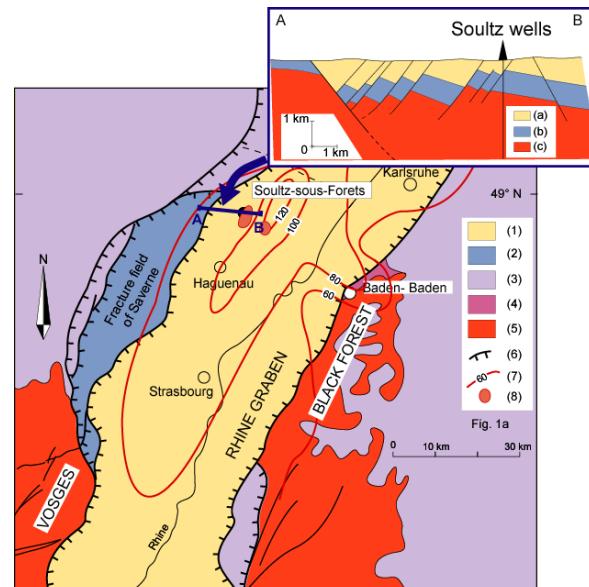


Figure 2: Location of the EGS Soultz site and geology of the Upper Rhine Graben (1) Cenozoic sediments (2) Cenozoic volcanism (3) Jurassic (4) Trias (5) Hercynian basement (6) Border faults (7) Temperature distribution in °C at 1500m depth (Haenel *et al.*, 1979). (8) Local thermal anomalies (Haenel *et al.*, 1979). Simplified cross-section through the Soultz site: (a) Cenozoic filling sediments (b) Mesozoic sediments (c) granite basement.

To build the triplet of the exchanger, three deep exploitation wells (GPK2, GPK3, GPK4) have been drilled to 5000m, added to the two deep exploration wells (GPK1, EPS1) (Baria *et al.*, 1992; Hettkamp *et al.*, 2004). The three exploitation wells were drilled from the same well pad and

are slightly inclined with depth. Because the wells are deviated, the three wells are aligned at 5000 m depth in the same orientation than the maximum main horizontal stress axis, which is N165°E direction, and the horizontal distance between adjacent wells is about 600 m (Figure 3).

Cuttings, cores, geophysical logs and borehole image logs acquired in the granite were analysed and interpreted to characterise the fracture network properties as well as the petrographical variations of the granite (Genter and Trainea, 1992; Genter et al., 1995; Genter et al., 1997; Genter et al., 1999; Genter et al., 2000; Dezayes et al., 2003).

Based on all well information of the five boreholes, a geological model of the Soultz reservoir has been updated. Several facies types of granite occur and then, the granite has been divided in several homogenous petrographic sections. The fracture network has been evaluated in the whole granite section with a high spatial resolution. Between about 4500 and 5000 m, within the heat exchanger, several major fractures intersect three deep wells, which form the potential fluid pathways. Hydraulic experiments conducted in the deeper part of GPK2 in 2000 (Weidler et al., 2002; Baria et al., 2004) 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, namely normal fault zones related to graben creation.

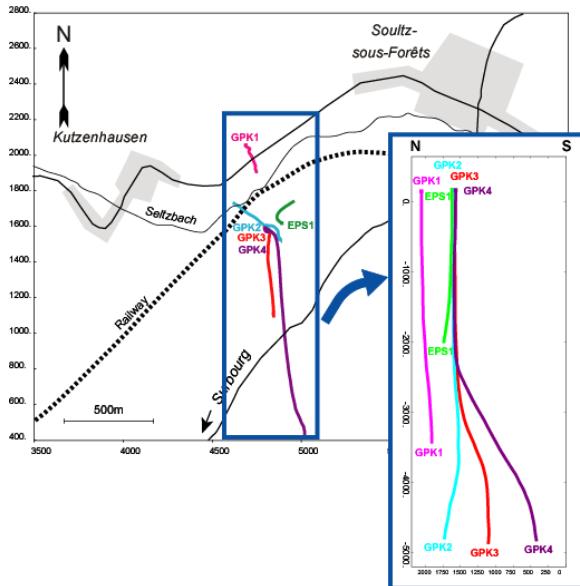


Figure 3: Map view and N-S cross-section of the EGS well trajectories at Soultz.

2. GEOLOGY OF GRANITE INTRUSIONS

2.1 Petrographic characterization

Because of the granite basement does not outcrop, its petrographic characterization has been determined only by well information, such as cores, cutting samples and well-logs.

The upper part of the massif is well known because one well has been fully cored to 2200m depth (Genter & Trainea, 1992). In the lower part of the pluton, only one core has been collected at around 5060m in the GPK2 well.

In this GPK2 well, a huge fracture zone occurs at 2100m and formed a total mud loss zone during drilling operations.

Consequently, drill cuttings were recovered when this zone has been cemented before deepening of this well, from 3900m and 5100m. So, cutting samples were collected normally in this interval.

The GPK3 and GPK4 wells have been drilled continuously from the surface to 5100m depth. The drilling provides cuttings, which have been collected regularly in the entire granite section. However, due to drilling problem, the granite rock was so crushed that the finest minerals have been lost in the drilling mud. So, clay minerals have not been collected and altered zones could not be detected properly.

After washing, the cuttings were examined by a conventional binocular microscope (10-50x) resulting in a well site cutting description. Several interesting depths in the basement were selected and thin sections were made.

The type of granite is based on the abundance of minerals in the sample, which are deduced from examining thin sections. Three main petrographic types were encountered in the granite (Figure 4):

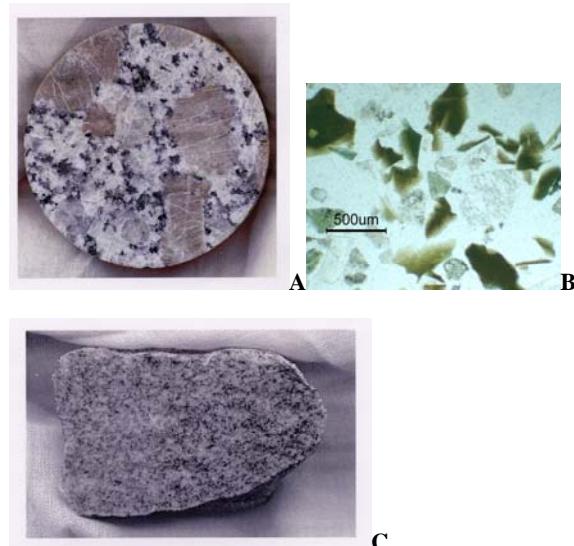


Figure 4: Types of granite encountered in the Soultz wells. A - Standard porphyritic granite, section of GPK-1 core. The sample diameter is about 75mm. B - Biotite and amphibole rich granite, thin section of cuttings from GPK-3. C - Two mica granite, core sample collected at 5058m depth in GPK-2. The sample size is approximately 70mm.

- Typical standard porphyritic granite (Figure 4-A) contains quartz, K-feldspar, plagioclase, biotite, amphibole and accessory minerals as magnetite, titanite, apatite, allanite and zircons. Characteristic pink K-feldspar megacrysts occur as individual grains on cm scale. The biotite is the dominant mafic component. Amphibole is generally scarce but can be quite abundant. Carbonates can also be present. This granite is described as a monzogranite with an emplacement age of 334Ma (Stussi et al., 2002; Cocherie et al., 2004).
- Biotite and amphibole rich granite does not differ much in primary mineralogy from standard porphyritic MFK-rich granite. It also contains quartz, K-feldspar, plagioclase, biotite, amphibole and several accessory minerals, but the biggest difference is the amount of biotite and amphibole

crystals, which is significantly higher than in standard porphyritic granite (Figure 4-B).

- The two mica granite is a more leucocratic very fine-grained granite and is characterized by the occurrence of primary muscovite flakes (Figure 4-C). Cross-hatched microcline is an often occurring feature. This leucocratic granite is a differentiated expression of the potassic magma that was at the origin of the monzogranite pluton and intrude later in this monzogranite. The estimated crystallization age is 327Ma, slightly later than, or sub-contemporaneous with, the emplacement of the monzogranite (Cocherie et al, 2004).

Besides the petrographic types, the form of hydrothermal alteration can be distinguished, such as pervasive alteration and vein alteration (Figure 5) (Traineau et al., 1991; Genter & Traineau, 1992).

Pervasive rock mass alteration takes place on a large scale in the granite without visibly modifying the texture of rock, but primary minerals have given way to secondary minerals (Figure 5-A).

The second type of alteration, vein alteration, is related to water-rock interactions occurring in the natural system. The primary minerals (silicates) of the granite have been partly dissolved developing a peripheral wall-rock alteration halo (Figure 5-B) (Genter et al., 2002).



Figure 5: Examples of hydrothermally altered granite.
A – Pervasive alteration which transforms primary minerals in secondary minerals but the texture is saved. Height of the sample is about 10cm. B – Vein alteration with dissolution and precipitation. Quartz deposition, brecciated granite and cataclased granite forming a hydrothermally altered zone. Height of core is about 12cm.

2.2 Geological model of the granite basement

In order to validate the deep-seated geology in terms of petrographic types and rock facies, we used spectral gamma ray logs and caliper logs with a statistical cluster analysis. This statistical analysis, named Hierarchy Ascending Classification (HAC), is a multivariable statistical method. The aim is to improve the vertical zoning having coherent U, K, Th contents and hole diameter. This method allows to group individuals based on their resemblance and produces a dendrogram that reflects the relations between the different groups. The resulting dendrogram reveals several classes. Based on fine petrographic examination of cuttings, the different classes have been characterized in terms of granite facies or altered fractured zones.

A comparative work has been realized for the GPK3 well, which is well documented, and a geological model has been

validated. That permits to reexamine the other wells and propose a new geological interpretation of the granite intrusions (Hooijkaas et al., 2004) (Figure 6).

The top of the pluton corresponds to a massive standard porphyritic MFK-rich granite, locally with some paleoweathering between 1420 and 1570m.

From 2700m to 3200m the same standard porphyritic granite is characterized by the occurrence of very intense alteration due to faulting (Figure 6). Below the high fracture density zone, the granite is very rich in biotite and amphibole but it gradually becomes standard porphyritic granite again (Figure 6). At the bottom, the fine grained two mica granite and biotite and amphibole rich granite are present and interpreted as intrusion into the standard porphyritic granite.

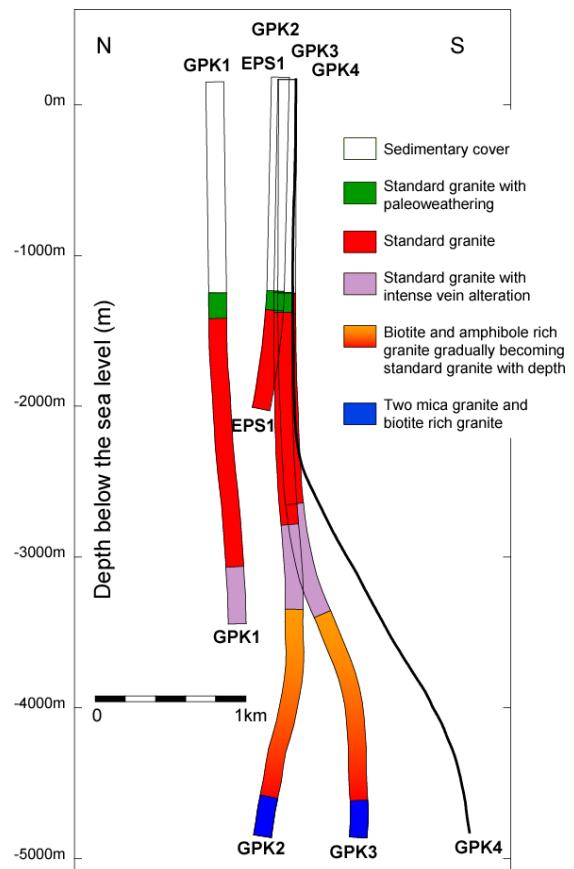


Figure 6: N-S geological cross-section between the Soultz wells. See location in Figure 3.

3. FRACTURE NETWORK

3.1 Data available

The exploration well EPS1 was fully cored and the orientation, location and morphology of about 3000 fractures were determined from 810 m of granite cores (Genter & Traineau, 1996). In the other wells, orientation of fracture have been measured on high high-resolution acoustic image logs 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 logs stopped at 3,800 m and no image data were acquired in the bottom part of the well between 3800 and 5100 m. In total, about 10000 m of image logs were analysed, and about 5000 natural

fractures were measured and characterized with a morphology in relation with their image signature.

3.2 Fracture network distribution

The distribution of the fractures versus depth, between the top of the granite and 5000 m, shows several sections with different fracture densities. The top of the granite is highly fractured with an average fracture density of 1 frc/m above 2000 m. Below 2000 m depth, the fracture density decreases to 0.4 frc/m. In the deeper part of the reservoir, the fracture density increases to 0.6 frc/m between 4600 and 5000 m, with several depth sections with higher value. This concentration of fractures in limited depth intervals is interpreted as fracture clusters (Genter et al., 1997).

The orientation of fractures in the granite based on cores and image logs shows good agreement between all the wells. Two conjugate fracture sets with a N-S principal direction and high dip values are present (Figure 7).

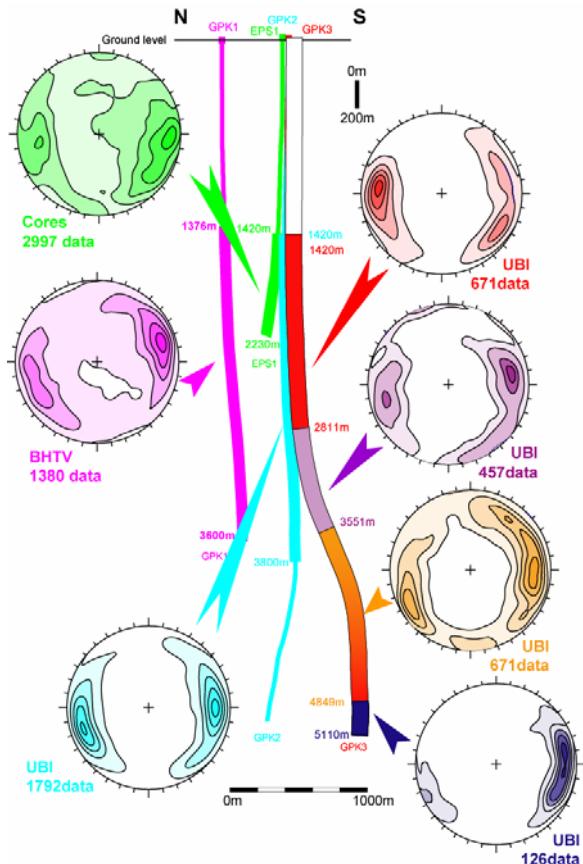


Figure 7: Fracture network orientation in the Soultz wells based on cores and various borehole image logs. Contour-density diagrams in Schmidt's projection, lower hemisphere at 10%, 30%, 50%, 70% and 90% of the maximum frequency.

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 7); 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 (Figure 3), it appears that west-dipping fractures are more dominant. On the GPK1 BHTV logs, the fracture orientations are highly scattered (Figure 7), with a dominant N165°E trend. The fractures dip either 80° to the west or 75° to the east.

In the GPK2 well, the fractures observed on UBI are gathered around two dominant sets oriented N170°E, which show the same proportion of nearly-vertical fractures (Figure 7). In GPK3, the fractures appear to show different orientations in the upper and lower part of the well. In the upper part, between 1420 and 2950m 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 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 also occurs. On the whole, the fractures are mainly oriented N-S and have high dips, but the dip direction is mainly eastward in the upper part and westward in the lower part (Figure 7).

Therefore, in the Soultz wells, fracture data obtained by using various analytical methods (cores, BHTV, UBI) show a consistency between all the wells: the fractures are always highly dipping with a dominant orientation close to N-S. The geometry observed at great depth within the Rhine graben shows that the origin of the fracture network is in relation with the extensional regime, which occurred during Oligocene time (Dezayes et al., 1995). The main direction is consistent with the present-day stress field (Klee and Rummel, 1993) that it permits to improve the fluid circulation within the geothermal reservoir.

3.3. Hydrothermal fractured zones

At large-scale, some fractured zones develop a hydrothermally altered halo, which representent some potential candidate for fluid circulation through the geothermal reservoir. Hydraulic tests, carried out in the open hole section between 4500m to 5000m, permit to identify some connections thoughout natural fractures. The location of the fluid exit zones is based on the analysis of both temperature and flow logs.

In GPK2 and GPK3, 7 and 8 fluid exit zones have been identified respectively. One of them connects the boreholes 700m away at 5km depth.

In GPK2 well, only a petrographic log based on cutting description is available, whereas in GPK3 and GPK4 wells more geophysical logs and UBI (Ultrasonic Borehole Image) are available.

In GPK2, the fluid loss zones are correlated with hydrothermally altered zones. In GPK3 and GPK4, the fluid loss zones have been observed and their orientations have been measured on UBI. 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. These zones show alteration with different degrees. The most important fracture zone corresponds to a huge void (cave) with a high potassium enrichment indicating the presence of hydrothermally altered granite (Figure 8-A). 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. 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 K-Feldspar porphyritic granite and the two-mica granite (Figure 6).

Other permeable fracture zones also correspond to significant variations visible on the geophysical logs, but with lower amplitude (Figure 8-B). As there is no anomaly in the transit time image, some of them appear 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.

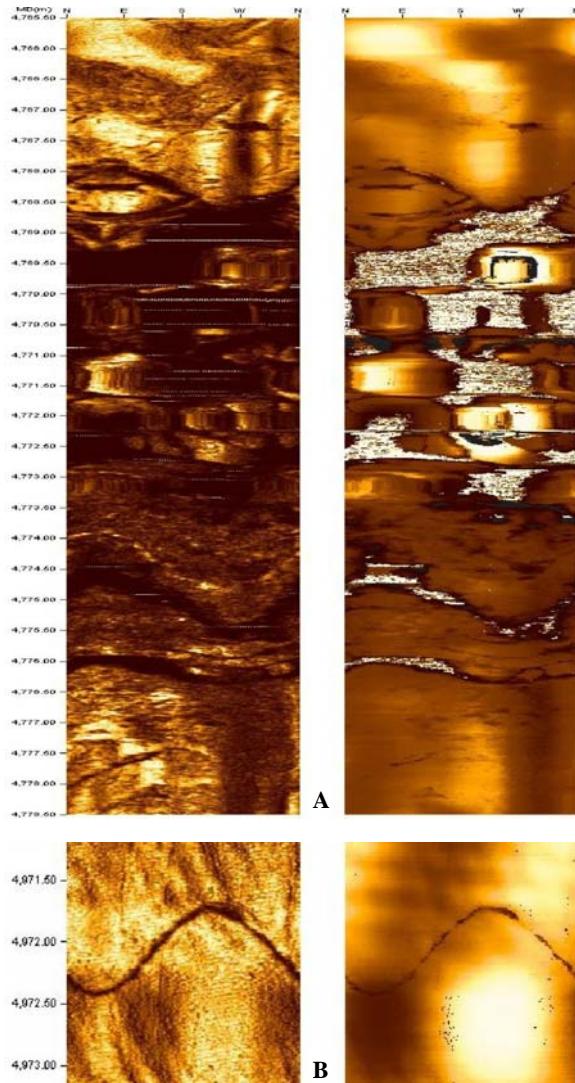


Figure 8: Examples of two types of permeable fractures on UBI log in GPK3 well. A- Fracture cluster at 4775 m which takes 63% to 78% of the fluid during hydraulic stimulation (image between 4765.5 and 4770.5m). B- Single fracture at 4972 m which takes 4% of fluid during the hydraulic stimulation (image between 4971.5 and 4972m). The left part of the images corresponds to amplitude measurement and the right part corresponds to transit time measurement. Each fracture appears as a sinusoidal trace.

Analysis of UBI data in the GPK3 well permits the determination of the orientation of fractures correlated to the fluid loss zones. Some zones correspond to several fracture planes forming a cluster, whereas other fluid loss zones correspond to more localized fracture planes (Dezayes et al., 2004). The average direction of the fluid loss zones is N150°E (Figure 9). Five of them are dipping to the West according to the main small-scale fracture set (Figure 9). Two fracture zones are dipping to the East and belong to a minor set of small-scale fractures (Figure 9).

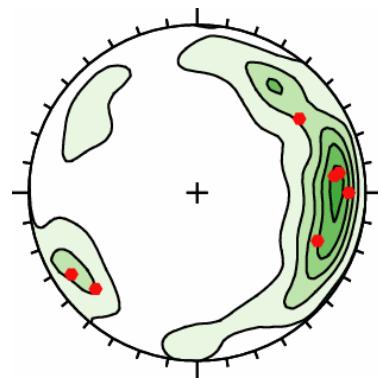


Figure 9: Orientation of fluid loss zones compared to the small-scale fracture orientation in the open-hole section of GPK3 well (4500-5100m). Blue circles indicate the average orientation of the fracture planes correlated to the fluid loss zones. The contour-density diagram in green represents the orientation of the small-scale fractures in Figure 7. Schmidt's projection, lower hemisphere.

4. CONCLUSION

The three deep wells drilled on the Soultz site give lot of geological information of the deep-seated geothermal reservoir.

Several types of granite were characterized in detail though a fine examination of the cuttings. According to a statistical cluster analysis (HAC) of the geophysical logs, a vertical zoning of the granite could be determined with more precision. Therefore, an updated petrographical model was designed, which reveals a more altered and fractured section in the porphyritic granite between 2700m and 3200m. In the lower part of the wells, an another granite body, leucocratic two-mica granite, has intruded the main porphyritic granite.

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 of the Rhine Graben.

Based on the hydraulic tests, the major fluid pathways, that take fluid during stimulation, have been identified. These zones have been characterized in terms of fracture zones and the main one being a fracture cluster oriented N160°E-52°W. This structure connects GPK2 and GPK3 and is observed in GPK4. Some permeable zones are single open fractures whereas other types correspond to closed fractures that were probably re-opened during the stimulation tests.

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