Fracture interpretation based on electrical and acoustic borehole image logs

Etude réalisée dans le cadre des opérations de Recherche du BRGM 2001-ENE-D01

avril 2001
BRGM/RP-50835-FR
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This report is written on BRGM by Anton Henriksen as part of a European Community research project. The project is called "Methodology for predicting fluid flow characteristics of wells in fractured reservoirs" (contract JOF-CT97-57007).

Keywords: Soultz-sous-Forêts (France), Reservoir, Natural fractures, Granite, Borehole image logs, Fracture aperture.

En bibliographie, ce rapport sera cité de la façon suivante :

**Abstract**

This work has been done in the framework of a Marie Curie Grant as part of a European Community research project (contract JOF-CT97-57007). The project was called "Methodology for predicting fluid flow characteristics of wells in fractured reservoirs". This methodology was applied on the available datasets of the Soultz Hot Dry Rock geothermal project. A series of electric- and acoustic borehole imaging techniques (e.g. FMI, UBI, and ARI) was used to set up a hierarchy of fractures in the near-well volume in the granitic section of well GPK1 (Soultz-sous-Forêts, Rhine graben, France). The hierarchy consists of the characteristics of the interpreted fracture patterns from the borehole images.

From the well GPK1, digital copies of borehole images and additional well log data from the depth interval 2850-3505 m have been loaded into a common database and depth-matched. The fracture hierarchy is described based on a detailed characterisation of the fractures and comparison between the different types of electric and acoustic images. The resolution of the images is inversely proportional to the range of measurement. Thus, the FMI image log can be used for characterising small-scale fractures, whereas the ARI log is used for characterising larger scale fractures but distant from the inner well surface. The ARI (advanced Dual Laterolog tool, DLL) log indicates that less than 25% of the 690 natural fractures (individual fractures and fractured zones included) detected on the inner borehole surface extend away from the borehole wall.

At Soultz, natural fractures tend to be found in clusters throughout the borehole, and can be separated into two distinct directional families. The dominant dip directions of these families are: over 3060 m N80W-N100W, between 3060-3260 m N90E-N100E, and below 3260 m depth both families of fractures are equally present. The fracture dip is quite consistent between 60° and 80°. Fracture spacing was also evaluated.

In order to provide additional information about where the more conductive fractures are located and how large they are, a fracture aperture analysis have been carried out. We tried to estimate the electrical apertures of open fractures around the wells by using different well log information, reflected Stoneley waves, electrical borehole images, and the Dual Laterolog response. On the electrical images, electrical fracture apertures can be estimated in several ways by integrating the electrical response around the borehole. Measurements of natural fractures on cores were used to calibrate the measured apertures. Several scales of relative fracture apertures have been estimated based on the conductivity contrasts on the electrical images.
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Based on the flow- and temperature logs (Evans, 2000), hydraulic active zones have been identified in GPK1. A comparison between the estimated electrical aperture and the hydraulic zones shows that a broad qualitative relationship is found, as all dynamic data are identified on the ARI image logs. The highest calculated fracture aperture values located at 3220 m and 3490 m depth match properly with the major permeable zones known in GPK1. The ARI estimated electrical apertures are capable of identifying more than 75% of the fractures which show some indicators of flowing behaviour in GPK1 Well.
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1. Introduction

This project is set up as a European Community research project, in a collaboration between the public research institution "BRGM" (Geological Survey of France) located in Orléans, France, and the private company "Z&S GeoScience" in Stavanger, Norway. The project is supported by the European Commission through a Marie Curie Fellowship. Anton Henriksen (Fellowship holder) and BRGM (host institution) have received the grant for three years (May 1998 - May 2001). The Fellowship is given under the Fourth RTD Programme, Non-nuclear energy, Security and Supply of Hydrocarbons.

In BRGM, the project is integrated in the framework of ongoing research projects on fractured reservoirs. The project was initially a part of the BRGM research projects PRR201 and PRR304 (both now finished), and is now a part of the BRGM research project on deep reservoirs 00ENED02.

Since the project start, Z&S GeoScience have experienced a decrease in activity due to turbulence in the petroleum industry, and they have now ceased activity. Consequently, the project is now only carried out under the responsibility of the Research Division of BRGM through Albert Genter, a geologist specialist of fractured reservoirs.

1.1. PROJECT SCOPE

The aim of this project is to develop a method for predicting fluid flow characteristics of near-well natural fractures in natural fractured reservoirs. The challenge is to create 3D models of fracture networks around boreholes based on 1D data of the fractures that intersect the borehole. The emphasis is thus on the characterisation of fractures, which actively supports fluid flow.

1.2. BACKGROUND

Thousands of fractured reservoirs have been analysed for fractures intersected by wells. Data are gathered with high-resolution electrical or acoustic sensors and used to generate images of the properties of the borehole wall. In this way, information is obtained about fracture frequency, orientation, and apertures (e.g. Luthi and Souhaité, 1990; Aguilera, 1995; Wennberg, 1999). On borehole images, open fractures of relevant aperture are easily identified as a resistivity or acoustic contrast between the formation and the openings in the borehole wall.

Also fieldwork has been investigating surface joint patterns and their scaling relationships (e.g. Castaing et al., 1996; Odling et al., 1999), and the influence of stress on fracture flow is well documented (e.g. Lehne, 1988; Cooper, 1992; Hillis, 1997).
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One of the important parameters controlling the flow in a fractured reservoir is the fracture aperture. It is commonly assumed that the rate of fluid flow in a fractured reservoir follows a cubic law of fracture openness (e.g. Thomasen, 1995; Odling et al., 1997). In addition, in the fractured reservoirs, relatively few fractures (or open faults) often serve as the primary conduits for fluid flow in the fractured rock mass. In addition, within a conductive fracture some areas can actively support flow more likely than others areas. This is often interpreted as a channelling effect, i.e., flow in a system of channels and islands (Gentier, 1986). Information about the direction of flow might also be extracted from the image logs.

However, from borehole images it is not easy to assess visually whether or not fractures are flowing, as there exist only very little information concerning the connectivity and extent of the fractures. Thus, it is interesting to find a method to identify (if possible) which of two apparent identical fractures, on an image log, is the most important one in terms of their hydraulic properties. This is, which fractures are the hydraulically active.

The real fracture network around the well is not described in details, as such effort would be very demanding due to the complexity of the fracture network.

When modelling a fracture network, one attempts to model the conditions of the network, by using the statistical properties of the observed fracture network as border conditions in the modelled fracture network.

Sometimes the intervals with a high frequency of fractures do not match the intervals with large fracture apertures (e.g. Dezayes, 1995; Hillis, 1997). It is therefore essential to know more about where the more conductive fractures are located and how large they actually are. Fracture aperture analysis attempts to provide such quantitative information for reservoir studies.

In addition, work on modelling fracture networks has led to new methods to generate the 3D-geometry of a fracture network, and investigations of its connectivity (e.g. Massoud, 1987; Gervais, 1993; Bourgine et al., 1995; Aarseth et al., 1996; Cacas et al., 1997).

However, still not enough information exist to either, simulate the 3D fracture network around the well or, simulate the flow in this network in order to compare the results with production tests.

1.3. IDEAS

Based on the common data available and the outline given above, we propose to work on a close interpretation of UBI, FMI and ARI image logs, and combine this interpretation with other data available. Calibration of images with core has established the resolution of the borehole images (Glass et al., 1996; Genter et al., 1997) and to which degree the image interpretation outside the cored interval could be extended with a high degree of confidence.
Detailed fracture characterisation on outcrops and cores recorded various parameters of importance of fracture modelling, including orientation, fracture type, likely conductivity, fracture infill, termination relationships, length, width and observed displacement.

Measurement of the fracture aperture of a fracture in a fractured reservoir is difficult to conduct, but some estimations of the apertures of open fractures around the wells can be made using different well log information, such as the reflected Stoneley waves, electrical borehole images, or the Dual Laterolog (e.g. Sibbit and Faivre, 1985; Hornby et al., 1992; Dyke, 1995; Tezuka, 1996). Apertures of in-situ fractures can thus only be estimated by indirect measurements around the borehole, whereas data from core analysis can provide an estimation of maximum geometrical apertures of fractures after unloading.

Each method is limited when used alone. More information can be derived by an integrated approach using all available methods, and backtracking through all available data thus reducing the uncertainty in any future evaluation.

Normally a model of the fracture network is built using high-resolution image well data, and then extrapolating into the volume surrounding the well. We propose to add valuable static and dynamic information about the near well fracture network. A comparison between the static data extracted from e.g. the ARI-images and the dynamic data (e.g. flow and temperature data) might thus give the information needed.

The idea of the project is therefore to verify: Is it by this method possible to extend an interpreted fracture pattern away from the well in a natural fractured reservoir with a higher degree of confidence than today?

First, the individual fractures that intersect the well are closely described based on the image logs. Second, the properties of the fracture sets are investigated to reveal the overall systematic of the fracture networks as seen from the well. Third, fracture aperture and extension are calculated. Last, these extensive fracture data are used as input in a geometrical modelling of the fracture network.

1.4. EXPECTED OUTCOME

The expected result of the work is a new methodology to extend fractures away from a well in a reservoir with fluid conductive natural fractures. This approach builds on an integrated study of the available surface and well data from the studied site.

The methodology may lead to a model of the connectivity of the fracture network in the reservoir around the well and the flow properties of the near-well fracture network. Taking the fracture properties better into account also helps the interpretation of the flow properties of the reservoir and gives better predictions of the production possibilities in fractured geothermal and petroleum reservoirs. Also the quantification of
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the fracture systems as soon as possible during or after drilling (fig. 1) is of paramount importance, as the drilling of the first well represents a major change in scale of available data. In more detail, a hierarchy of fractures will be based on an analysis of images and qualitative or quantitative measurements of fracture apertures combined with dynamic data. Also might be found a prediction of the least stress direction or the channelling effects in the natural fractures based on an analysis of the likely maximum directions of the image contrasts. Hence the results of this project is expected to be a general better understanding of the flow-properties and distribution of the fracture networks in deep natural fractured reservoirs.

Fig. 1 - The development of an exploration project (Selly, 1985). When the first well is drilled, a near-well fracture model can be developed based on the initial data.

1.5. REFERENCE SITE

As a reference site is chosen the Hot Dry Rock HDR-Soultz (also known as Hot Fractured Rock or HFR-Soultz) geothermal site at Soultz-sous-Forêts in Alsace, France. The site is chosen as a good candidate for trying to assess an overall methodology on basis of a well-known and simple geological setting and a set of geological and geophysical data where very many parameters are present. In addition, the data are not confidential, as the HDR-Soultz project forms part of other European Community research projects. After Z&S GeoScience left the project, there have been non-fruitful negotiations with other petroleum service companies about access to additional data.
2. Site presentation

The first task of this project was the identification of a well with a set of data as extensive as possible and with a known and simple geological setting. BRGM is conducting exhaustive scientific research at the geothermal Hot Fractured Rock project HDR-Soultz. Thus due to the availability of data, the well chosen was GPK1 at Soultz-sous-Forêts in Alsace, France (fig. 2).

Fig. 2 - Location of Soultz in the French part of Rhine graben (left). Location of the wells EPS1, GPK1 and GPK2 between the villages Kutzenhausen and Soultz-sous-Forêts. The NW-SE seismic profile line also marks the position of the geologic cross section in figure 3 (left).

This well penetrates a thick sedimentary cover of about 1.4 km, and continues down into naturally fractured granite (fig. 3). From GPK1 are recovered several thousand metres of good quality electric- and acoustic images which form the basis for the present study. In the following paragraphs are described the Hot Fractured Rock concept, the local geology, common fracture properties, and the data available from Soultz.

2.1. HOT FRACTURED ROCK CONCEPT

The target of various geothermal projects is to establish the basis for the construction of geothermal power plants.

The main part of a Hot Fractured Rock geothermal power plant is in principle a gigantic heat exchanger the size of the reservoir between injection and production wells. Cold water is injected in one well and overheated steam is produced from the other and used to generate electricity from a steam turbine. The condensed water is then re-injected and the water thus recycled.
Fig. 3 - Geologic cross-section (NW-SE line - fig. 2) with GPK1 and the Rhine Graben horst system between Kutzenhausen and Soultz-sous-Forêts. Major fracture zones in the granite basement are indicated along the well trajectory (modified by Genter, 1993).
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The upper part of the Earth crust consists mainly of crystalline rock with low permeability. If a crystalline rock mass has a temperature sufficiently high for utilisation but it do not itself contain sufficient fluid to extract the heat, such a crystalline rock could be referred to as a Hot Dry Rock (HDR). The Soultz reservoir is dominantly a single porosity system where flow and storage take place in the fracture system.

A "Graben Concept" is associated with areas of Graben where the regional stresses tend to be low, allowing stimulation and circulation to be carried out at relatively moderate pressures.

The creation or the enhancement of natural permeability forms the heart of HDR technology. An artificial heat exchanger (reservoir) which forms an underground fluid circulation system fulfilling these conditions by enhancement of the natural permeability is the most general definition of an HDR geothermal system. (Baumgartner et al., 1999).

In figure 4 is shown how the concept has evolved from that of a single penny-shaped fracture system, borrowed from the oil industry, to the present Graben concept in which the pre-existing fractures are stimulated and used as major fluid pathways.

![Fig. 4 - The evolution of the Hot Fractured Rock or Graben concept. From the initial Penny shaped system (taken from petroleum industry), over the Hot Dry Rock concept with shear on natural joint, and to the present Graben concept evolved by Soconine and partners (http://www.soultz.net).](image)

2.2. FAULTS AND FRACTURES

A natural fractured reservoir contains faults and fractures resulting from natural stress differences in the reservoir rock. These stress differences are related to the tectonic history of the rock through burial, uplift, folding etc. Fractures are considered as any kind of break or planar discontinuity of the rock. They can be found in all kinds of
Fracture interpretation based on borehole image logs

sedimentary, igneous or metamorphic rocks, and have all sizes from continental rifts of hundreds of kilometres to micro fractures measuring only a few microns. Natural fractured reservoirs can therefore be found in all kinds of rocks under stressed conditions (Aguilera, 1995).

In examples from the North Sea, are given an oil-reservoir where a fracture-system provides a useful pathway to drain a reservoir from oil, but where the same fractures are likely to cause early breakthrough of water. In addition, mineralised fractures or fractured zones can create a permeability barrier across which no liquid will flow (Aguilera, 1995).

The ability for a fracture to act as a pathway for flow is also dependent of the stress of the formation. If no displacement has taken place along a fracture, or if no minerals is present in the fracture, then the opening of the fracture largely depends on the net normal stresses across the fracture. However, if the fracture is partly filled with mineralised rock, then the natural fracture tends to stay open even under strongly increasing normal stress. This is thought to be due to the mechanical properties of the crystal grains that in general are much stronger than the surrounding rock of same mineral composition (Aguilera, 1998).

If a displacement has taken place along the fracture plane, it is very unlikely that the two internal fracture surfaces fits into each other after the displacement. The fracture is therefore kept open by a system of "islands" surrounded by "channels" (Gentier, 1986).

In a few words, most fractured reservoirs are hard to interpret and it is though even harder to try to foresee the flow properties. Most fractured reservoirs are different and the methods that worked just fine in one well can fail in the next.

A fracture can be described by the depth, dip type, dip angle and horizontal direction (azimuth), and eventually the displacement along the fracture plane (table 1).

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description of feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>Depth of fracture where a supposed full sinus wave cuts the mid-point of the well.</td>
</tr>
<tr>
<td></td>
<td>Calculated from Recall sine waves. Depth of partial sine waves are measured in the</td>
</tr>
<tr>
<td></td>
<td>mid-point of the partial sine wave.</td>
</tr>
<tr>
<td>Dip type</td>
<td>The description of the continuity of a fracture as interpreted based on the borehole</td>
</tr>
<tr>
<td></td>
<td>images and assigned in Recall (for details, see chapter 5.2)</td>
</tr>
<tr>
<td>Dip</td>
<td>True dip angle of fracture (fracture dip)</td>
</tr>
<tr>
<td>Azimuth</td>
<td>True azimuth angle of fracture (dip direction)</td>
</tr>
<tr>
<td>Displacement</td>
<td>Measure of fracture displacement (cm)</td>
</tr>
<tr>
<td></td>
<td>Cut-offs used to define fracture/microfault/fault categories</td>
</tr>
</tbody>
</table>

Table 1 - Description of main fracture features.

Ideally, also the aperture of a fracture is a fixed value, but the fracture aperture can be measured in a number of different ways as follows:

- geometrical on core, fracture infill, partial fractures, with a slidegauge;
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- hydraulic flow-, and temperature logs, production tests;
- mechanical laboratory tests;
- electrical electrical image logs (i.e. FMS, FMI, ARI...);
- acoustic acoustic image logs (i.e. UBI, BHTV...).

The fractures (fig. 5) can also be classified into (Dezayes, 1995):
- natural fractures (type 1);
- natural partial fractures (type 2);
- induced en-echelon fractures (type 3);
- induced vertical fractures (type 4).

![Geometrical fracture classification based on borehole images (Dezayes et al., 1997).](image)

*Fig. 5 - Geometrical fracture classification based on borehole images (Dezayes et al., 1997).*

Type 1 – continuous fracture; Type 2 – partial fracture; Type 3 – en echelon fractures; and Type 4 – vertical fracture (originating from an en echelon fracture). Above (A) are shown the fracture traces as they are recognised on a borehole image, and below (B) the same fractures marked on a core.

In this study, is concentrated on the natural fractures (i.e. type 1 and 2). Based on the borehole images the fractures have been further subdivided as a function of their presence on the borehole images.

Advantages of borehole images:
- high image resolution, which allow fractures to be described in detail;
- the possibility to orientates fracture data, which allows 3D fracture modelling from data within the well.
<table>
<thead>
<tr>
<th>Year</th>
<th>Organisation</th>
<th>Tasks</th>
<th>Programme 1987/1988</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>German-French agreement Ottrott Le Haut</td>
<td>Bibliography</td>
<td>Drilling exploration well GPK 1 (2000m) then logging, Feasibility microseismic monitoring, Small sized hydraulic test</td>
<td>140°C at 2000m Design microseismic monitoring network Discovery of half opened fractures within the granite Salted thermal water (100g/l) In situ stress analysis</td>
</tr>
<tr>
<td>1987</td>
<td>German-French agreement of Kutzenhausen, supported by the CCE Scientific project committee Sector working groups</td>
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<td>1988</td>
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<tr>
<td>1989</td>
<td>Extension of the duration of the Kutzenhausen agreement Creation of the &quot;Policy Group&quot; and the &quot;Technical Advisory Group&quot; &quot;Industrial Consortium&quot; (Siemens, RTZ, BRGM)</td>
<td>Interpretation/Publication Recover of 3 old oil wells for microseismic monitoring Coring well EPS1 (2227m)</td>
<td>Special issue of &quot;Geothermal Science and Technology&quot; Recovered oil wells deepened to 1400, 1500 and 1600m EPS1 cored from 930m to 2227m Petrographic calibration of logs within the granite 150°C at 2200m</td>
<td></td>
</tr>
<tr>
<td>1991</td>
<td>HDR Forum Nuremberg, creation of EHDRA Soconine becomes operator Agreement CCE-EHDRA-Soconine for 92-95 programme</td>
<td>GPK1 stimulation test at 2000m (7 l/s then 15 l/s) Deepening of GPK1 to 3600m Install 2nd generation microseismic network GPK1 stimulation between 2850m and 3500m GPK1 production test</td>
<td>Low pressure of stimulation, stable result: fracture propagation to N170° 150°C at 3500m &quot;Permeable&quot; fractures found at 3500m (flow: 0.5 l/s at 10 bars wellhead pressure) Stimulation: max. pressure 100 bars, max. flow 50 l/s Production: Slowly decreasing flow from 10 l/s to 8 l/s at 7 bars wellhead pressure Connections well-mussif self propelled</td>
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<td>1992</td>
<td>HDR Forum Nuremberg, creation of EHDRA</td>
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<tr>
<td>1993</td>
<td>Soconine becomes operator Agreement CCE-EHDRA-Soconine for 92-95 programme</td>
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<tr>
<td>1994</td>
<td>New industrial group of interest (Pfizer, ENEL, EdS) EC Experts committee</td>
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<tr>
<td>1995</td>
<td>Creation &quot;Scientific Advisor Panel&quot; Organisation EUG &quot;Industries&quot;</td>
<td>Drilling well GPK2 GPK2 stimulation Successful circulation test GPK2 =&gt; GPK1</td>
<td>GPK2 total depth 3867m, temp &gt;160°C at 3800m Stimulation between 3200m and 3700m Performances as good as in GPK1 but deeper (injected fluid density controlled) Circulation: stable equilibrated flow balance at 1 kg/s, thermal power 9MWe</td>
<td></td>
</tr>
<tr>
<td>1996</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td>1996/1997 proposal to EC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>Planned construction of a 25 MW scientific test plant by EBG which is : EDF, ES (France), Pfalzwerke and RWE (Germany), ENEL (Italy) and SHELL (Holland).</td>
<td>Deepening of well GPK2 to 5100m Stimulation of the 5000m reservoir Successful circulation in the 5000m reservoir</td>
<td>GPK2 total depth 5100m, temp. &gt; 200° at 5000m Well deviation at bottom is 15 degrees. Production test s with 10-15 l/min, 500 m³ produced Less natural fractures in the deep reservoir</td>
<td></td>
</tr>
</tbody>
</table>

(Socconine - http://www.soulz.net)

**Table 2 - Overview of the geothermal HDR project at Soultz, sous Forêts, France.**
Fracture interpretation based on borehole image logs

Various other methods exist with which to characterise a reservoir. However, as the resolution of the measurements performed is inversely proportional to the range of measurement the image logs provides the best basis of characterising fractures in wells.

2.3. SOULTZ-SOUS-FORÊTS

In table 2 is given an overview of the evolution of the HDR-Soultz project since 1987, and in figure 6 is found the evolution of the reservoir (the heat exchanger) at Soultz-sous-Forêts. Soultz is located in the upper Rhine graben, close to its western border, about 50 km north of Strasbourg (fig. 2). The Rhine graben extends for 300 km in the north-north-east direction between Basel and Frankfurt. The graben is known for its positive geothermal anomaly, and Soultz is placed in the area where the geothermal anomaly is strongest (Dezayes, 1996). The thermal anomaly has been known for a long time, as Soultz is placed on the site of the Péchelbronn oilfield, which was abandoned in 1965. At Péchelbronn, mining of oil and tar has been known since the 1600th century, and it was here that the world’s first oil well was drilled in 1813. It was also at Péchelbronn that the Schlumberger brothers introduced well logging in 1927 (Schnaebele, 1948).

![Fig. 6 - The evolution of the HFR-Soultz heat exchanger. In year 1997 (a), present phase 2001 (b), and expected in year 2003 (c) (www.soultz.net).]
Fracture interpretation based on borehole image logs

Soultz is placed on a horst structure which forms part of the Péchelbronn basin. Six kilometres to the west are the Rhenane fault system that separates the Rhine graben from the Saverne area. Further west lies the northern parts of the Vosges Mountains, which forms the eastern part of the Paris basin. At Soultz, the granite is covered by about 1400 meters of Triassic to Tertiary sediments (Elsass et al., 1995).

The are several granite types at Soultz, that commonly can be divided into altered or fresh granite as follows (Genter et al., 1999):
- fresh granite with no alteration and only few fractures;
- intervals in the granite (fracture zones) with high fracture density;
- fresh or altered granite in and around fractures and fractured zones;
- fractures or fractured zones with hydrothermal fillings, partly filled, or totally mineralised, with secondary minerals as quartz, clay and calcite.

The large-scale fault system (fig. 3) is well known due to the high volume of geological data collected for oil exploration at Péchelbronn. An integrated interpretation of the data from wells penetrating the sedimentary formations, combined with the interpretation of seismic reflection data and large scale geological maps have lead to several structural maps of the area around Soultz (Genter et al., 1993 and 1998).

Genter et al. (1995) have studied whether it is the present state of stress or the previous tectonic history of the Rhine Graben which control the origin of the faults and fractures in the granite basement. The three major geological events that structured the area were the Variscan orogeny, the subsequent late-tectonic extension, and the Cenozoic opening of the Rhine graben system.

Two types of faults (Synthetic and Antithetic) can be distinguished in the structural model that extends eastwards from the Rhenane fault onto the eastern part of the Soultz horst. The study by Genter et al. (1995) was based on the cored section of well EPS1, and supplemented with study of image logs from GPK1 and GPK2. Both natural fractures and induced fractures resulting from the drilling were found and two main types were identified.

One type of fractures is the pre-existing fractures. Most of these show a conjugate, normal fault type pattern, which reflect the Oligocene opening of the Rhine Graben. The second type of fractures is revealed by core relaxation by drilling and unloading.

Thus, the fractures intersecting the borehole do not have the same origin. Genter and Dezayes (1993) and Genter et al. (1997) have established a typology of the origin of the planar discontinuities in the Soultz wells based on the their presence on the FMI and FMS images and on a the study of the cores from nearby well EPS1. The location of EPS1 is seen on figure 2.
The Soultz granite massive does not outcrop in the Rhine graben. Granite of same age exists at Windstein close to Soultz, but it is sited outside the Rhine graben and has thus been subject to another tectonic history. In addition, the Windstein granite is difficult to study due to intense vegetation.

About outcrops in general it should be mentioned that, an outcrop is most likely to have a higher fracture density than a subsurface reservoir because of the unloading, stress relaxation and erosion. Therefore, an outcrop normally gives the upper limits for fracture intensity, and therefore it is difficult to find such a thing as a perfect surface analogue to a subsurface reservoir. It is however often possible to use an analogue, and then state in what way the analogue system is an analogue and in which way the analogue is different from the reservoir in question (Alexander, 1993).

In the present case, the most detailed information about the geology of the Soultz granite that is provided by the analysis of the 810m cored section of EPS1.

2.4. WELLS

Three deep wells at Soultz-sous-Forêts all penetrate the upper sediments and continue down into the granite basement of the Rhine graben: GPK1, EPS1, and GPK2 (fig. 2).

The first well drilled was GPK1 that was drilled from surface to 2000 m depths in 1987, with 50 m of spot cores collected. It was further deepened to 3570 m in 1992. The granitic basement was reached in 1376m depth. The bottom temperature is 160°C, and the well deviation at bottom is 6 degrees. Only one core was taken in the lower part.

The second well was EPS1. It was originally drilled to 830 m in the 1950s as an appraisal well for petroleum exploration. It was reopened in 1990 and drilled with full coring from 930 m to 2227 m depth. At this depth, drilling was stopped due to a deviation of 22 degrees. From EPS1, are recovered about 800 meters of cores from the Palaeozoic granite (reached at 1417 m depth), and about 400 meters of cores from the overlaying Buntsandstein.

The latest well was GPK2 that was drilled to 3880 m in 1995, and further deepened to 5100 m depth in 1999. The temperature in GPK2 is 160°C at 3900 m and 200°C at the bottom. The well deviation at 5100 m is 15 degrees (e.g. Genter et al., 1999)

Other abandoned oil wells in the area are being used for micro-seismic monitoring. A compilation of geological and geophysical well-logging data collected in the period 1987 to 1999 at the HDR site Soultz-sous-Forêts can be found in Genter (1999), and a compilation of thermal and hydraulic data can be found in Pribnow et al. (1999).

The data from Soultz-sous-Forêts including the borehole imaging techniques are presented in the next chapter.
<table>
<thead>
<tr>
<th>Which type of measurement?</th>
<th>Electrical Image</th>
<th>Acoustical Image</th>
<th>Azimuthal Resistivity</th>
<th>Array Sonic</th>
<th>Mud losses</th>
<th>Flow logs</th>
<th>Core</th>
</tr>
</thead>
<tbody>
<tr>
<td>What is detected?</td>
<td>Mud invasion into fracture, resistivity contrasts.</td>
<td>Contrast in acoustic properties of rock/fractures</td>
<td>Mud invasion into fracture, resistivity contrasts</td>
<td>Stoneley energy reflected by fracture</td>
<td>Flow of mud into fracture</td>
<td>Fracture permeability</td>
<td>Fracture/Matrix character and relationships</td>
</tr>
<tr>
<td>What are common nomenclatures?</td>
<td>FMS, FMI</td>
<td>BHTV, UBI</td>
<td>ARI</td>
<td>DSI (Stoneley)</td>
<td>Mudlog</td>
<td>PLT</td>
<td></td>
</tr>
<tr>
<td>How narrow a fracture can be detected?</td>
<td>Down to the order of microns, given sufficient electrical contrast</td>
<td>Down to the order of microns, given sufficient acoustic contrast</td>
<td>Down to the order of microns</td>
<td>Down to the order of microns</td>
<td>0.20mm</td>
<td>Depends entirely on flowrate</td>
<td>Order of microns</td>
</tr>
<tr>
<td>Are any features mistaken for permeable fractures?</td>
<td>Fracture porosity, induced fractures, drilling damage, sealed fractures</td>
<td>Fracture porosity, induced fractures, drilling damage, sealed fractures</td>
<td>None</td>
<td>Washouts, bed boundaries, drilling damages</td>
<td>None</td>
<td>None</td>
<td>Fracture porosity, induced fractures</td>
</tr>
<tr>
<td>What is the depth of Investigation?</td>
<td>10mm (treated as borehole wall)</td>
<td>3mm (treated as borehole wall)</td>
<td>About one meter, depending of rock and fluid properties</td>
<td>10mm =&gt; 15m</td>
<td>Depth of mud invasion &gt; 1m</td>
<td>Depends of the connectivity of the fracture network</td>
<td>Core diameter</td>
</tr>
<tr>
<td>Are strike and dip provided?</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Is there any mud limitations?</td>
<td>Water based mud only</td>
<td>Best results with mud weight below 1.65 kg/l</td>
<td>Water based</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Comments:</td>
<td>Difficult to distinguish high- and low permeable fractures</td>
<td>Difficult to distinguish high- and low permeable fractures</td>
<td>Gives high permeability fractures</td>
<td>Fractures plugged with mud are rarely detected</td>
<td>Yields information on formation damage and stimulation requirements</td>
<td>Measures flow close around the borehole</td>
<td>Highly fractured or crushed zones not recovered</td>
</tr>
</tbody>
</table>

*After Dyke & al. (1992) and Aarseth & al. (1997)*

**Table 3 - Fracture detection techniques.**
3. Well data

In this chapter, different fracture detection techniques and the data acquired from the three wells in Soultz. The data are mainly acquired by wireline logging which is today the most common way to measure the properties of the rocks and fluid in the surroundings of a well.

Measurements are normally performed while pulling the tool slowly up pass the geologic formations. The basic units used under a logging operation is the downhill equipment (the cable and the logging tool) and the central logging unit on the surface. The cable carries the logging tool and is the only connection between the downhole tool and the surface unit. While logging, the main way to control the logging tool from the surface unit is through the speed of the logging cable. In the following chapters, the fracture detection techniques are further described, and a summary of the different fracture detection techniques can be found in table 3.

In table 4 are summarised the image logging tool characteristics, and in figure 7 is shown the principle of the GPIT tool (General Position and Inclinometer Tool) which are used when measuring orientated data (fractures).

3.1. ACoustIC IMAGeS

The borehole televiewer (BHTV) normally provides measurements of both travel time and amplitude for the reflection from the borehole wall of an ultrasonic source signal emitted from the tool. The UBI tool (Schlumberger) is a new generation BHTV. The UBI tool has a transducer, which are both transmitter and receiver. The transmitter rotates with 7.5 revolutions per second, when it emits its focused ultrasonic pulse (250 or 500 kHz) and receives the reflected pulse. Both the travel time (TT) of the sonic pulse and the reflection coefficient (Amplitude) is recorded. Full 360-degree coverage of the borehole is provided with either 140 or 180 sonic pulses per revolution. A logging speed of 800 ft/h using the lower operating frequency of 250 kHz corresponds to a vertical sample rate of 0.4". At 400 ft/h and with the higher operating frequency of 500 kHz the vertical sample rate is 0.2".

In the 6.25" section of GPK1 the borehole wall was covered with 180 samples for each revolution with a sample rate of 0.4".
Fracture interpretation based on borehole image logs

<table>
<thead>
<tr>
<th>Image tool specification</th>
<th>FMI</th>
<th>UBI</th>
<th>ARI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical resolution</td>
<td>3 mm at logging</td>
<td>10 mm at logging</td>
<td>200 mm in a</td>
</tr>
<tr>
<td></td>
<td>speed 470 m/h</td>
<td>speed 244 m/h</td>
<td>6.25&quot; hole</td>
</tr>
<tr>
<td>Horizontal resolution</td>
<td>5 mm (in 90% of a</td>
<td>5 mm (100%) at</td>
<td>30° or ~45 mm at</td>
</tr>
<tr>
<td></td>
<td>6.25 inch borehole)</td>
<td>500 kHz</td>
<td>inner surface</td>
</tr>
<tr>
<td>Formation resistivity</td>
<td>0.2 to 100,000 ohmm</td>
<td>(not applicable)</td>
<td>0.2 to 100,000 ohmm</td>
</tr>
<tr>
<td>range</td>
<td>(not applicable)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum mud resistivity</td>
<td>&lt;50 ohmm</td>
<td>16 lbm/gal (water)</td>
<td>&lt;2 ohmm</td>
</tr>
<tr>
<td>/ weight</td>
<td>16 lbm/gal (water)</td>
<td>11.6 lbm/gal (oil)</td>
<td></td>
</tr>
<tr>
<td>Operating temperature</td>
<td>175°C</td>
<td>175°C</td>
<td>175°C</td>
</tr>
<tr>
<td>(max)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(data from Schlumberger and Genter et al., 1997)

Table 4 - Fracture detection in well GPK1 (6.25") by three image logging techniques.

Fig. 7 - General Position Inclinometry Tool (GPIT), which measures true orientation of tool during logging operation. AX, AY and AZ measures which way is up; FX, FY and FZ measures which way is magnetic north (Schlumberger Educational Services).
3.2. ELECTRICAL IMAGES

High-resolution imaging tools give a detailed mapping of fractures on the borehole wall. The principle is, when an open fracture is intersected by a well, highly conductive drilling fluid (mud) intrudes into the fracture. The electrical tools measure the contrast between the fluid and the formation, and several methods have been developed to estimate apertures and extension of the natural fractures. In granite which is a high-contrast formations ($R_t >> R_m$) the electrical response is controlled by four parameters (Sibbit and Faivre, 1985):

- the resistivity of the formation;
- the resistivity of the invading fluid;
- the extent of invasion;
- and the fracture opening (aperture).

The FMI tool (Schlumberger) is a 4-arm, 8-pad micro resistivity-imaging device. Each arm carries a pad and a flap each with two arrays of 12 measuring electrodes arranged as two rows on each pad, spacing 0.3 inches. The button current intensity is sampled every 0.1 inch. In the 6.25 inch section of GPK1 (below 2850 meter), this result in coverage of close to 100% of the inner borehole walls. An older version is the FMS tool (Schlumberger) which has only four pads. The maximum operations temperature for all the tools are 175°C, as this is the temperature limit of the electronic parts in the logging tools.

Luthi and Souhaite (1990) has established an empirical relationship between fracture aperture parameters and integrated exceed conductance (the degree of contrast on an image) from electrical image logs. This model is based on a finite element model. Depending on the quality of the borehole image logs, this model can be used either as a quantitative method to estimate a real fracture aperture, or as a qualitative method to classify and distinguish between the relative importance of different fractures.

Luthi and Souhaite (1990) gave this formula for estimation of the fracture aperture (opening) based on the FMI images:

$$W = c \cdot A \cdot \frac{R^p}{R^m} \cdot \frac{R^a}{R^f}$$

(1)

where: $W$ ($mm$) is fracture Width,
$A$ ($ohm \cdot m$) is Area of added conductivity,
$R_m$ ($ohm \cdot m$) is mud resistivity,
$R_f$ ($ohm \cdot m$) is formation resistivity,
and $a$, $b$, and $c$ are tool and well dependent constants.

The three constants need to be determined from the current well and tool configuration. Best results for fractures vertical to the well or with fracture dips below 40°. Fracture evaluation using the FMI electrical borehole images has the advantage of high vertical and horizontal resolution in addition to quantitative information regarding the fracture
dip and azimuth. The major limitation is the depth of penetration (perhaps less than one inch) and that the calculation of the aperture is very sensible to the constants.

3.3. THE DUAL LATEROLOG AND ARI IMAGES

Low-resolution electrical tools also give a mapping of the structures of the borehole wall. In a high contrast formation \((R_t \gg R_m)\), the Dual Laterolog response is controlled by \(R_t, R_m\), the extent of mud invasion and the fracture aperture.

For a fracture perpendicular to the borehole Sibbit and Faivre (1985) have estimated the fracture aperture based on the DLL curves as follows:

\[
C_{LLD} - C_{LLS} = 4 \times 10^{-4} \cdot \varepsilon \cdot C_m
\]

where \(\varepsilon (\mu \text{m})\) is the fracture aperture,

\(C_m (\text{mho/m})\) is mud resistivity,

\(C_{LLD} (\text{mmho/m})\) is shallow conductivity,

and \(C_{LLD} (\text{mmho/m})\) is deep conductivity.

For fractures parallel to the borehole, in a similar way:

\[
C_{LLD} - C_b = 1.2 \times 10^{-4} \cdot \varepsilon \cdot C_m
\]

where \(C_b (\text{mmho/m})\) is formation conductivity.

Quantitatively, Sibbit and Faivre found the horizontal behaviour to be dominant for fractures dipping less than 60° and the vertical behaviour to be dominant for fractures in excess of 75°. Between 60° and 75° the aperture can be estimated as a weighted average of the two formulas. Sibbit and Faivre also note, that apertures estimated on basis of more than one fracture, or on irregular fractures, will be "some sort" of average of the opening along the fractures.

The Dual Laterolog approach is particularly useful where the electrical images shows poor data quality due to enlarged borehole size and/or irregular borehole though these intervals are potential zones of extensive fracturing.

In such intervals, reliable quantitative evaluation can only be achieved by integrating all the relevant information available and the Dual Laterolog can thus provide useful complementary information to fracture evaluation. However, the Dual Laterolog alone can not provide quantitative information on the orientation and dip angle of the fractures.

The ARI tool (Schlumberger - Azimuthal Resistivity Imager) is a standard Laterolog tool (DLL tool) which in addition makes directional deep resistivity measurements around the borehole. Thus the ARI tool retains the standard shallow- and deep readings (LLS and LLD), but add a dozen deep oriented resistivity measurements (Faivre, 1993). As any electrical tool, the ARI is sensitive to fractures filled conductive fluid, and the readings can be displayed as an azimuthal resistivity image. This image has much lower
Fracture interpretation based on borehole image logs

Spatial resolution than acoustic or micro-electrical images of the inner borehole surface. The Dual Laterolog and the ARI images are only useful in wells with high electrical contrast between the formation and the well fluid.

Faivre (1993) has developed a formula to estimate the fracture aperture based on ARI images:

\[ E = a \times AAC^b \times R_i^c \times R_m^{0.9952-c} \]  

where \( E (\text{mm}) \) is fracture aperture,  
\( AAC \ (\text{ohm} \cdot \text{m}) \) is Area of added conductivity,  
\( R_i \ (\text{ohm} \cdot \text{m}) \) is matrix resistivity,  
\( R_m \ (\text{ohm} \cdot \text{m}) \) is mud resistivity,  
and \( a \ (0.9952), b \ (0.863), \text{ and } c \ (0.0048) \) are tool constants.

Best results for fracture dip below 60 to 75 degrees, but the larger the formation resistivity is, the smaller is the angle effect on the AAC. In a granite borehole with high electric contrast between the granite and the waterbased mud, the angle effect could be neglected below 75 degrees.

The problem of estimating apertures based on an electrical contrast is, that the electric response depends both on the fracture aperture and the extend of the fracture, and it is thus not possible to calculate the one without doing assumptions about the other. In addition Faivre (1993) found, that the FMI and ARI tools have similar responses in terms of lateral extension of a fracture under ideal conditions in the laboratory, and hence a combination of both logs do still not allow the derive of both aperture and extension.

This means, that the two methods return identical results in the perfect case of a vertical well, where is given a single planar fracture of infinite extent, and filled with a conductive fluid. However in real cases the fracture aperture calculated on the basis of the ARI appears to be less sensitive to secondary effects as borehole size, eccentric movements, dipping fractures, break outs, etc. (Faivre, 1993)

3.4. REFLECTED STONELEY WAVES

The borehole Stoneley wave (from the DSI tool) can be considered as a pressure pulse propagating in a cylindrical borehole. When the borehole Stoneley wave encounters a permeable fracture crossing the borehole, the pressure drop gives rise to both attenuation of the direct arrivals and a secondary (or reflected) wave. The secondary reflected Stoneley wave might be generated by a secondary source located where the fracture plane intersects the borehole. The strength of the secondary Stoneley wave is relative to the amount of pressure released into the fracture and thus to some extent to the fluid conductivity of the fracture.

Hornby et al. (1989) have estimated the apertures by use of the reflected Stoneley wave, and Hornby and Luthi (1992) computed the reflected Stoneley wave response as a
function of open fracture aperture and dip. They integrated the interpretation of fracture aperture and orientations computed from electrical borehole scans with the reflected Stoneley waves arrivals apertures and thus obtained information of the opening of the fractures based on their strike dip.

Reflected Stoneley wave arrivals can not be used alone to derive fracture aperture, as it requires information of estimation on the fracture dip angle. Other weaknesses of the method include low resolution (about 2.5 ft) compared to ca 1.5 cm (2.5 mm sample rate) of FMI. The calculated apertures may sometimes represent the sum of several closely spaced fractures.

DSI data from GPK1 has, (through a co-operation with ETH Zurich) been sent to Japex in Japan and they have estimated fracture apertures from the lower part of GPK1 based on the Stoneley wave arrivals. The interpretation of this data is however still subject to questions.

3.5. TEMPERATURE PROFILES AND FLOW LOGS

Permeability can be detected using spinner logs (flow logs) or temperature logs which measure inflow or outflow of the well. A spinner tool has the advantage of giving a quantitative value of the flow but the tool have a stall speed, which mean that inflow below a certain limit pass undetected. Spinner measurements corrected for varying cross section area (CSA) give quantitative data. Packertests sometimes shows useful but are difficult to use, as a section of the well need to be isolated by packers and then stimulated (over- or under pressure). No results from packertests were recovered from GPK1 due to technical problems.

The temperature logs are efficient when it comes to the identification of smaller flowing fractures, as in the cases where the flow is below the stall speed of the spinner tool. Though the temperature logs are very sensitive to even small-scale turbulence in flow, the spinner logs are more capable to identify which fractures are actually flowing (Barton, 1997).

Evans (2000) has studied the spinner logs and the temperature logs run in GPK1 (below 2850 m) before and after the hydraulic stimulation's in 1993. Evans found than only 12 fractures and fractured zones account for more than 95% of the flow. However, 20% of some 500 natural fractures identified by Evans on the UBI images support flow. In addition, Evans has established a qualitative flow scale with six flow levels, and this interpretation is taken into account in the present study.

3.6. MUDLOGS AND ANALYSIS OF CUTTINGS

While making a new hole, the mud (might be oil or water based) is circulated from, the mud tanks down the drillstring, through the bit, up the hole annulus and back into the tanks. Drilling-fluid losses is a manner of detecting conductive naturally fractures, as
the system is closed except for downhole losses, and a small amount of evaporation and adhesion to cuttings.

Previously (Drummond, 1964) this method was the most used in early evaluation permeability. High losses were evidence of high future production and no losses was an ominous sign. Dyke et al. (1995) has established the potential to detect small losses as indicative of in-situ permeability. He found that the method have the capability to detect mud losses into in-situ fractures with aperture more than 150 μm when using standard mud. In addition, the mud losses correlate well (up until 80%) with the actual open fractures observed in cores, and the method is very useful in differing fracture porosity from fracture permeability. This makes the mudlog an interesting companion to the image logs, as this is their main problem. One mudlog has been recovered from GPK1.

The analysis if cuttings can be done while drilling, and gives information about the composition of the formations being penetrated. The different types of granite in GPK1 are described by Genter and Traineau (1993). The vertical resolution of these data is coarse (about 10 meter), due to the uncertainty of the time it takes the cutting to appear at the surface.

3.7. DATA ACQUISITION

Seventeen REEL tapes (LIS-tapes) with data from the Soultz project were picked up at Socomicne, the 3 July 1998. The tapes were first attempted read at BRGM, but no hardware was available to read the 9-track REEL tapes. The tapes were then taken to Z&S GeoScience in Stavanger (Norway), where all the content of the LIS tapes (LIS - 9 track - 6250 bpi) were copied to disk as PC-TIF files on 18-20 July 1998. Tape image files can be read with the LIS tape reader in RECALL. Two copies of the PC-TIF files were then saved on 4mm DAT tapes (90 m, non compressed, 1,1 Gb) of which one copy is kept in the BRGM, and the other copy was returned to Soromatic together with the original LIS tapes. The PC-TIF files (one file for each LIS tape) are stored on the DAT tape as a single UNIX-TAR archive.

The above data include petrophysical logs and image logs from before and after the hydraulic stimulation's of GPK1 in spring 1993. On the LIS-tapes were only found raw non-processed data from the 1992 and 1993 Schlumberger loggings in GPK1. A list of the data loaded into RECALL from these tapes is found in table 5, and an overview of the depth intervals of the image logs available is found in figure 8.

Additional data from a 1987 logging campaign was found in BRGM. Data included a set of petrophysical curves, ASCII formatted, stored on a 3½" floppy. They were loaded into the Soultz database as log "ELEC_8/12/87".

BRGM/RP-50835-FR 31
Fracture interpretation based on borehole image logs

<table>
<thead>
<tr>
<th>Tape / Image file</th>
<th>Logs</th>
<th>Service</th>
<th>Log Interval / m</th>
<th>Log-date</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>01.tif</td>
<td>DSI</td>
<td>DSSTA</td>
<td>3497 - 2805</td>
<td>08/12/1992</td>
<td>DSSTA.045, MERGE.001</td>
</tr>
<tr>
<td>02.tif</td>
<td>DSI</td>
<td>DSSTA</td>
<td>2862 - 2192</td>
<td>08/12/1992</td>
<td>DSSTA.041</td>
</tr>
<tr>
<td>03.tif</td>
<td>DSI</td>
<td>DSSTA</td>
<td>2201 - 1949</td>
<td>08/12/1992</td>
<td>DSSTA.042</td>
</tr>
<tr>
<td>04.tif</td>
<td>ARI</td>
<td>ALAT</td>
<td>2271 - 3196</td>
<td>08/12/1992</td>
<td>ALAT.004 (logged downwards)</td>
</tr>
<tr>
<td></td>
<td></td>
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Table 5 - Database tape listing for Soultz project (original data format: LIS, 9 track REEL, 6250 bpi).

![GPK1 - Image Logs used in this study](image)

Fig. 8 - Image log sections (ARI, FMI and UBI) from well GPK1. The names ALAT (ARI), FBST and MERGE (FMI) are the file names used by Schlumberger.
The different types of granite in GP1 based on the analysis of cuttings (described in Genter and Traina, 1993) are loaded into the Soultz database as a zonation named "CHIP SAMPLE LOG". The vertical resolution of these data is about 10 meter.

Data from the 1993/94 hydraulic tests (Pribnow and Jung, 1999) are loaded into the Soultz database as log "CFALL94Q2", and a qualitative flow-scale based on these data, defined by Evans, is loaded into the Soultz database as log "EVANFRAC".

Data are loaded into several different databases to compensate for an initial separation of the data on several physical disks. The main database is thus named "soultz" (U25, Solaris) and the additional databases "soultz_a", "soultz_b", "soultz_c", and "soultz_d". With this naming convention "soultz*" as database delimiter search string to inquire on all data in all Soultz databases.

The RECALL database system is described in the next chapter.
Fracture interpretation based on borehole image logs

4. Data treatment and tools

In this chapter are described the software, the borehole data from the well GPK1, the data processing and interpretation.

The data used are mainly acquired in the deep part of GPK1 from the reservoir below the casing shoe at 2850 m logging depth. The work with the image logs is based on a re-processing of the original raw image data that was delivered to Socomore by mainly Schlumberger. The image data include FMI, UBI and AR1 image logs.

4.1. RECALL PORTFOLIO

The RECALL software suite and the corresponding Review user interface are a state-of-the-art software suite for Unix, which covers all aspects of storage, management, processing and interpretation of geo-scientific data.

Z&S GeoScience has supplied a copy of their RECALL software to BRGM for use throughout the project period. RECALL (4v1) for Solaris 2.6 is installed on the UNIX station U25. Installation and maintenance of the RECALL software and databases was included as part of the project work.

RECALL is versatile, flexible and very complex! In RECALL, the capacity of the database is only limited by the harddisk storage capacity on the system. Databases have been constructed in RECALL containing more than 50,000 wells with more than a million data curves. There is no logical limit to the number of fields, wells or curves which may be held in the database. Unrestricted sampling frequencies and data types can be stored within the database. Projects may contain any combination of single or multiplexed sampled records of continuous or discrete data, referenced by depth or time. Any records may be extended at any time.

RECALL has a set of data loaders which allows the load of all general data types into one common database. These tools deal with the laborious identification and loading of all the various kind of data and tape storage formats used by the service companies. Tools are present to keep track of the data, disk space and backups.

Review is the name of the user-interface between the database RECALL and contains the different modules of the software suite. The most frequently used module when doing image analysis under Review is Image, which is the borehole data visualisation tool kit. Image is used for all kinds of initial treatments of image based wireline logs. Data can then be further treated with Incline, a dipmeter and dip-processing module or with Petros3, used for petrophysical analysis. An example on a screen dump of the Review interface set-up for this project is found in appendix.
4.2. OUTLINE OF RAW DATA TREATMENT

In this chapter are described which routines were used to load the different kinds of data into RECALL, and how was made the iterative process of processing electrical and acoustical borehole images.

4.2.1. Identification and loading of data

First, the raw well data need to be loaded from the storage media to a system disk. This task is often laborious, as very many tape formats exists. Most logging contractors use their own data formats. Also the format incompatibility between the Unix, Mac and Windows platforms are very well known. The first step is: always to identify the present data formats and chose the adequate data loader from the INPUT menu in RECALL.

4.2.2. Pre-processing

In REVIEW is a PREPASS routine, which provides additional information on the raw data that is not directly available from the input data tape. This routine facilitates the creation of a set of standard curves from diverse types of tools by introducing a common nomenclature. The PREPASS routine also allows re-sampling of the curves to standard depth increments (i.e. from feet to meter) and adds the correction for magnetic declination.

Raw logging data need correction before creating the images needed for fracture interpretation. The raw image log data are single multiplexed curves that need to be further processed to form the images.

4.2.4. Quality Control

Before commencing any image dipmeter interpretation study, a thorough Quality Control (QC) of the data is necessary to confirm the validity and self-consistency of the data and hence any interpretation based upon it. The initial QC is best done from within RECALL, and divided into four key stages:

Are the raw (image) data reliable?
Before processing commences, a review of the essential raw curves (orientation, caliper, tool motion, resistivity traces, wellsite dips) as loaded from the tape is undertaken. A SPATIAL template (Review) displays this information in a convenient plot, which also may include essential log attributes (e.g. mud types, logger comments) in the header.

Are the inclinometer units (fig. 7) responding correctly?
The tool positioning (P1AZ, RB) and wellbore orientation curves (HAZI, DEVI) are determined from six inclinometer curves (FX, FY, FZ, AX, AY, AZ), which are normally also present on the raw tapes. Field norm curves (ANOR, FNOR) and magnetic inclination (FINC) should give steady, predictable reading. Wellsite orientation calculations are verified by the ORIENTATE module; ANOR, FNOR and FINC are checked with a FORMULA job. Where tool orientation is in question, a cross
Fracture interpretation based on borehole image logs

plot (X PLOT) of pairs of inclinometer curves are useful in identifying problems (i.e. fig. 9 and 10) which may then be remedied.

**Fig. 9 - Cross-plot of three directional accelerometer data AX, AY and AZ (m/s²) [above]; and magnetometer data FX, FY, and FZ (A/m) [below].**
The plots of tool orientation data are used for the verification of the well site orientation curves of the FMI log data (MERGE.011). The symmetry of the plots approves the data quality.

**Fig. 10 - GPK1 (3468m-3575m). On the left, cross-plot of accelerometer data AX versus AY (m/s²). On the right, cross-plot of magnetometer data FX versus FY (A/m).**
The two plots show erroneous orientation curves in FMI log EBST.003. The data was thus corrected before processing and creation of images. The green circles show the position of the data after correction.
Are automatic computed dips consistent with wellsine data?
Following the standard DIPMETER processing chain (PREPASS, ACCEL and DEPTHMATCH – see below), automatic dips can be computed (using four or six rows of electrodes). These are checked against Wellsite dips for consistency. In this way, it is also possible to check if the supplied tool orientation curves had already been corrected for magnetic declination and if the orientation and inclinometer curve readings are correct.

Are manually picked dips consistent with automatic dips?
Finally false colour images of the processed dipmeter resistivity curves are generated (statically and dynamically normalised using the DIPMETER/IMAGE and IMAGE/DYNAMIC menus) for manually dip picking in IMAGE/DISPLAY (e.g. fig. 12), and again the manual results are compared with the automatic dips for consistency (Lofts and Bourke, 1999).

At each of the above stages, any other relevant information are brought into the interpretation process e.g. field prints, seismic, prognosis, main and repeat sections of data, other wells or other surveys. Each independent part of information helps to verify and improve the confidence in the data. Often later problems with the structural interpretation can be foreseen already based on these QC-plots.

After the data has been checked for quality and consistence, data are further optimised before the final images are created.

4.2.5. Speed correction

The accelerometer speed correction is used to correct data for minor variations in recording velocity induced by tool cable friction (like a sliding yo-yo effect). There must be accelerometer curves in the log for the curves to be accelerometer corrected. Information about the logging speed is used to calibrate the speed curve derived from the integration of the accelerometer information. The logging speed is obtained either from the cable speed curve (CS), frame time (FTIM) or an average logging speed value entered manually (if no other curve are available). A tie-depth distance (10m) is used to prevent incremental errors from being introduced while double integrating the Z direction (AZ) accelerometer curve.

4.2.6. Depth Match

The different logs at GPK1 were out of depth match with more than 20 meter. At the logging in 1987, the first deepened upper part of GPK1 (2005,0 m) the spectral gamma log was used as depth reference (Ground Level (GL) 153,0 m, Drill Floor (DF) 158,1 m and Kelly Bushing (KB) 158,4 m). Schlumberger has used this gamma ray as universal depth reference as a spectral gamma was run from TD to 1400 m the (7/12-1992) thus also covering the upper part of the well. It is thus chosen to continue with the spectral gamma as absolute depth reference and all other logs in use have been depths matched
Fracture interpretation based on borehole image logs

with respect to the spectral gamma. In this way, the casing shoe can be calculated to 2848 m well depth.

Initially Schlumberger has merged some data curves to compensate for missing data (below the casing shoe). The MERGE.012 file is thus composed of several smaller sections of FBST files. In this sections, the universal GR is copied over the local original GR, and the depth match can thus not be verified.

4.2.7. Image generation (FMI)

An artificial image of the borehole wall is created from the multiple sampled data curves once the data has been loaded, pre-processed, speed corrected and depth matched. From a static normalised image, a dynamic normalised image can be created. The purpose of a dynamic normalisation is to enhance the local contrast in conductivity, and thus use the whole spectrum of possible colours. A histogram of the relevant contrast data is build up over a sliding window interval. In this interval the input data values are re-scaled to values between zero and one so a histogram of the colours used over the sliding window becomes as flat as possible. In a dynamic normalised image, the resistivity/conductivity values are relative and this type of images can thus not be used for fracture aperture evaluation. For the electrical image logs the image normalisation can be done electrode wise or pad wise.

4.3. PROCESSING OF IMAGE DATA

In this paragraph is summarised the steps taken in preparing the raw image data from GPK1 for fracture interpretation.

4.3.1. FMI processing

The borehole deviation remains close to vertical throughout the entire logged interval, with a deviation of 3,5° at 2800 m, increasing to 6,4° at 3550 m depth. The magnetic declination found on tape was -1,434° and magnetic inclination was 64,404°.

At 6 December 1992, the mud type was salty water with a mud weight (Md) of 1,070 g/cc, and a mud resistivity (Rm) of 0,106 ohm.m. (data from tape 8, table 5).

The 6.25 inch GPK1 well located at Soultz was logged with a Schlumberger Formation Micro Imager tool (FMI) on December 5-6 1992. The cable speed (CS) was smooth over the interval of interest and de-spiking was not necessary. The cable speed indicates a logging speed between 1800 ft/hour to 2400 ft/hour. Before speed correction (time-depth conversion), all conductivity data were synchronised with the accelerometer data by applying shifts corresponding to the physical distance along the tool axis between various electrode rows, the accelerometer and tool zero reference (=lower electrode row of pad). The following shifts were applied to the electrode rows:
After this synchronisation, the accelerometer was integrated twice, with a sliding window of 2 m, using the cable speed curve for time-depth conversion. The resulting depth shift curve was applied to the data with various zero-shift values depending on the severity of irregular tool movements. The accelerometer speed correction corrects FMI data for minor variations in recording velocity induced by tool cable friction prior to correlation or image creation. The tie-depth distance (in this case of 2 m) is used to prevent incremental errors from being introduced, while double integrating the AZ curve.

Images were generated from the depth-converted data, applying the actual physical distance between the electrode rows. In addition to the static image, a dynamic normalised image version was produced, using a sliding window of 2 m length, normalising electrode by electrode. To improve the quality of the image, the dynamically normalised image was median filtered.

It should be noticed, that the valid FMI log data is separated on three different logs. Two original logs and one merged log where data verification is not possible. However the caliper, gamma, magnetometer and accelerometer of the FMI record valid values from TD to 2850 m, and the only missing data is thus a part of the GR curve in the MERGE.012 log. At 2850 m, the pads were closed and caliper reading above 2850 m is constantly 4.5 inches.

In general, the log is of good quality. The shape of the hole over the processed interval is mostly round with minor irregularities, and only in front of major fractured zones, irregularity in images are being observed. Below 3468 m, (FBST.003) the tool string rotates 360 degrees with a frequency of 911 else only moderate tool rotation is observed.

**4.3.2. UBI processing**

Run 11, 12 and 13 (run 1) shows tool revolution (rotation) every 3-4 m (RB) and a constant cable speed of around 820 ft/h. AZ shows large localised amplitude increase and decrease in vertical acceleration at approximately 1 m intervals which could reflect heaving problems.

Run 14 and 15 (run 2) shows tool revolution varying between 0.5-4 m interval (RB). In the lower part of the logged interval, the cable speed is 800 ft/h gradually decreasing to 500 ft/h. It remains at that speed over the rest of the logged section. This run shows less variation in AZ compared to run one. Acoustic caliper below 3205 m shows electronic noise. The UBI data from the two logging runs were loaded into five RECALL logs, UBI.011, UBI.012, UBI.013, UBI.014 and UBI.015. The logs each contain the amplitudes and travel times measured by the tool orientation curves.
The UBI and GPIT data from the logging were saved into separate files on the LIS tapes and was merged before processing. Below is given the result of a PREPASS of the raw UBI data file from the REEL tape number 13:

- File 1: No data.
- File 2: UBI Run 11, 3465 - 3164m. Loaded into log UBI.011
- File 3: GPIT Run 11, 3465 - 3164m. Loaded into log UBI.011
- File 4: No data.
- File 5: UBI Run 12, 3465 - 3164m. Loaded into log UBI.012
- File 6: GPIT Run 12, 3465 - 3164m. Loaded into log UBI.012
- File 7: No data.
- File 8: UBI Run 13, 3465 - 3164m. Loaded into log UBI.013
- File 9: GPIT Run 13, 3465 - 3164m. Loaded into log UBI.013
- File 10: No data.

The gyroscope (GPIT) which tracks tool orientation was mounted further up on the tool string than the UBI leading to an accumulation along the tool string of relative bearing (RB) error. The required correction to the orientation curves for the relative bearing (RB) and pad1 azimuth, P1AZ, have been taken into account in the two curves UBRB and UPAZ, respectively. Independently calculated orientation curves based on magnetometer (FX, FY and FZ) and accelerometer (AX, AY and AZ) data showed good agreement with orientation curves on tape except over intervals with rapid tool rotation. As the disagreement can be explained as an algorithm artefact, the orientation curves on tape were judged acceptable and used for image orientation.

Speed correction was tested using a depth adjustment window of 7 ft. Both travel time and amplitude static and dynamic normalised (0.9 m downhole normalisation) images were created for both runs for both speed corrected and non-speed corrected data. As a comparison showed that speed correction gave inferior images, the final images have not been speed corrected. The final, normalised image logs are UBI.011N to UBI.013N. As reference-point for start of image cycle, the field print indicates use of UBAZ. Such a curve was not provided on tape. Instead UPAZ was found on tape and used which resulted in images that compared well with the field prints.

For run 2 as for the previous run (run 1) an independent check of the tool orientation was made and concluded that the data already were corrected for magnetic declination of -1.43 degrees so no correction was made.

Images were created using the curve UPAD as offset curve for the scaling perpendicular to the borehole axis. The images were dynamically normalised with a 2 m window.
Fig. 11 - Depth-matched images from GPK1 (3089 m–3104 m) ready for interpretation.
From left to right: spectral gamma and caliper curves, FMI, ARI and UBI images. The three first logs are (from left) are run shortly after the completion of GPK1. The right image is an UBI image of the same depth interval, but logged after a hydraulic stimulation of the well in summer 1993.
Fracture interpretation based on borehole image logs

The images were surprisingly good, with only minor sticking events. A speed correction was anyway tried with an z-axis accelerometer curve shifted accordingly to the values specified in the UGOS (UBI GPIT offset). However, the coarse nature of the data made data worse and did to resolve in any extra useful geological information. The speed-corrected images were rejected for interpretation. The final, normalised image logs are UBI.014N and UBI.015N. The ARI data are processed in a similarly way as the UBI images. Note that UBI.014 and -015 was logged 04/11/93 after a hydraulic stimulation of GPK1, and UBI.011, 012 and 013 was logged 23/4/93 before the hydraulic stimulation.

When all image data are ready for interpretation, they can be presented as in figure 11, which is a plot of a 15-meter section of the well GPK1 (scale 1:75). The section of the well covered is 3089 m to 3104 m. Note the slightly elevated potassium response (left) from the natural spectral gamma log in an area with quartz veins. The first of the images (from left to right) is an electrical contrast image from a FMI tool, which measures the electricity contrasts on the inner borehole surface. The second image is an electrical image from an ARI tool, which measures absolute resistivity values deeper into the formation (depending of the conductivity of the formation). The two images to the right is acoustic reflection images (UBI) recorded before (left) and after (right) an artificial hydraulic stimulation of the well. It is seen how the black areas have increased after stimulation showing an activation of the natural fracture network.

For later reference, the processed and depth-matched image log data from GPK1 have been saved in 30-meter sections each featuring six images. An FMI image, an ARI image, two UBI images (Amplitude and Traveltime) from before hydraulic stimulation and finally, two UBI images (Amplitude and Traveltime) from after the hydraulic stimulation of GPK1 in summer 1993. For each 30-meter section has been created two plots (scale 1:10 and scale 1:25). The plots are stored in CGM file format.
Fracture interpretation based on borehole image logs

Fig. 12 - Depth-matched ARI, FMI and UBI images.
The section covered is 3150 m to 3160 m. Example from interactive workstation analysis on images recorded by wireline logging in GPKI. Of the two apparently identical fractures identified on the UBI image (right) only the upper can be identified on the ARI image to the left. A family of induced en-echelon fractures are also clearly seen in the UBI image.
5. Fractures

In this chapter are described the fracture interpretation of fractures on images from GPK1.

5.1. INTERPRETATION

The natural fractures of type 1 (fig. 5) are the most easily to detect on the borehole images. They are characterised by a continuous sinusoid formed trace on the images (resistivity or acoustic contrast).

The image colours are artificial and can be changed to optimise the interpretation capabilities, but in general, dark colours are chosen as high conductivity on electrical logs and low contrast on acoustic logs.

The type 1 and type 2 fractures normally occur either as:
- single natural fractures appearing as a distinct sinewave trace in the surrounding rock mass,
- or multiple natural fractures in fractured zones.

In the latter case, the identification of single fractures can be quite difficult or even impossible, and therefore the zones tops and bottoms were carefully measured. Both the natural fractures and the natural partial fractures occur grouped, isolated or spatially associated with the other types of fractures.

The vertical induced fractures and the en-echelon fractures (type 3 and type 4) that often occur in the same intervals as the creation of both types of fractures are favoured in the least stress direction.

The major geological events on the images are first interpreted using a 10-meter sliding window along the borehole axis. Second, minor events are interpreted using a 3-meter sliding window, and finally, a 1,5-meter sliding window is applied in heavily fractured zones with lot of events. In addition, it is possible to magnify each image separately for closer examination.

Figure 12 is a 10 m section from the interactive workstation analysis of fractures in GPK1 once the initial processing of data has been performed and the generated images are ready for interpretation. The section of the well covered is 3150 m to 3160 m.

From left to right:
- depth scale in meters;
- tadpoles and the natural background gamma-ray radiation;
Fracture interpretation based on borehole image logs

- ARI image, coarse resolution resistivity contrast image;
- FMI image, high resolution resistivity contrast image;
- BHTV image, high-resolution acoustic reflection contrast image.

Several steeply dipping fractures are clearly seen on all of the three images ARI, FMI, and UBI. They all correspond to fractures dipping 60-80 degrees. From this image is seen, that by interpreting the UBI and FMI images alone, it is difficult to differentiate between natural and induced fractures, and which of the two fractures at 3155 m and 3156 m are the most important one.

5.2. TYPOLOGY

The fractures types 1, 2, 3, and 4, can be closer described by the geometrical properties measured on the logging images. The dip type classification (or the circumreferential continuity of each conductive and/or reflective anomaly) was recorded for each of the electric- and acoustic images, as fractures are clearly seen as a black sinusoid across the image. On the electrical images, it is a conductive band, on the acoustic images it is low degree of reflection. The features can be described as below.

5.2.1. Dip type classification FMI

F4 (Frac4): Conductive anomaly interpreted as an open fracture and traceable across all four pads/flaps (>70% of image).

F3 (Frac3): Conductive anomaly interpreted as an open fracture and traceable across at least three pads (40%<70% of image).

F2 (Frac2): Conductive anomaly interpreted as an open fracture and traceable across two pads (<40% of image). Probably fracture, but sometimes difficult to distinguish from annular and spiralling scratches produced by drill bit. Fracture could be natural or induced. If the features shows a band structure (e.g. several F2/U2 fractures with same orientation of maximum contrast then they are most probably induced.

Vein: Resistive anomaly, no evidence of offset.

Hybrid: Anomaly that changes character from conductive to resistive around the circumference.

Zone (Top of Bottom): Plane marked by change in conductivity contrast. May mark change from normal to altered granite, or from altered granite to fractured granite.

C-fault: Conductive anomaly interpreted as an open fault and indicated by deflection (small offset) and conductivity contrast.
Fracture interpretation based on borehole image logs

R-Fault: Resistive anomaly interpreted as an open fault and indicated by deflection and conductivity contrast.

Fault: Fault indicated by offset. May or may not be associated with an anomaly.

5.2.2. Dip type classification UBI

U4 (Frac4): Non-reflective anomaly correlated across more than 70% of the borehole image, and with no evidence of offset. Interpreted as a continuous fracture or fracture with high confidence.

U3 (Frac3): Non-reflective anomaly correlated across 40-70% of the borehole image, and with no evidence of offset. Interpreted as an semi-continuous fracture or fracture with moderate confidence.

U2 (Frac2): Non-reflective anomaly correlated across less than 40% of the borehole, and with no evidence of offset. Interpreted as an discontinuous fracture or fracture with low confidence. Sometimes difficult to distinguish from annular or spiralling scratches produced by drill bit. Fracture could be natural or induced.

Vein: Reflective anomaly, no evidence of offset.

Zone (Top or Bottom): Marked by contrast in acoustic character. Often marks change from normal to altered granite.

5.2.3. Dip type classification ARI

A4 (Type1): Conductive anomaly interpreted as an open fracture and traceable across the image.

A2 (Type2): Conductive anomaly interpreted as an open fracture but not traceable across the image.

The geometric properties of fractures found on the images can thus be summarised as follows: A4 and A2; F4, F3 and F2; U4, U3 and U2. (In principle also the possibilities A0, F0 and U0 exist, which indicate a fracture seen on a neighbouring image but not on the image in question). With all three types of images interpreted simultaneously this gives 48 theoretic combinations of fractures (4 FMI, 4 UBI, 3 ARI => 4*4*3 = 48).

The 48 possible combinations of geometrical fracture properties of images are listed in table 6. It is though not possible to work with 48 different theoretical fracture types. Therefore, the most prominent feature in each fracture class is chosen as designation of all fractures in that class (e.g. the fracture type F3-U3-A4, also includes the combinations F3-U2-A4, F2-U3-A4, and F2-U2-A4).
Fracture interpretation based on borehole image logs

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<td>See text for further explanation</td>
</tr>
<tr>
<td>F4-U2-A4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F3-U4-A4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2-U4-A4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F3-U3-A4</td>
<td>F3-U3-A4</td>
<td>Green</td>
<td>(F3 or U3 =&gt; other follows up)</td>
</tr>
<tr>
<td>F3-U2-A4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2-U3-A4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F4-U4-A2</td>
<td>F4-U4-A2</td>
<td>Yellow</td>
<td>(F4 or U4 =&gt; other follows up)</td>
</tr>
<tr>
<td>F4-U3-A2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F4-U2-A2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F3-U4-A2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2-U4-A2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F3-U3-A2</td>
<td>F3-U3-A2</td>
<td>Magenta</td>
<td>(F3 or U3 =&gt; other follows up)</td>
</tr>
<tr>
<td>F3-U2-A2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2-U3-A2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2-U2-A2</td>
<td>F2-U2-A2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F4-U4</td>
<td>F4-U4</td>
<td>Cyan</td>
<td>(F4 or U4 =&gt; other follows up)</td>
</tr>
<tr>
<td>F4-U3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F4-U2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F3-U4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2-U4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F3-U3</td>
<td>F3-U3</td>
<td>Orange</td>
<td>(F3 or U3 =&gt; other follows up)</td>
</tr>
<tr>
<td>F3-U2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2-U3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2-U2</td>
<td>F2-U2</td>
<td>Purple</td>
<td>(common, but often induced)</td>
</tr>
<tr>
<td>F4-A4</td>
<td>v</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F3-A4</td>
<td>v</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2-A4</td>
<td>v</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F4-A2</td>
<td>v</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F3-A2</td>
<td>(F3-A2)</td>
<td>Black</td>
<td>rare (if A2 present also features on FMI or UBI)</td>
</tr>
<tr>
<td>F2-A2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U4-A4</td>
<td>v</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U3-A4</td>
<td>v</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U2-A4</td>
<td>v</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U4-A2</td>
<td>v</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U3-A2</td>
<td>(U3-A2)</td>
<td>Black</td>
<td>rare - (see also F3-A2 above)</td>
</tr>
<tr>
<td>U2-A2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F4</td>
<td>F4/F3</td>
<td>Scarlet</td>
<td>SCARLET</td>
</tr>
<tr>
<td>F3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2</td>
<td>F2</td>
<td>Brown</td>
<td>BROWN (common, but often induced)</td>
</tr>
<tr>
<td>U4</td>
<td>U4/U3</td>
<td>Pink</td>
<td>PINK</td>
</tr>
<tr>
<td>U3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U2</td>
<td>U2</td>
<td>Violet</td>
<td>VIOLET (common, but often induced)</td>
</tr>
<tr>
<td>A4</td>
<td>(A4)</td>
<td>Black</td>
<td>Not found</td>
</tr>
<tr>
<td>A2</td>
<td>(A2)</td>
<td>Black</td>
<td>Not found</td>
</tr>
<tr>
<td>no-no-no</td>
<td></td>
<td></td>
<td>no, 4B1 (4<em>4</em>3=48)</td>
</tr>
<tr>
<td>I-F2</td>
<td></td>
<td></td>
<td>Induced fracture only identified on FMI image</td>
</tr>
<tr>
<td>I-F2/U2</td>
<td></td>
<td></td>
<td>Induced fracture seen on FMI and UBI images</td>
</tr>
<tr>
<td>I-U2</td>
<td></td>
<td></td>
<td>Induced fracture only identified on UBI image</td>
</tr>
<tr>
<td>Zone-top</td>
<td>Top</td>
<td>Black</td>
<td>Top and Bottom of fractured or altered zones</td>
</tr>
<tr>
<td>Zone-bottom</td>
<td>Bottom</td>
<td>Black</td>
<td>Top and Bottom of fractured or altered zones</td>
</tr>
</tbody>
</table>

Table 6 - Possible combinations of geometrical fracture properties on images.
5.3. FRACTURE STRIKE AND DIP ANGLE

A tadpole is used to show the dip and the direction of the fracture plane. Dip of the fracture plane in measured in degrees from 0° (horizontal) to 90° (vertical) is seen as the position of the tadpole in the second column in figure 12. The dip scale is from 0° (left) to 90° (right). The direction of the fracture dip from 0° to 360° is seen as the direction of the tadpole 'tale'.

It is known (Herda, 1999) that it is not possible to accurately measure the strike of shallow dipping fractures with dips less than 20°. The problem worsens rapidly with decreasing dip until the planar horizontal fracture that cannot be assigned any dip at all. On shallow dipping fractures, the discrepancy on strike can easily exceed 20° or 30° which is due to the standard deviation of the shallow dip itself rather than to measurement error. In GPK1 there are one only very few shallow dipping fractures below 20°.

5.4. FRACTURE DATA

The number of fractures identified within the different typologies in GPK1 is summarised in table 7.

<table>
<thead>
<tr>
<th>Combination</th>
<th>Number</th>
<th>Sub-total</th>
<th>Color</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>F4-U4-A4</td>
<td>56</td>
<td></td>
<td>Red</td>
<td>(F4 or U4 =&gt; other follows up)</td>
</tr>
<tr>
<td>F3-U3-A4</td>
<td>40</td>
<td></td>
<td>Green</td>
<td>(F3 or U3 =&gt; other follows up)</td>
</tr>
<tr>
<td>Total A4 :</td>
<td>96 (type 1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F4-U4-A2</td>
<td>23</td>
<td></td>
<td>Yellow</td>
<td>(F4 or U4 =&gt; other follows up)</td>
</tr>
<tr>
<td>F3-U3-A2</td>
<td>98</td>
<td></td>
<td>Magenta</td>
<td>(F3 or U3 =&gt; other follows up)</td>
</tr>
<tr>
<td>F2-U2-A2</td>
<td>128</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total A2 :</td>
<td>249 (type 2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total on ARI</td>
<td>345</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F4-U4</td>
<td>34</td>
<td></td>
<td>Cyan</td>
<td>(F4 or U4 =&gt; other follows up)</td>
</tr>
<tr>
<td>F3-U3</td>
<td>138</td>
<td></td>
<td>Orange</td>
<td>(F3 or U3 =&gt; other follows up)</td>
</tr>
<tr>
<td>F2-U2</td>
<td>123</td>
<td></td>
<td>Purple</td>
<td>(common, but often induced)</td>
</tr>
<tr>
<td>FMI and UBI</td>
<td>295</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F4/F3</td>
<td>88</td>
<td></td>
<td>Scarlet</td>
<td></td>
</tr>
<tr>
<td>F2</td>
<td>72</td>
<td></td>
<td>Brown</td>
<td>(some frac. might be induced)</td>
</tr>
<tr>
<td>Only on FMI</td>
<td>160</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U4/U3</td>
<td>304</td>
<td></td>
<td>Pink</td>
<td></td>
</tr>
<tr>
<td>U2</td>
<td>177</td>
<td></td>
<td>Violet</td>
<td>(some frac. might be induced)</td>
</tr>
<tr>
<td>Only on UBI</td>
<td>481</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total not ARI</td>
<td>936</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I-F2/U2</td>
<td>241</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I-F2</td>
<td>58</td>
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<td></td>
</tr>
<tr>
<td>I-U2</td>
<td>94</td>
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<td></td>
</tr>
<tr>
<td>Total induced</td>
<td>493</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7 - Number of fractures for the twelve chosen combinations identified on the image logs from GPK1.
Fractures and fracture sets are characterised by: size, type, orientation, surface, spacing, density, displacement, distribution, and aperture:

Genter et al., 1997:

This depth interval:
ARI (2780-3500) 233
UBI (2850-3505) 500

Larger depth interval:
FMI (2000-3600) 593
BHTV (2000-3600) 1380

5.5. SPACING

Figure 13 is a fracture intensity plot (spacing) of all natural fractures identified in well GPK1 (2850-3480 m). Each vertical bar represents a fracture. First are all fractures. Second are all ARI fractures. Third are all other fractures. Figure 14 is a similar plot, but with only ARI data present. The fracture intensity plot (spacing) shows all the fractures identified on the ARI images in well GPK1 (2850-3480 m). First is all fractures identified on ARI images. Second is all ARI fractures type 1. Third is all ARI fractures type 2. The cumulative number of fractures versus depth is plotted in figure 15. The lower is the slope, the higher is the fracture content. There are some depth intervals with a higher fracture content such as 3250 m and 3320 m. There is no clear relationship between the occurrence of major flowing fracture and the cumulative number of fractures. In figure 16 are plotted the spacing and the cumulative number of fractures as function of the distance between each of the fractures A4 (type 1) and A2 (type 2). In both cases, the plot of cumulative fractures fit a negative logarithmic curve.

5.6. FREQUENCY

In the depth interval 2850 m to 3485 m (635 m) the fracture frequency is calculated to:

- Fractures A4 (type 1) = 0.15 m⁻¹;
- Fractures A2 (type 2) = 0.39 m⁻¹;
- Total A2/A4 = 0.54 m⁻¹;
- For all ARI fractures total = 1.62 m⁻¹
  (Dezayes et al., 1995, 0.72 m⁻¹, on FMI images, 2870-3570 m);
- Fracture frequency for all fractures total 0.78 m⁻¹
  (Genter and Traineau 1992, 0.72 m⁻¹, on cores from EPS1 1420-2230 m).
Fracture interpretation based on borehole image logs

**Fig. 13** - Fracture intensity plot (spacing) of all natural fractures identified in well GPK1 (2850m–3480m).
Each vertical bar represents a fracture. First is all fractures. Second is all ARI fractures. Third is all other fractures. Finally are marked the positions of the major flowing fracture zones in GPK1.

**Fig. 14** - Fracture intensity plot (spacing) of the fractures identified on the ARI images in well GPK1 (2850m–3480m).
Each vertical bar represents a fracture. First is all fractures identified on ARI images. Second is all ARI fractures type 1. Third is all ARI fractures type 2. Fourth are marked the positions of the major flowing fracture zones in GPK1.
Fracture interpretation based on borehole image logs

**Fig. 15** - Cumulative number of fractures versus depth over the interval 2850 m to 3480 m in well GPK1. Fracture type 1 (A4), type 2 (A2), and all fractures identified on the ARI images. The major fractured zones in GPK1 are indicated.

**Fractures type A4**

**Fractures type A2**

**Fig. 16** - Spacing and cumulative number of fractures as function of the distance between each of the fractures A4 (type 1) and A2 (type 2) in GPK1. The lines fit a negative logarithmic curve.
Fracture interpretation based on borehole image logs

From a comparative work by Genter et al. (1997) between the images of GPK1, GPK2 and EPS1 and the cores from EPS1, it is estimated that less than half of the minor fractures present in the well is recorded by the imaging devices. However, the fracture evaluation of cores in EPS1 (1420-2230 m) by Genter and Trainneau (1992) and the fracture evaluation by BHTV in nearby GPK1 (1420 m-2000 m) show a reasonable agreement. Therefore, the fracture frequency found in this study for the lower part of GPK1 is in good agreement with the actual circumstances. When the fractured or altered zones are not included, as the detection of fractures in these zones are underestimated, as it is not possible to actually distinguish every single fracture.

In figure 17, the fracture frequency and the logged density of the granite show are plot together. The bulk density is related to the fracture density through a linear relationship: \( \rho_B = 2.66 - 1.29^*N_{\Phi} \). This is agreement with the geology of the Soultz granite found in EPS1, where the fresh granite have a low fracture density and where the altered granite have a somewhat higher porosity. This means, that a a lower bulk density of the rock mass can reflect a higher density of fractures in the granite.

5.7. ORIENTATION

Stereographic projections of all of the natural fracture types (fig. 18 and 19) show two principal fracture sets for both single fractures and fractured zones. They are striking N020E and N170E with main dip directions 70E and 65W respectively. There are thus no significant differences in strike and dip directions between the different types of natural fractures. The fracture dip (fig. 20) is quite consistent between 50° and 80°.

5.8. FRACTURED ZONES

The fractured zones in GPK1 can be identified on the borehole images as a clear change in resistivity or acoustic contrast seen as a dark band on the images.

Figure 21 is a summary of the characteristics of the fractured and altered zones in GPK1. Upper left (a) is seen the fracture log of the major fracture zones intersecting the well GPK1. Each vertical bar represents a fractured zone. In (b) is seen the Rose diagram of the two main strike directions (N020E and N150E) of the fractured zones in well GPK1. The rose diagram can be compared with the rose diagram in figure 12 (far right). This rose diagram covers the depth interval 3150 m to 3160 m, and it is seen, that the fractures in this section are oriented similar to one of the main strike directions N020E found for the fractured zones in the interval 2800 m to 3550 m. The cumulative distribution of fractures as a function of the distance between each fracture is plotted in (c). The points fit a negative logarithmic line. In (d) is shown a variogram of the relationship between the different kind of fractures. The variogram is a way to estimate the probability of to which degree the properties of the next fracture can be foreseen based on the present. A positive relationship between fractures is seen below a distance of 30 meter.
Fig. 17 - GPK1 (3200m-3250m). Plot of logged fracture density (NPHI) versus logged bulk density of granite (RHOB).
Fig. 18 - Rose diagram with fracture dip and strike for different geometrical fracture types in well GPK1.
Fig. 19 - Rose diagram with fracture dip and strike for ARI (type 1 and 2 fractures (blue) and for other natural fractures (yellow).
Fracture interpretation based on borehole image logs

GPKI: Fractures vs. Dip intervals

Fig. 20 - Data from 48 fractured and altered zones in GPKI.
The dominating dip fall between 50° and 80°, with a tail of zones down to 20° (above). The orientation plot (below, left) show the two main strike directions (N020E and N170E). In the Rose diagram a red triangle marks the upper limit (▲) of a fractured zone, and a green triangle marks the lower limit (▼) of a fractured zone. The black diamond (◆) is used when the bottom of one zone forms the top of the zone below.
Fracture interpretation based on borehole image logs

Fig. 21 - Characteristics of the 48 fractured and altered zones in GPKI. Fracture intensity log (a), Rose diagram (b), Cumulative distribution of fractures (c), and variogram (d).
6. Aperture and hydraulic properties

As mentioned earlier, a number of methods have been developed to estimate the aperture or the extension of fractures based on measurements in wells. Sibbit and Faivre (1985) have developed a simple method to estimate apertures in the borehole by the Dual Latero Log (DLL). Hornby et al. (1988) have estimated the apertures by use of reflected Stoneley waves. Luthi and Souhaité (1990) have used finite element modelling to calculate the theoretic response of the electrical logs on different fracture types and dip angles. Faivre (1993) have shown that the response in terms of conductivity is closely related to both the opening and the extension of a fracture. Dyke (1995) has measured apertures based on mud logs.

The invasion of a conductive fluid into high resistive formation causes a high conductive anomaly on the shallow Laterolog, thus resulting in a large separation between the shallow and deep Laterolog. The invasion depth of the drilling fluid is dependent on the penetration depth of the open fracture and the difference between the well pressure and the pore pressure.

The ARI tool has a deeper penetration that the electrical FMI tool due to the tool configuration. For the ARI penetration has been priority, for the FMI resolution has been the priority. Apertures from the ARI method may reflect the average for a larger penetration depth than the method using FMI images and may not be affected by vugs unless the vugs are connected with open fractures forming a conductive network of fluid flow in the reservoir.

The fracture extension is a critical parameter when trying to characterise a natural fracture. The depth of investigation of a fracture with the ARI tool increases with the ratio $R_t/R_m$ and the aperture of the fracture. This means we cannot quantify both the fracture aperture and the extension with the ARI measurement alone. We can only compute a lower limit to the fracture aperture and to the fracture extension.

6.1. APERTURE ANALYSIS

The aperture has been estimated by three different methods.

- Method 1: estimating fracture apertures based on the ARI conductivity curves (Faivre, 1993);
- Method 2: estimating fracture apertures based on the LLS and LLD curves of the Dual Latero Log (Sibbit and Faivre, 1985);
Estimation of electrical fracture apertures by ARI and FMI log data are in principle identical, and therefore method one and three will be described together in the following paragraphs.

The results have been compared with the physical apertures measured on cores from EPS1 by Genter and Traineau (1993), and apertures estimated by using the ARI paper images (Genter and Genoux-Lubain, 1994).

6.1.1. Method one and three (Faivre, 1993; Luthi and Souhaité, 1990)

The data used for estimating fractures based on the conductivity curves of the ARI log are: the raw conductivity values which are used to create the ARI and FMI images, the standard DLL curves, the results of the structural analysis (the VISU-log from RECALL), and other petrophysical logs for calibration.

Based on the principle outlined by Faivre's equation, statistical and filtering methods are combined to make practical use of the quantitative expression. The essentials of the method are the following:

- ARI and FMI data re-processed for aperture calculation. (Images processed for structural interpretation are normalised (static or dynamically) and have lost their true pixel values which is the link to the raw conductivity data);
- trace the Area of Added Conductivity on ARI images by restricting the excess conductance to the vicinity of specified potentially open fractures (i.e. type A2 and type A4 on ARI images). In figure 22 is seen the conductivity curve response in front of an open fracture. The AAC is the area between the background conductivity level of about 0.4 mohm, and the conductivity curve;
- calculation of the Area of Added Conductivity by integrating excess conductivity along the relevant fracture traces. This means calculating the area under each of the twelve conductivity curves for the ARI, or calculating the area under each of the 192 conductivity curves for the FMI. This includes analysis and determination of filter parameters of the images.

The method is a series of image filters applied to an electrical image and a simple optimisation procedure, implemented in the above steps. In figure 23 is seen an example of how the conductivity values can be extracted from an ARI image. The extracted conductivity values from the ARI log in plotted in front of different types of fracture dips which are identified in RECALL by simultaneously using ARI, FMI, and UBI images. Conductivity values are given in mohm (log scale). Fracture dips in degrees from 0° to 90° (the tail of the tadpole marks the direction of the fracture dip, 0° to 360°). ARI image, with a strong contrast at 2886 m depth, and weaker contrasts above and below. Far right is by sinusoids indicated the position of the six natural fractures in the ARI image. For controlling the quality of the filtering and aperture analysis, we compare the conductivity values measured in successive images having a significant overlapping. This is seen in figure 24, which is a crossplot of ARI conductivity data from the three different ARI logs in the bottom part of well GPK1. The data fall on a line, which indicates the filtering method is consistent, and works well on all the ARI
Fracture interpretation based on borehole image logs

images from GPK1. In appendix, are found the details of calculating fracture apertures based on the ARI and FMI images.

Dipping Infinite Fracture

\[ E = 0.1 \text{ mm}, \ R_m = 0.1 \text{ ohm.m}, \ R_b = 2000 \text{ ohm.m} \]

![Dipping Infinite Fracture Graph]

**Fig. 22 - Theoretical ARI conductivity curves in front of an infinite dipping fracture.**

The AAC (area of added conductivity) is the area of the additional conductivity measured in front of a conductive fracture. There are twelve conductivity curves which form the ARI image and the AAC is measured each curve (figure from Paivre, 1993).

Based on the principle outlined by Luthi and Souhaite, RECALL is used to evaluate the fracture aperture of fractures seen on the high-resolution electrical FMI image log. When it come to large open fractures, on a scale of several centimetres, a simple measurement of the physical distance between the upper and lower edge of the fracture might be a reasonable procedure (taking the dip angle into account). Smaller fractures however require a combination of filtering and image analysis. A direct geometrical measurement on an image needs a clear open fracture.
Fig. 23 - GPK1, ARI log (2882m-2892m depth). From left to right: Extracted conductivity values from the ARI log in front of different types of fracture dips. Conductivity values in mmho (log scale). Fracture dips in degrees from 0° to 90° (the tail of the tadpole marks the direction of the fracture dip, 0° to 360°). ARI image, with a strong contrast at 2886 m depth, and weaker contrasts above and below. Far right is by sinusoids indicated the position of the six natural fractures in the ARI image.
Fracfure interpretation based on borehole image logs

Image logs quality is a direct function of well conditions, acquisition conditions and tool type. Although the FMI electrical image tool is designed to give a higher resolution than the UBI acoustic image tool in a granite environment as the present the UBI shows better results. The FMI and UBI images have been integrated with ARI images to determine possible zones of open or conductive fractures. Through a collaboration with ETH in Zurich on Stoneley wave analysis on acoustic waveform data it should be possible to determine the possible zones of open or conductive fractures with a higher degree of confidence.

It can be argued, whether or not the Luthi and Souhaite equation is actually a quantitative measurement of the fracture aperture as in some cases the measured apertures closely follow single parameters in the equation. However on a first try, the measured apertures can be taken as qualitative values, and in this way be used to improve the hierarchy of the fractures as it is initially set up on basis on the fracture analysis of the images.

Fig. 24 - Verification of ARI conductivity data by cross-plot of data from the ARI log in the two depth intervals (3165-3190 m (Φ) and 3428-3460 m (△)) where the ARI image data are overlapping. X-axis and Y-axis are filtered ARI conductivities expressed in mmho. If the data fall on the green line (1:1), the conductivity measurements are homogeneous in the overlapping zones, and thus expected to be homogenous in the entire logged part of GPK1.
6.1.2. Method two (Sibbit and Faivre, 1985)

Using a quantitative expression of the magnitude of the separation between shallow and deep Laterolog caused by the presence of an open fracture the fracture aperture method by Sibbit and Faivre gives the fracture aperture. The following is an example on a simple aperture estimation based on the DLL curves (Sibbit and Faivre, 1985). The fracture dip is 70°, depth 3225 m. In this case, the fracture aperture is estimated as a weighted average of the formulas (2) and (3).

\[
\begin{align*}
R_{LS} &= 1000 \text{ ohm} \cdot \text{m} \Rightarrow 1.00 \text{ mmho} \cdot \text{m} \\
R_{LD} &= 3000 \text{ ohm} \cdot \text{m} \Rightarrow 0.33 \text{ mmho} \cdot \text{m} \\
R_b &= 100.000 \text{ ohm} \cdot \text{m} \Rightarrow 0.01 \text{ mmho} \cdot \text{m} \\
R_m &= 0.106 \text{ ohm} \cdot \text{m} \Rightarrow 9.43 \text{ mho} \cdot \text{m}
\end{align*}
\]

From formula (2): \( \Delta C = (0.33 - 0.01) = 1.2 \times 10^{-4} \cdot \varepsilon \cdot 9.43 \Rightarrow \varepsilon \sim 280 \mu\text{m} \)

From formula (3): \( \Delta C = (1.00 - 0.33) = 4 \times 10^{-4} \cdot \varepsilon \cdot 9.43 \Rightarrow \varepsilon \sim 175 \mu\text{m} \)

The coefficients (2/3 and 1/3) represent the dip effect in the formula and therefore the fracture aperture can be estimated to:

\[
2/3 \times 280 + 1/3 \times 175 \sim 245 \mu\text{m}
\]

In figure 25 is shown the fracture distribution versus the estimated electrical aperture. Here is chosen three ways of calculating the "electrical" fracture aperture on basis of the ARI logs. The numbers of cumulative fractures are plotted versus the estimated fracture aperture: ARI images digital (green), and ARI images manual (red) (Faivre, 1993) and from the DLL - curves (blue) (Sibbit and Faivre, 1985).

The fracture apertures are also calculated on basis of the FMI logs. However, the FMI only measures conductivity very close to the inner borehole surface (scale of millimetres), and the FMI data are therefore more sensible to the borehole conditions than the ARI measurements. According to Schlumberger, the ARI measurements reach several decimetres into the surrounding formation.

The core data points (black) in figure 25 are geometrical apertures measured on the unloaded cores from EPS1 with a slide gauge. Though the data are not from the same well, the four curves show the same trends, but the calculated values are more than an order of magnitude lower than expected from the core analysis. The calculated apertures however prove very useful to build a relative hierarchy between the natural fractures.
Fig. 25 - Estimated fracture apertures versus normalised fracture frequency. The green curve ("ARI raw curves"), are electrical apertures estimated on basis of filtered raw conductivity values from the ARI log in GPKI (Faivre, 1993). The red curve ("ARI created image") are estimated electrical apertures based on a visual interpretation of the ARI paper log from GPKI (Genter and Genoux-Lubain, 1994). The blue curve ("ARI curves (DLL)") is the way of manually estimating fracture aperture from the standard LLS and LLD curves by using a quicklook overlay chart (Sibbit and Faivre, 1985). The black curve ("Core data") are geometrical apertures measured on cores (30 fractures from an interval of 810m) from the granulic basement in the nearby well EPS1 (Genter and Traineau, 1996).
Fracture interpretation based on borehole image logs

On the basis of the ARI tool (advanced DLL tool), it is concluded that less than 25% of the 690 natural fractures detected with high resolution image tools extend away from the borehole wall. Also when the calculated electrical fracture apertures are plotted against the dynamic flow and temperature data (fig. 26 and 27), in front of each flow anomaly is seen a clear response on the ARI image. The hydraulic active zones are therefore all identified on the ARI images, whereas a part of the fractures found on the ARI images are not flowing when compared to the flow- and temperature logs. The relative fracture apertures have been calculated based on electrical images. The highest fracture aperture values located at 3200m and 3500m depths correspond properly with the two major permeable zones known in GPK1. In table 8 is summarised, that all of the major fracture zones in GPK1 are properly identified by the aperture estimations.

![Diagram](image_url)

Fig. 26 - Comparison between flow properties of fractures (Evans, 2000), and electrical fracture apertures derived from ARI logs in well GPK1. The upper scale limit of the qualitative flow scale is "F-maj", which is a significant flow. Lower limit is "P??", which is only a slight temperature anomaly.
Fig. 27 - Electrical fracture apertures from GPK1 compared with the qualitative flow and temperature scale defined by Evans. Left figure is data before verification. Right is data after checking. There is a good agreement between the dynamic data and the calculated electrical apertures.
Table 8 - Some characteristics of the major fracture systems zones in GPKI. The ARI response has been properly identified in front of all the major fracture zones with exception of the bottom of zone 6, which was not covered by the ARI logging.

6.2. PERMEABILITY ANISOTROPY?

Fractures may enhance or obstruct permeability. In either case, the presence of the fractures creates anisotropy in the reservoir. Permeability anisotropy ratios as high as 1.000:1 have been found (Aguilera, 1995). Permeability anisotropy can also exist in matrix, but matrix permeability anisotropy is only a small secondary effect in the cases where fractures dominates fluid flow (Harstad et al., 1998).

In table 9 is given the total number of fractures (type1 and type2) where the interpreted fractures can be assigned a direction where the image has a maximum contrast, or two opposite contrasts. Of the type1 (full sinusoids) fractures about 50% can be assigned a direction where the conductivity contrast is significant higher that at the rest of the sinusoid. Of the type 2 fractures, about 70% can be assigned a direction of maximum conductivity contrast.
Fracture interpretation based on borehole image logs

<table>
<thead>
<tr>
<th>Dipytes</th>
<th>Number</th>
<th>in %</th>
<th>Total A2/A4</th>
<th>In %:</th>
<th>&quot;Dipaux&quot;</th>
<th>in %</th>
<th>Total in %</th>
<th>Two focus points</th>
<th>in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>F4-U4-A4</td>
<td>55</td>
<td>14.4</td>
<td>101</td>
<td>26.4</td>
<td>26</td>
<td>47.3</td>
<td>-</td>
<td>6</td>
<td>5.9</td>
</tr>
<tr>
<td>F3-U3-A4</td>
<td>46</td>
<td>12.0</td>
<td>101</td>
<td>26.4</td>
<td>26</td>
<td>56.5</td>
<td>44-26%</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>F4-U4-A2</td>
<td>26</td>
<td>6.8</td>
<td>282</td>
<td>73.6</td>
<td>17</td>
<td>65.4</td>
<td>-</td>
<td>18</td>
<td>10.6</td>
</tr>
<tr>
<td>F3-U3-A2</td>
<td>92</td>
<td>24.0</td>
<td>101</td>
<td>26.4</td>
<td>72</td>
<td>78.3</td>
<td>A2-35%</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>F2-U2-A2</td>
<td>164</td>
<td>42.8</td>
<td>101</td>
<td>26.4</td>
<td>113</td>
<td>68.9</td>
<td>-</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>383</td>
<td>100</td>
<td>383</td>
<td>100</td>
<td>254</td>
<td>63.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 9 - Total number of fractures (type 1 and type 2) from GPKI. "Dipaux" means that a partial single or double sinusoid have been assigned to the fracture.

Does this effect reflect a channel effect on some of the fractures on the images and can this be verified?

On the images are commonly observed that some parts of the sinusoids are more conspicuous than other parts. This effect might be due to a sort of channelling effect within the fracture. The direction of this stronger contrast can be measured in RECALL by assigning a partial sinusoid to the fracture like orientating the fracture opening within the fracture plane. However when picking a partial features, the depth is measured in the middle of the interval designated as a partial feature. Otherwise, the depth is taken in the middle of the sinusoid. This means, that when changing sinusoids to partial sinusoids, then the depth can change with up to the height of the sinusoid (several meters for steeply dipping features).

Based on the analysis, the orientation maximum can be divided into the following three groups:
- Sinusoids with apparent equal thickness (about 26% of total);
- Sinusoids with one focused direction (about 35% of total);
- Sinusoids with two opposite focused directions (about 16% of total).

The remaining 23% correspond to fractures difficult to interpret in terms of equal thickness and focused directions.
7. Results and discussion

In the present fractured reservoir, we have observed that relatively few fractures (or open faults) serve as the primary conduits for fluid flow in the fractured rock mass. It is also observed that the intervals with a high frequency of fractures do not necessarily match the intervals with large fracture apertures. Lately fracture aperture analysis is used to provide additional information about where the more conductive fractures are located and how large they are. We have tried to estimate the apertures of open fractures around the wells by using different well log information, reflected Stoneley waves, electrical borehole images, and the Dual Laterolog response. On the electrical images, fracture apertures can be estimated in several ways by integrating the electrical response around the borehole on the image logs. Measurements of natural fractures on cores are used to calibrate the measured apertures. We found that the highest of these relative aperture values correspond properly with the major permeable zones in the well, thus there is a connection between the relative aperture, the flow rate and the pressure gradient. However, there are still some apparent conductive fractures on the images that show no evidence on flow when compared with the flow and temperature logs.

When processing images, interpreting fracture patterns and combining the different types of geophysical data, the procedures involved could be summarised as follows (fig. 28):
- load of data into processing and interpretation software (RECALL);
- data QC, processing, depth matching, and image generation;
- structural geological analysis;
- identification of fractures;
- classification of fractures by: type (natural or artificial, open, mineralised or closed, single fracture or fractured zone);
- weight (full sinusoid, seen on all images or only partly);
- orientation of fracture planes;
- length;
- thickness or aperture.

Once all fractures has been fully described the later data treatment comprise a classification of the fracture sets and families:
- spacing (distance between fractures);
- number of families (fracture planes orientated alike belongs to the same family, seen from Rose diagrams);
- density (density of the fracture population);
- distribution;
Fracture interpretation based on borehole image logs

Fig. 28 - Work flow on fracture analysis which includes image logs.
Fracture interpretation based on borehole image logs

Fig. 29 - A three dimensional geometrical model (3DEC) of the near-well fractured zones in GPK1.
Fracture interpretation based on borehole image logs

Fig. 30 - Well GPK1 (3480-3500 m). Geologic Summary plot. The two images at left is an UBI amplitude image and a travel-time image. There is a clear response of most of the petrophysical logs in front of the fracture zone (3490-3496 m) which has two major flowing zones at top and bottom.
Fracture interpretation based on borehole image logs

- possible connections;
- dynamic properties (flow, temperature).

As an example on a 3D visualisation which can be made based on this type of fractured zone characteristics is seen in figure 29. This model includes the major fracture zones intersecting the well GPK1. In addition this plot is based on information from Rose diagrams that gives the two mains strikes directions (N020E and N160E) of the fractured zones in well GPK1. A summary plot of one of the fractured zones in GPK1 is seen in figure 30, where the hydraulic active parts of a fractured zone is located along the upper and lower borders of the fractured zone.

The FMI and UBI images have been integrated with ARI images to determine possible zones of open or conductive fractures. These data have then been matched with the dynamic flow and temperature data from the well. In addition, electrical apertures have been calculated which shows a remarkably connection between the highly conductive zones and the electrical apertures. Through collaboration with ETH in Zurich on Stoneley wave analysis on acoustic waveform data, it has been possible to determine the possible zones of open or conductive fractures with a higher degree of confidence.

The primary advantages of borehole images are the high image resolution, which allow fractures to be described in detail combined with the possibility to orientates fracture data, as this allows 3D fracture modelling from data within the well. Various other methods exist with which to characterise a reservoir. However, as the resolution of the measurements performed is inversely proportional to the range of measurement the image logs provides the best basis of characterising fractures in wells.

The combined analysis of UBI- and FMI-images allows detection of individual fractures with a higher degree of confidence than when only one type of image is studied. In the well GPK1, a detailed characterisation of the fractures and comparison between the different types of electric and acoustic image logs indicate, that less than one fourth of the fractures detected on the borehole surface extend away from the borehole wall. Fractures identified in the ARI image show a larger spacing (several fractures per meter) than those identified in the UBI/FMI-images (more than 10 fractures per meter). Based on the UBI- and FMI-image data, the main strike direction in GPK1 is N020E and a secondary strike direction is N160E. Similar orientations are found for fractures seen on the ARI image, but the ARI-images rate the strike direction N160E highest. A cumulative distribution of fractures found on the ARI images as a function of the distance between each fracture forms a negative logarithmic fit.

Series of electric- and acoustic borehole imaging techniques (e.g. FMI, UBI, and ARI) are used to set up a hierarchy of the near-well fractures, which are used to make near-well fracture models. These models consist of the available well information, including the characteristics of the interpreted fracture patterns from the images. A methodology designed as a workflow gives the key for a correct use of the data available in each interpretation study.
Fracture interpretation based on borehole image logs

From the well GPK1 (Soultz-sous-Forêts, Rhine graben, France) digital copies of borehole images and additional well log data from the depth interval 2850-3505 m have been loaded into a common database.

The fracture hierarchy is described based on a detailed characterisation of the fractures and comparison between the different types of electric and acoustic images. The ARI (advanced DLL tool) log indicate, that less than 25% of the 690 natural fractures (composite fractures and fractured zones included) detected on the inner borehole surface extend away from the borehole wall.

These natural fractures tend to be found in clusters throughout the borehole, and can be separated into two distinct families. The dominant dip directions of these families are: over 3060 m N80W-N100W, between 3060-3260 m N90E-N100E, and below 3260 m depth both families of fractures are equally present. The fracture dip is quite consistent between 60° and 80°.

Also several scales of relative fracture apertures have been calculated based on the electrical images, and hydraulic active intervals has been identified in GPK1 on basis of the flow- and temperature logs. When these data are combined a qualitative connection is found, as all dynamic data are easily identified on the ARI images. The calculated fracture aperture permits the precise location of the major permeable zones known in GPK1.

- The combined analysis of UBI- and FMI-images allows detection of individual fractures with a higher degree of confidence than when only one type of image is studied.

- In the well GPK1, a detailed characterisation of the fractures and comparison between the different types of electric and acoustic image logs indicate, that less than one fourth of the fractures detected on the borehole surface extend away from the borehole wall.

- Fractures identified in the ARI image show a larger spacing (several fractures per meter) than those identified in the UBI/FMI-images (more than 10 fractures per meter).

- Based on the UBI- and FMI-image data, the main strike direction in GPK1 is N020E and a secondary strike direction is N160E. Similar orientations are found for fractures seen on the ARI image, but the ARI-images rate the strike direction N160E highest.

A cumulative distribution of fractures found on the ARI images as a function of the distance between each fracture forms a negative logarithmic fit.
Literature


Fracture interpretation based on borehole image logs


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Gentier S. (1986) - Morphologie et comportement hydromécanique d’une fracture naturelle dans un granite sous contrainte normale, Ph.D. Dissertation, Université d’Orléans, Orléans, France.


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Fracture interpretation based on borehole image logs


Fracture interpretation based on borehole image logs


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Thomasen J.B. (1995) - Fracture modelling for fluid flow simulation, examples from Danish chalk fields. EAEG-EAPG Workshop on Faults and Fractures, extended abstract, p ??.


Fracture interpretation based on borehole image logs


Acknowledgements

The European Commission supported this project under the fourth framework programme through an individual Marie Curie Fellowship. The support of all partners participating in the project is gratefully acknowledged. In particular, BRGM and Albert Genter, Z&S GeoScience which supported the project with the RECALL software and discussions (Johanne Paludan and Morten Pedersen). Socomine and ETH Zurich (Keith Evans) have kindly supplied data.
APPENDIX

Excess conductivity and aperture calculation
Measuring excess conductivity on an electrical ARI or FMI image are done by applying a series of image filters to an electrical image. This is, define the fractures by image analysis, and then trace the excess conductance near the specified potentially open fracture. This conductivity value is in principle similar to the area between two Dual Laterolog curves, but yields a more precise result.

The following is an outline of the main steps taken:
- define the upper and lower border of fracture surroundings by a filter;
- assign a value representing the fractures anomaly amplitude. Integrate this excess conductivity along the fracture trace;
- estimate the aperture of the fracture;
- calculate fracture porosity;
- evaluate the uncertainty in the estimation.

In Luthi’s original numerical model, fracture dip angle was restricted in a range from 0° to 40° (relative to the borehole axis). Any dip angle larger than 40° is out of the range than that used in their model and this estimation is thus restricted to this dip interval.

It can be seen from Luthi’s experiments that the effect from the fracture dip angle is a function of formation resistivity. The larger the formation resistivity is, the smaller the angle effect on the integrated excess conductance will be. In the present case where the granite formation has a high resistivity, the effect on the integrated excess conductance should be negligible.

**Description of the RECALL filter pages:**

The Filter page enables filters and dip-based filters to be applied to image logs. The dip-based filter can of course only be applied after the fractures have been identified on the image. The dip type selection allows filtering to be carried out on a specific dip type. The image filter controls the overall appearance, and it is processed before the dip filtering.

In RECALL are the following build-in image filters and dip filters:

**Image filter types:**
- Edge V: Vertical edge enhancement;
- Edge H: Horizontal edge enhancement;
- Average;
- Geometric Average;
- Median;
- Percentile;
- Above average;
Fracture interpretation based on borehole image logs

- Above Geometric average;
- Above Median;
- Above Percentile;
- Above cut-off;

**Dip filter types:**
- Above CTOF: above cut-off filter;
- Above A/CUOF: average above cut-off filter;
- Max A/CUOF: maximum above cut-off filter.

To the above image-filters are assigned the following parameters:
- Filter size across: Chose a value between 1-250. The unit of the value may be pixel, which has a length of 2.5 mm. Filter size across value determines the width of a filter rectangle;
- Filter Size Down: Chose a value between 1-250, which determines the height of the filter rectangle;
- Filter Percentile: Applicable only to the Percentile filter. The pixel value will be assigned to be zero if the pixel value is less than the corresponding value of the specified percentile;
- Filter cut-off: Takes a value between 0-1 if the image is normalised (otherwise it takes a value between 0-212). The pixel value will assign to be zero if the pixel value is less than the corresponding cut-off value designed.

To the dip-filters are assigned the following parameters:
When a dip filter applied, it will assign zeros to all the area except from that picked trace exist. (See fig. 29 and figure 8.3) The width of the trace is depends upon the value of the dip filter size. The filter parameters include the search size for excess conductance near an open fracture and the cut-off values for integration of the excess conductance.

**Dip filter size:** Takes value from 1 to 250 for normalised image and 0-212 for the raw data images. This value will determine the height of the trace. The width of the trace is automatically assigned to the spherical length of the ellipse of fracture plane.

**Dip Filter Cut-off:** Takes a value between 0-1 for normalised images. A zero will be assigned to the pixel if its value is less than the cut-off value.
Fracture interpretation based on borehole image logs

Recall main pages, and main workspace for Soultz project.
Fracture interpretation based on borehole image logs

Recall main page setup for Soultz project.
Fracture interpretation based on borehole image logs

Details of the iterative process of filtering fracture conductivity values from an ARI image. Same technique are used for FMI images.
Applying a filter to an image with a corresponding dip log

Choose a regular filter and its parameters, and a dip-based filter and its parameters. A dip filter will need an input dip log; furthermore, the filter options AVE A/CTOF and MAX A/CTOF will generate the curves of calculated conductivity values. Note that choice of either of these two filters will suppress creation of an output filtered image log. Otherwise, an output image log will always be created.

The essentials of the calculations are a series of filters: e.g. (1) an "above percentile" filter to get the "excess conductivity" of the image, and (2) a "dip filter" to restrict consideration of excess conductivity to the vicinity of the specified dips. Finally this excess conductivity is "integrated" along a dip trace, and to this dip "plane" is thus assigned a value representing this excess.

The idea of the filter page is to apply such filters over long sections of image off-line. The mirroring of these filters in Image Display is for finding which thresholds, filter types, sizes etc. and to verify (over a short section) what the effects/results are.

Problems may arise, as a large search size could mix the conductivity anomaly of an open fracture with others in the vicinity, therefore overestimating the fracture aperture. Similarly, a small search size may only integrate excess conductance from a part of a large fracture, therefore underestimating the aperture. Furthermore, a large cut-off value causes the filters to ignore small fractures, while a small cut-off value will certainly include non-fracture features in the calculation. Poor borehole condition results in non-fracture related variation in wideness of conductivity anomalies and make the selection of filter parameters more difficult.

All filters should be applied on non-normalised data by default that is using values of the original data rather than the image values from normalised images which is in the range from 0-1. The normalised image values can not be used for aperture calculations.

Data required for aperture calculation:
- Raw FMI or ARI log data (FMI with Emax curve)
- Interpreted open fractures and associated features (VISU log)
- Resistivity logs (including mud resistivity log – if it exist)
- Porosity logs (neutron, density and sonic)
- Other petrophysical and survey logs.
- Independent Dual Latero logs survey for data verification.

Checklist and option applied in RECALL:
- Image data re-processing for aperture estimation - Done
- Speed and shift corrections - Done
- Image generation - Done
Fracture interpretation based on borehole image logs

**Image generation options:**
- Normalisation: Yes
- Output data: Raw (1)
- Output increases with: Conductivity
- Input increases with: Resistivity
- Amex corrections: No

(1) This option automatically cross-links the normalised image to the original values.

**Image filtering and Dip filtering**

Two types of image filters are applied:
- The low pass filters: to reduce the noise in the images, and the above cut-off filters: to extract anomalous features from the images.
- The dip filter used for aperture calculation is the above cut-off filter. The selection of filter parameters should be based on the experiments of the cut-offs and the excess conductance. A cross plot provides a useful tool for analysis of the relation between cut-off and the integrated excess conductance, and can help to determine the range of cut-off values suitable for the estimation.

**The coefficients in Luthi’s equation**

There are two parameters (b and c) in Luthi’s expression, which are dependent on tool configuration and borehole conditions, and sensitive to the filter parameters.

A calibration technique to estimate the coefficients when geological constraints are available can be used for the aperture calculation. To determine the parameters in Luthi’s equation, a calibration was made by comparing the fracture porosity estimated from sonic and neutron logs with those from the calculation of the integrated excess conductance in an interval carefully selected.

The calibration technique has the advantage of allowing different types of aperture to be estimated. For example, if a set of effective permeability values measured from well tests was available, the calibration and optimisation procedure will allow a hydraulic aperture instead of an electrical aperture to be estimated.

The parameters in Luthi’s empirical expression were derived by a calibration procedure that minimises the difference between the calculated values and calibration values. Reliability of the fracture aperture estimation is largely dependent on the reliability of the calibration data set. Uncertainty in the calibration data set will ultimately be transformed to the estimation results through the derived unknown parameters.
Fracture interpretation based on borehole image logs

Uncertainty of fracture apertures:

All the fracture apertures methods (e.g. Sibbit, 1985; Luthi, 1990; Faivre, 1993) are estimates with uncertainties from various sources. The followings are the major sources of uncertainty in the estimations:

Uncertainties related to filter parameters:

Determination of the filter parameters is crucial in the estimation of fracture apertures using the resistivity images. The filter parameters include the search size for excess conductance near an open fracture and the cut-off values for integration of the excess conductance. A large search size could mix the conductivity anomaly of an open fracture with others in the vicinity, therefore overestimating the fracture aperture. A small search size may only integrate excess conductance from a part of a large fracture, therefore underestimating the aperture. A large cut-off value causes the filters to ignore small fractures, while a small cut-off value will certainly include non-fracture features in the calculation.

Poor borehole condition results in non-fracture related variation in wideness of conductivity anomalies and make the selection of filter parameters more difficult.

Uncertainty in the determination of coefficients in Luthi’s equation:

The parameters in Luthi’s empirical expression were derived by a calibration procedure that minimises the difference between the calculated values and calibration values. Reliability of the fracture aperture estimation is largely dependent on the reliability of the calibration data set. Uncertainty in the calibration data set will ultimately be transformed to the estimation results through the derived unknown parameters. A reliable calibration data set as in GPKI is therefore crucial for the fracture aperture calculation. Good relationship between the integrated excess conductance and the calibration data set will be less subject to uncertainty. While poor correlation between these two variables will result in large uncertainty in the parameter estimation.

Uncertainty inherited from geological interpretation:

Uncertainty can also be inherited from structural interpretation of the micro-resistivity images. Intervals that have wide and large electrical conductivity anomalies and large separation between the deep and shallow resistivity indicate these zones are highly conductive for fluid flow. However, whether the nature of these conductive zones is tectonic or hydraulic is difficult to determine if no other data available.

If fracture aperture calculations were applied in the sedimentary cover at Soultz, the main problem could have been bedding picked as fracture and vice versa due to complex structural geology. The uncertainty inherited from the geological interpretation can only be reduced by a better understanding of the geology of the study area and by quality control procedures in the interpretation. Certainly there are no problems with bedding in the granite environment.
Uncertainty due to data quality

On the FMI images, irregular borehole shape and enlarged borehole have significant impact. The poorer the pad contact is ("stand-off" in Luthi et al., 1990), the wider the conductive anomaly becomes and the lower the anomaly amplitude will be. Irregular borehole shape and enlarged borehole cause variations in stand-off and lead to different signatures on the FMI, consequently influencing the excess conductance integration and the determination of filter parameters.