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Geological monitoring of GPK-2 HDR borehole, 1420-3880 m (Soultz-sous-Forêts, France)

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ABSTRACT

The drilling of the HDR GPK-2 borehole (Soultz-sous-Forêts, France) from 0 to 3880 m gives access to an insight within a 2.5 km thick section at the top of the Soultz granite massive. Chip samples have been logged on site in order to characterise the petrography of the granite and to identify fracture zones from 1420 (top of the granite massive) to 2110 m only. No cuttings were collected below 2110 m due to the occurrence of a main fault which caused total losses during drilling. Conventional well-logs measurements (Western Atlas) and borehole imagery data (Schlumberger), were carried out on the whole granite section and supply information.

Between 1420 and 2110 m depth, fractured and altered zones represent basically the only significant feature which disrupt the relative homogeneity of the granite massive. By comparison with the closer borehole EPS-1, the upper section of GPK-2 well from 1420 down to 1542 m shows a similar reddish facies. Deeper, occurrences of biotite rich units which were crossed-cut by major fault zone (2110 m) were observed from drill cuttings analysis. Based on stable values of bit penetration and caliper logs, and a sligth decreasing in natural radioactivity, a massive poorly fractured granite was penetrated from 2110 down to 2960 m. A lot of major fractured zones, deduced from caliper data, occur from 2960 down to 3510m. Deeper (3510-3820m) a poorly fractured section was penetrated. It does not show a typical well logging response related to granite, as variability of both natural radioactivity and vertical magnetic field component with stable sonic P and S velocities. Bottom hole section (3210-3880m) is mainly made of altered and fractured granite.

Acoustic borehole imagery logs (UBI tool) were carried out from 1427 to 3804 m in order to record natural and artificial planar discontinuities. The orientation and frequency of the joint system were determined as well as the apparent aperture and its predominant orientation. The maximum strike direction of 406 discontinuities is N05°E (25%) coexisting with subsets in N155°E (14 %) and N170°E (9%). The orientation of a large, hydraulically open fault system intersected at 2118-2125 m depth is N140-155°E with dip of 75-80° to the East. Between 1422m (9 5/8" casing shoe) and 3804 m depth, the horizontal and vertical distributions of fractures are presented. Over a horizontal distance of more than 100 m and a vertical distance of more than 2350 m the orientation of the maximum strike of the joint system is around N-S. With the help of investigations on nearly-vertical fractures the orientation of the maximum horizontal stress direction was determined as N175°E ± 17°. These results are consistent with previous fracture analyses performed in the closer boreholes (GPK-1, EPS-1).

CONTEXT

List of figures

LIST OF TABLES

1. Introduction

In the framework of the European Hot Dry Rock (HDR) project, the borehole GPK-2 was drilled from the surface down to 3883 m depth (driller reference) starting on the 20th October 1994 and completing on the 13th February 1995 (fig.1).

The Soultz site is located on the western side of the Rhine Graben at Soultz-sous-Forêts (France). The objective of this HDR project is to develop an artificial heat exchanger within a granite massive overlain by a sedimentary cover (Kappelmeyer et al., 1991; Garnish et al., 1994). The purpose of GPK-2 was to be a second deep near-vertical wellbore that intersected the dominant fracture network created during the previous hydraulic experiments in the GPK-1 well (Jung et al., 1995).

The initial target of GPK-2 well was to reach 3600 m - 4300 m depth with an anticipated temperature of 165-175°C. The drilling rig was supply by COFOR. SOCOMINE assisted by Southern International Incorporated acted as the operator for the drilling operations.

Geological monitoring was conducted on site by the geologists of BRGM and Stadtwerke Bad Urach. This study was carried out as a part of BRGM scientific research programme (Project S07) applied to HDR Soultz project. The general objective of this research consists of the geological characterisation of the deep granite massive dedicated to HDR experiments.

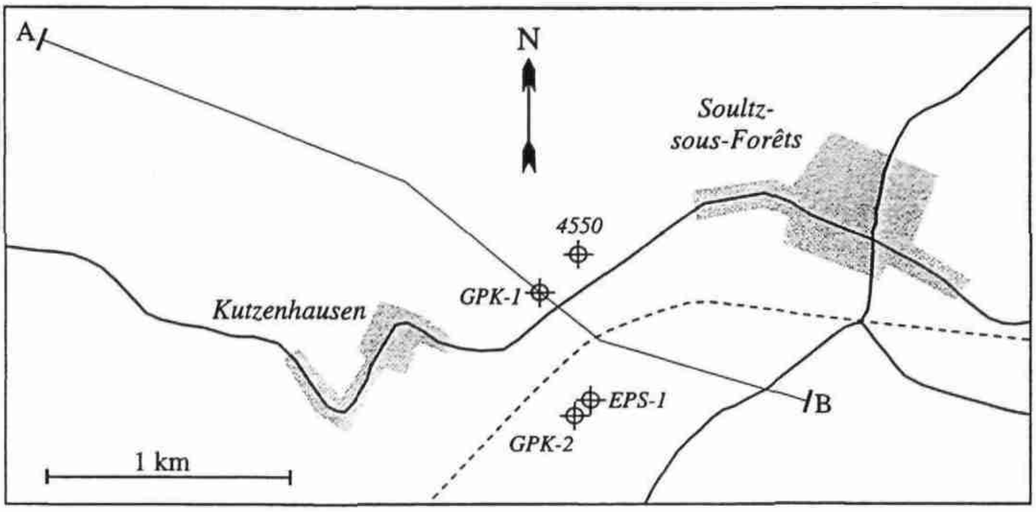


Figure 1 - Borehole network at Soultz.

This field report is organised into two different parts :

- the synthetic petrographic log of GPK-2 deduced from the examination of the chip samples in the upper part of the granitic section (1420 - 2110 m)
- a first evaluation of geophysical well logging and borehole imagery in the whole granitic section (1420 - 3804 m)

GPK-2 was drilled in 8-1/2" diameter between 1430 and 3218 m and in 6-1/4" diameter between 3218 and 3883 m (driller depth reference). The driller depth reference is based on the rotating table located at 6.70 m above the ground level. All the geological data (petrography, alteration, ROP) will be provided and plotted according to the driller depth referential.

Schlumberger logs are depth matched according to the 9-5/8" casing shoe at 1427 m. In this Schlumberger depth referential, the change of borehole diameter (8-1/2" to 6-1/4") occurs at 3222 m on the UBI log.

2. SYNTHETIC PETROGRAPHIC LOG FROM CHIP SAMPLES

2.1. METHODS AND PROCEDURES

The drill cuttings from the borehole GPK-2 were collected by Datalog Technology Ltd at two or three meter intervals from 1410 m to 2110 m. Below 2110 m, total mud losses occurred and no cutting sample was collected until the final depth (3883 m). So, there is no direct geological information within this depth range. These cuttings were washed to remove drilling mud and lost circulation material. They were first logged in detail on site by conventional binocular microscope examination at 10-50 x magnification. Moreover, three cutting samples were packaged by Datalog as reference collection for further investigations.

Cuttings collected from GPK-2 are fine-grained, averaging less than 1 mm. This small size hinders accurate characterization of grain size feature of coarse or medium grained facies. It also prevents from recognizing fracture fillings accurately.

Because of the possible mixing of cuttings from neighbouring levels in the drilling mud during its ascent to the surface, the samples represent an average composition for a certain level. For instance, the volume of one meter long drilled section represents respectively 36 and 20 liters for 8-1/2" and 6-1/4" borehole diameters.

Thus, examination of the chip samples can only identify change in petrographic facies and/or the type of alteration if it affects a reasonably thick layer of granite. It appears difficult to detect variations covering less than three or four meter.

The drilling rate, namely ROP (rate of penetration), expressed in meter per hour was provided by Datalog Technology from 1410 to 3883 m.

2.2. EXAMINATION OF THE CHIP SAMPLES

A binocular microscope examination of all chip samples was carried out on site.

Data logged included the sample color, primary mineralogy, style and intensity of alteration and hydrothermal fillings. From the previous investigations (Genter, 1989; Genter et al., 1989), two alteration styles are known to occur within the Soultz granite. Pervasive (or so-called propylitic) alteration took place on a large scale within the granite without any macroscopic modification of the rock texture. Vein alteration is related to fracture zone where hydrothermal fluid circulations strongly modify the granite.

Color : The small size of the cuttings gives a homogeneous sample color which is a good indicator for characterizing facies variations. The color varies from dark, grey, red, pink, and orange.

Primary mineralogy : Abundance of quartz, K-feldspar, plagioclase and biotite was estimated providing a qualitative evaluation of the primary mineralogical content variations. According to the geological investigations previously performed on EPS-1 core sections (Genter et Traineau, 1991 and 1992a,b) and on GPK-1 cuttings (Genter and Traineau, 1993a), primary biotite content was used as the main indicator for evidencing petrographic variations and hydrothermal alteration types.

Style and intensity of the alteration : Chloritisation of primary biotite is used as an effective index of pervasive alteration. Primary, black colored biotite is partially transformed into a green colored chloritized biotite. Three degrees (weak, moderate and strong) of biotite replacement were defined.

Illitisation of primary biotite and plagioclase is used as an effective index of vein alteration. Biotite is replaced into pale green illite. Primary granite white colored plagioclase is also replaced by green colored illite. In this case, the illitised facies shows a prominent cream colored hue.
As for chloritisation, the intensity of illitisation includes three degrees (weak, moderate and strong). Hematisation developed on primary minerals (biotite, K-feldspar) and into fracture filling gives also evidence of vein alteration.

The distinguo between chloritization and illitisation is difficult from binocular examination because they are both green colored minerals. X-ray diffraction patterns would be useful for a more accurate characterization of these clay minerals. As a consequence, the alteration style deduced from the on site macroscopic examination may be regarded with caution (see annex) and will be checked by X-ray data.

2.3. PETROGRAPHY

We considered as a main assumption that the drilling of the GPK-2 borehole should cross the same granite massive as previously due to its large vertical and lateral extension. We also assumed that possible departures from the standard porphyritic granite facies should be ascribed to texture variations of the granite or vein alteration with associated fracturation.

So, petrographic units defined through the logging of the GPK-2 borehole have been tentatively correlated with rock types identified in the upper part of GPK-1 (Traineau et al, 1991), in the lower part of GPK-1 (Genter and Traineau, 1993a) and in the EPS-1 well (Genter and Traineau, 1992b; Traineau et al., 1992). Correlation was accomplished primarily through comparison of GPK-2 chip samples with representative petrographic facies observed on the EPS-1 core sections. The following petrographic types encountered in GPK-2 between 1410 and 2110 m, listed below will be discussed : (a) standard porphyritic granite, (b) biotite-rich granite, (c) K-feldspar rich porphyritic granite, (d) altered porphyritic granite related to fractured zones and divided into four alteration grades (low, moderate, high and very high).

2.3.1. Standard porphyritic granite

Chip samples contain primary quartz, K-feldspar, plagioclase, biotite and amphibole. This color is dominantly grey to dark. The percentage of biotite grains is roughly estimated around 25 %. This amount does not represent the true content of biotite within the granite because it is probably richer in the chip sample than in the rock penetrated.

Small variations of biotite content are ascribed to slight changes in the granite texture, or to drilling features (variations in grinding at the drill bit, enrichment or impoverishment in the ascending mud column).

Individual grains up to 1 mm in diameter of pink K-feldspar are indicative of the porphyritic texture of the granite. Biotite grains form well-shaped black flakes. They are sometimes partially altered to chlorite with green color. It is the dominant mafic constituent. Hornblende is scarcely observed in the chip samples, probably because more powdered by drill bit than biotite (Glenn et al., 1981). Quartz and plagioclase occur as anhedral grains.

2.3.2. Biotite-rich granite

Chip samples contain primary quartz, K-feldspar, plagioclase, biotite and amphibole.
It is distinguished from standard porphyritic granite by its relatively high biotite content (> 30 %) leading to a darker color. It is interpreted as reflecting textural variations like schlieren or mafic minerals rich granite.

A portion of the biotite is partially replaced by secondary chlorite.

2.3.3. K-feldspar rich porphyritic granite

A distinctive K-feldspar-rich granite was intersected between 1552 and 1566 m. This facies is characterised by abundant pink to orange K-feldspar chips.

2.3.4. Altered porphyritic granite related to fractured zones

The standard porphyritic granite has been more or less altered within and near fractured zones.

The examination of the chip samples leads to determination of four main grades of alteration and inferred fracturation. The determination of these four grades was based on the general trend to the argilization of the samples as previously stated into EPS-1 core sections and GPK-1 cuttings (tab. 1). The most characteristic feature is the development of illite removing primary biotite and plagioclase. Altered granite is typically biotite free and cream-white colored. It contains grains of colorless to pale green illite. Fragments of intermingled hematite and carbonate are sometimes observed. Occurrence of quartz veins with euhedral crystals reflects the highest grade of alteration. No geodic quartz was observed during this geological survey. However, drilling events such as total losses combined to high rate of penetration value are indicator of very high alteration within some intervals of GPK-2 well.

The small size of drill cuttings hinders determination of cataclasites. Therefore, the four grades of alteration probably represent the whole range of different cataclastic facies deduced from EPS-1 cores examination as breccia, microbreccia, argilised wall rock and oriented cataclasites (Genter et Traineau, 1992a; Genter et al., 1992).

Altered porphyritic granite (low grade)

* Biotite in process of illitisation
* Plagioclase non modified

Altered granite (moderate grade)

* Biotite transformed into illite
* Plagioclase non modified

Altered granite (high grade)

* Biotite transformed into illite
* Plagioclase in process of illitisation

Altered granite (very high grade)

* Biotite transformed into illite
* Plagioclase transformed into illite
* Occurrence of geodic quartz vein + (total losses, high ROP)

Table 1 : Key for estimating the vein alteration grade in the altered granite facies observed in cutting samples of the GPK-2 borehole

2.4. LOG DESCRIPTION

The main objective of the on-site chip samples logging was to recognise fractured and altered zones within the Soultz granite massive while drilling was in progress and also to assist the drilling operation. The synthetic petrographic log of GPK-2 (fig.2, annex) includes all the geological data obtained from 1410 to 3880 m depth.

From the well-known petrographic homogeneity of the Soultz granite, it is impractical to give a written account of every lithogical variation metre by metre throughout the granitic body.

No Permian aged sediments were logged although the prognosis anticipated the existence of a limited horizon of Permian sandstones, based on a 10 m-thick clastic rock cored in the close EPS-1 well. The limit between the sediment and the granitic section was deduced from Gamma Ray measurement interpretation and located at 1411 m (Western Atlas log depth reference).

No cuttings were collected below 2110 m due to the occurrence of a main fault which caused total losses during drilling. Therefore, the log description is based on cuttings analysis collected in the upper part of the well (1410 - 2110 m). From the top of the granite to 2110 m, fractured zones alternate with standard granite section. The upper fractured zone is extended from 1430 to 1540 m. Three other fractured and altered zones are located deeper (1610 - 1720 m, 1780 - 1930 m, 1970 - 2110 m).

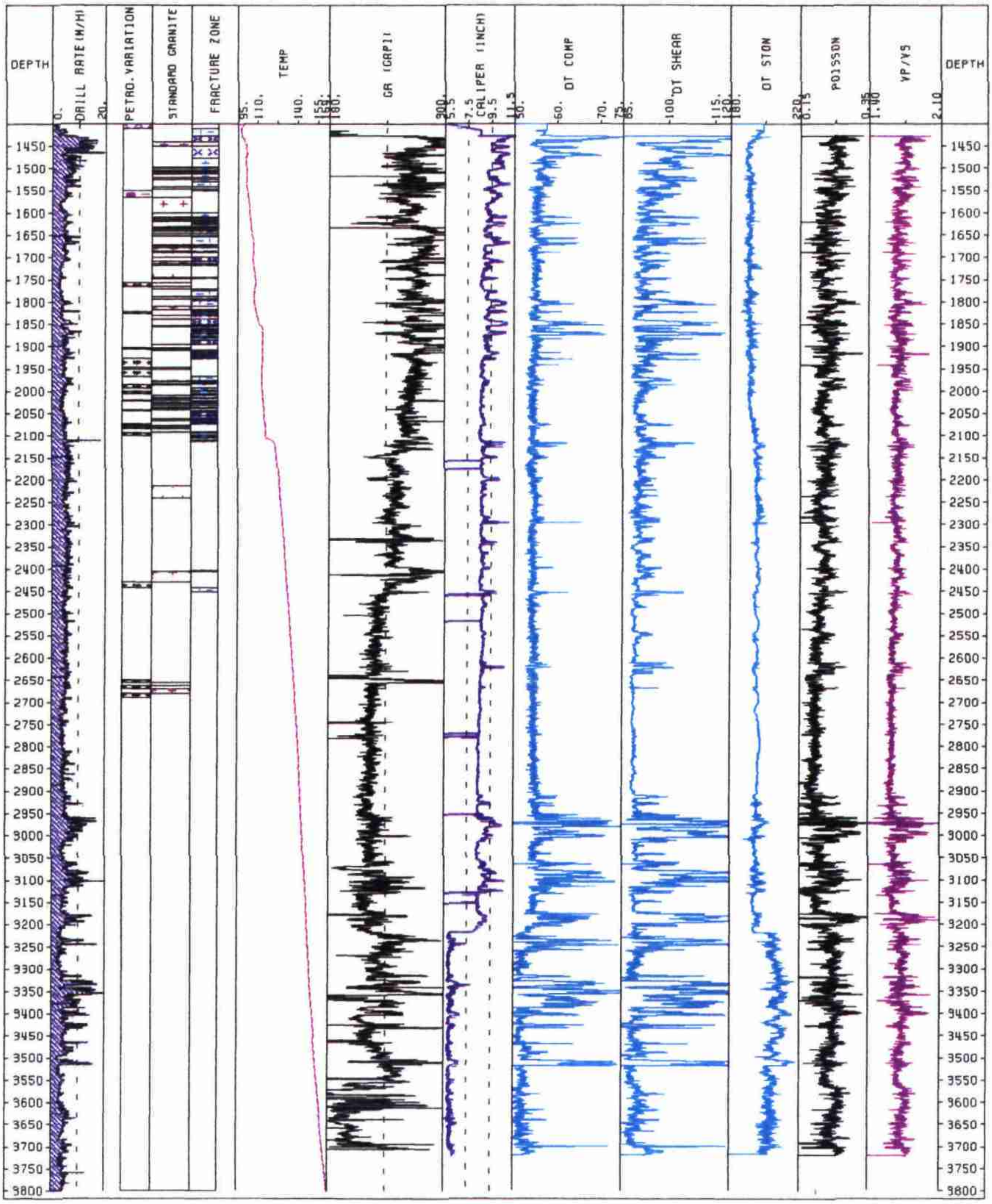


Figure 2 - Synthetic composite log of GPK-2 between 1420-3880m including chip samples logging and conventional well logs data (Western Atlas). Drill rate in meter/hour, three distinctive petrographical types, temperature log (NLfB data), GR (Gamma Ray), Mean Caliper, DT COMP (transit time compressionnal wave in µs/f), DT Shear (transit time shear wave in µs/f), DT STON (transit time Stoneley wave in µs/f), Poisson ratio, VP/VS (P wave/S wave velocity ratio).

Some facies variations occur such as K-feldspar rich granite (1552-1566 m) and biotite rich granite (1757-1766, 1823-1826, 1903-1906, 1926-1947, 1950-1967, 2074-2078, 2081-2085, 2094-2100). The distinguo between biotite rich granite and standard granite is based on the percentage of biotite content in the sample. As biotite content can be influenced by the flow properties of biotite flakes during drilling mud circulations, some of these biotite-rich horizons could be only represent artefacts. Then, the exact limits between these two unaltered facies could be rather artificial. The relative abundance of biotite rich granite sections between 1757 and 2100 m could modified significantly the mechanical response of the rock to drilling process, inducing a softer granite.

The general reddish color of the cutting samples is extended from 1420 down to 1540 m. The first unoxidizing cutting sample, showing fresh biotite and a dark color, occurs at 1542 m. However, it seems that due to the vertical persistence of the reddish color of cutting samples, the fresh granite facies is really penetrated from 1700 m only. Standard granite sections are disrupted by steeply hydrothermally altered and fractured zones. Altered granite is typically biotite free and reddish to orange colored. No geodic quartz was observed in the sample collected in the upper part of the well. At 2110 m, a sharp increasing of ROP values fits rather well with total mud losses.

2.5. INTERPRETATION AND COMPARISON WITH OTHER DEEP SOULTZ WELLS

The entire upper GPK-2 section was drilled within the Soultz granite massive composed of a porphyritic granite (named standard granite on the log). This granite is fairly petrographically homogeneous from the top of the basement to the major fault located at 2110 m, except in some zones of limited extension between 1757 and 2100 m where variations of the percentage of primary minerals (biotite and K-Feldspar) are ascribed to magmatic heterogeneities.

The granite intersected by the closer EPS-1 borehole is a fairly homogeneous porphyritic granite with K-feldspar megacrysts, quartz, plagioclase, biotite, hornblende, and accessory titanite and magnetite (Genter and Traineau, 1992b). Variations in K-feldspar-megacryst (MFK) content are seen throughout the 810 m of cores as MFK-rich granite or MFK cumulate, which rarely exceeds 1 to 2 m in thickness. Complete gradation occurs between these zones and the standard granite. MFK-depleted granite also occurs. Xenoliths up to a decimeter in size are common; they are fine-grained, dark-colored and rich in biotite in GPK-2 well. A cumulative length of 80 metres of biotite rich granite has been observed from drill cuttings analysis between 1757 and 2100m. It could suggested that the granite composition is sligthly different in GPK-2 than in EPS-1 in the same range of depth interval. In GPK-1 well, some rich biotite granite horizons were observed from drill cuttings analysis but deeper (2125-2275, 2985-3030m).

In the cored EPS-1 well, the granite is grey-colored, except in its upper part (1420-1550 m depth) where hematization led to a pronounced reddish color. At a similar range of depth, a general red color of cutting sample is detected within GPK-2 well. This red color could be related to the superimposition of oxidising conditions related to Permian paleo-weathering effects and to hydrothermal alteration controlled by fluid circulations throughout the fracture network.

From a general point of view, the top of the granitic section (EPS-1 and GPK-2) is highly fractured and altered. Basically, fractured and altered zones represent the only significant feature which disrupts the homogeneity of the granite massive (although the occurrences of biotite rich granite are suspected in the upper part of the GPK-2 well). Fractured zones were probably developed during successive tectonic stages which may have affected the massive since its setting.

The examination of chip samples enables to produce a petrographic log of the drilled GPK-2 borehole illustrating the distribution of fractured and altered zones and facies variations within the upper granite section (1420 - 2110 m). The drilling rate values (m/h) are well correlated with the petrography of the granite. There is a clear relationship between high drill rate values and occurrence of altered zones. Values higher than 10 m/h are common for such zones, whereas the standard porphyritic granite or biotite rich granite show a mean drill rate of penetration around 5 m/h only. This close relationship was still observed in the deeper part of the GPK-1 well between 2000 and 3600 m from cuttings analysis (Genter and Traineau, 1993b). ROP values are much higher in GPK-2 than in GPK-1. If we assume that drilling conditions used for GPK-2 are similar to those used for GPK-1, the granite penetrated in GPK-2 could be softer, i.e. richer in biotite content, as well as more fractured than in GPK-1.

3. FIRST EVALUATION OF GEOPHYSICAL WELL LOGGING AND BOREHOLE IMAGERY

3.1. WELL LOG DATA

Conventional well logs (sonic, gamma ray, 6-arms caliper) and borehole imagery (UBI) were performed in GPK-2 by Western Atlas and Schlumberger, with the Maxis-500 data acquisition system, respectively (tab. 2).

In order to compare the various runs of well logs, it was necessary to match their depth with respect to absolute reference point. All the tools were run with the gamma-ray tool in order to correlate all geophysical data each others.

Type	Tool	Parameters	Depth (m)
Sonic	Multipole Acoustic MAC	Slowness P, S, Stoneley	2135 - 3800
	Digital Acoustic DAC	Wave forms, Poisson Ratio	1420 - 2135
Caliper	Diplog - 6 arms	C1, C2, C3 (3 diameters) R1, R2, R3, R4, R5, R6 (6 independent radii) 6 pads - resistivity	1420 - 3800
UBI	Ultrasonic Borehole Imager	Oriented Borehole Imagery Magnetic field	1420 - 3800

Table 2 : List of the geophysical well logs and borehole imagery carried out in the GPK-2 borehole

3.2. LOG RESPONSES

3.2.1. Presentation

Various standard open-hole well logs (caliper, sonic, resistivy and gamma ray logs) were performed in the well in order to determine the main distribution of the petrographic facies in terms of facies variations, standard granite and hydrothermally altered and fractured zones. For a better understanding of the existing fracture network, Ultrasonic Borehole Imager (UBI) was run over the complete section providing fully processed images in real time on the Maxis 500 data acquisition imaging system.

3.2.2. Conventional well loggings

Gamma ray data permit to distinguish three main part within the GPK-2 well (fig.2): (1) from the top of the granite (1420 m) down to 1900 m, in which GR values are very high and strongly variable, (2) from 1900 m down to 2960m, in which Gamma Ray curve shows a slight and regular decreasing trend versus depth as it was already mentioned in the other Soultz wells (Traineau et al, 1991; Genter and Traineau, 1993b), (3) from 2960 m down to the bottom hole logged section (3820 m), in which Gamma ray values slightly increase but are very variable.

Generally, radioactivity is rather stable for unaltered granite and varies strongly for fractured and altered zones. Two different Gamma ray logs were run into GPK-2 and their general response are very similar each others (fig.3).

The caliper data indicate two kinds of different behaviours (fig.4): (1) some values which are close to nominal borehole diameter induced by standard unaltered granite or magmatic heterogeneities, (2) some values which are higher than borehole size and which could be related to the occurrence of cavities induced by hydrothermally altered and fractured granite.

Between 1420 m and 1950 m, mean caliper data are very high and numerous caves occur. Between 1950 to 2900 m, caliper data are very stable except locally within altered and fractured zones. The lower part of the well shows noisy data even in unaltered facies. A lot of cavities also occur in the deeper part which are related to fractured zone occurrences.

3.2.3. Sonic log

The DAC and MAC tools acquire and analyse compressional waves, shear waves and Stoneley waves. The two first waves are sensitive to strong modifications of the mechanical properties. The slowness of both P and S waves are rather stable for standard granite, respectively 55 and 90 µs/f (fig.2). But they show a sharp increasing for fractured and altered zones over 70 and 120 µs/f for P and S waves respectively. From both, GPK-2 can be separated into four main distinctive sections: (1) 1420 - 1950 m, which are characterized by rather high P and S slowness suggesting that the granite is rather altered and fractured, (2) from 1950 to 2960 m, low and stable values for both related to a massive crystalline medium, and (3) from 2960 to 3520 m, very strong anomalies clearly related to fractured zones are present, and (4) from 3520 m to 3820 m, P and S slowness are noisy but very low suggesting than GPK-2 penetrated a massive poorly fractured geological unit. The noise could be related to the borehole roughness which is very high in this section as it was observed from caliper data (fig.4).

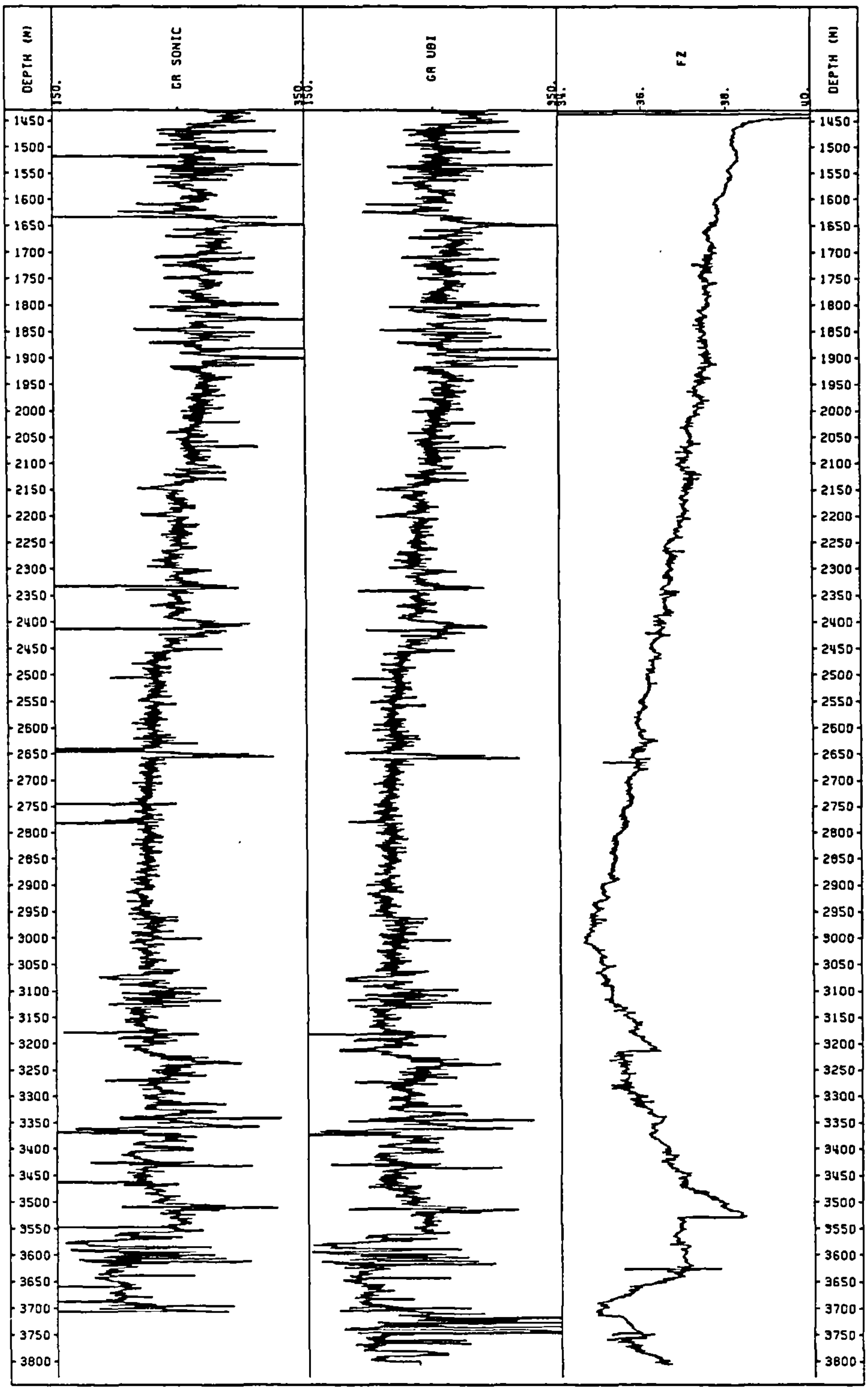


Figure 3 - Comparison between two different Gamma ray measurements (GAPI unit) and vertical magnetic field component in GPK-2 well.

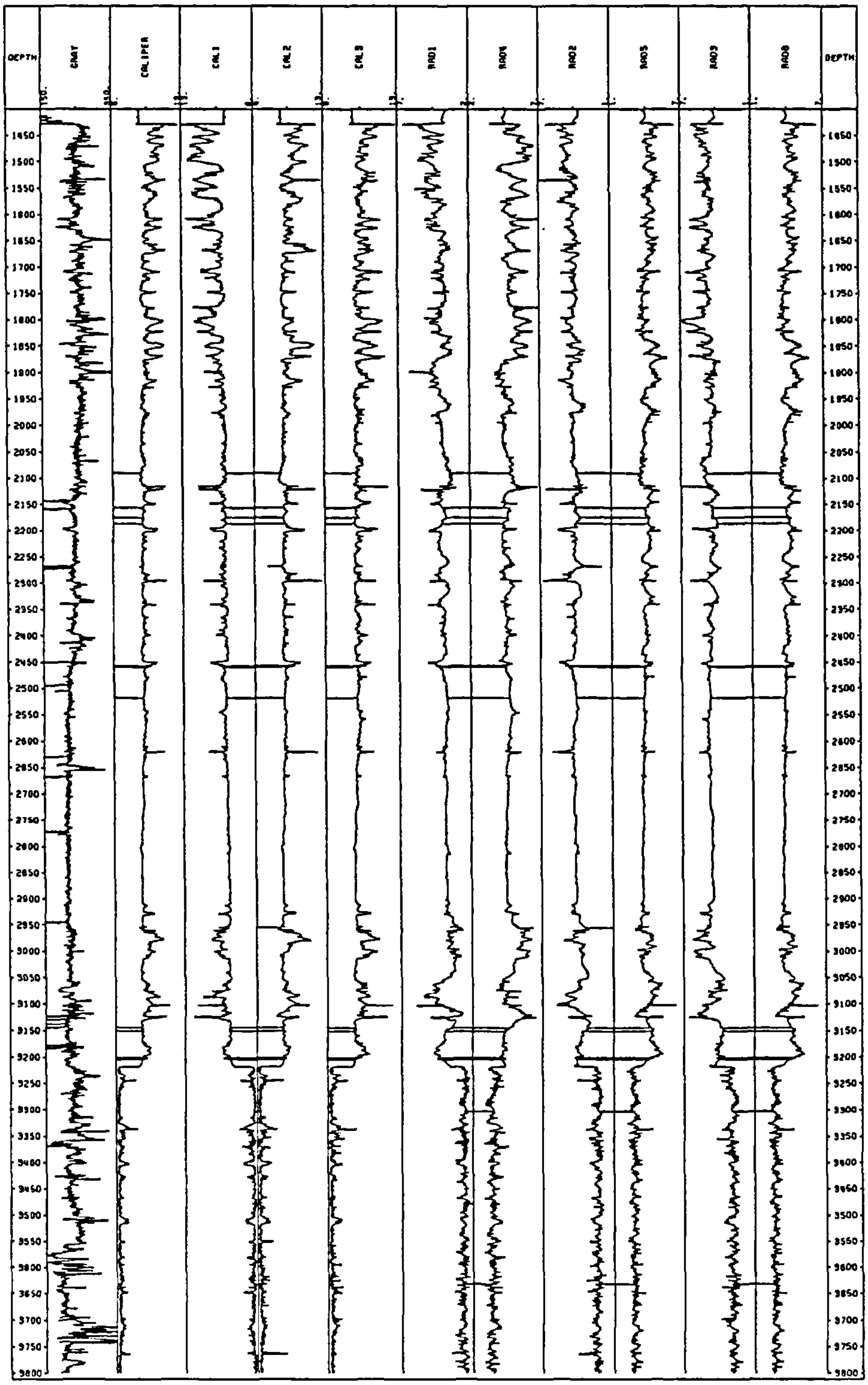


Figure 4 - 6 arms-caliper data in GPK-2 well (Western Atlas data). Gray (Gamma ray in GAPI), Mean Caliper in inch, CAL1, CAL2, CAL3 are the 3 different calipers expressed in inch, RAD1, RAD2, RAD3, RAD4, RAD5, RAD6 are the different radii expressed in inch.

The presence of fractures can be deduced from the Stoneley waveform measurements. In zones containing open fractures, the Stoneley wave data have been seen to change considerably. In GPK-2, the major anomalies visible from Stoneley slowness are located in the deeper part of the well (2980, 3100, 3400, 3500m, see fig.2). They could represent the major fractured zones. Sharp increase in Stoneley wave slowness at 3220 m depth is related to the change in borehole diameter.

3.2.4. Borehole imagery : UBI

The drillhole GPK-2 was logged between 3804 and 1427 m depth by the UBI system. The 9 5/8" casing shoe was detected at 1427 m depth. The change of borehole diameter from 8 1/2" to 6 1/4" occurs at 3222 m depth on the UBI log.

The quality of the UBI reflection is very high in the 8 1/2" hole section. On the opposite, the quality of the acoustic signals in the 6 1/4" sections seems to be sligtly noisy. Nevertheless in both sections, discontinuities can clearly be identified. With these acoustic measurements, the coverage of the borehole wall is up to 100 %. Therefore nearly-vertical fractures can be identified with high accuracy, in contrast to electrical imagery logs.

A magnetic log expressed in gamma units is available in order to evaluate the effect of the magnetic field variations. The vertical component of the magnetic field FZ mimics the Gamma Ray measurements (fig.2). A general decreasing of FZ appears from 1420 m down to 3000 m. Deeper, FZ values are increasing in combination with strong varaitions. In the upper part of the well, the granite seems slightly depleted in magnetic properties, probably due to a depletion in magnetic minerals content (magnetite).

3.3. First evaluation between chip samples and well logs

Due to total mud losses during drilling, the comparison between chip samples and well logs is only effective in the upper part of GPK-2. Due to its structural location at the top of the granite, the section located between 1420 and 1540 m is very different from the lower part. It corresponds to a crystalline unit which is highly influenced by the superimposition of hydrothermal paleo-circulations in fracture network (clay minerals) and paleo-weathering (red color related to haematite). This zone is characterized by high Gamma Ray, ROP, S slowness values and a lot of caves.

From 1540 down to 1900 m depth, GPK-2 has penetrated an alternating of fractured zones and massive granite. Basically, fractured zones are characterized by high Gamma Ray and S slowness values, and occurrence of caves on caliper logs, if compared with a massive granite.

From 1900 to 2110 m, a lot of sections showing a biotite rich content occur which probably induced high Gamma ray content. These sections are cross-cut by major fractured zones as it was evidenced on ROP values and total losses (2110 m).

From 2110 down to 2960 m, radioactivity decreases regularly, and ROP data, calipers and sonic waves velocities are rather low and stable. In this section, GPK-2 has encountered a massive crystalline unit poorly fractured with some minor facies variations (2410m, high Gamma ray content).

From 2960 down to 3510 m, both vertical magnetic field component and Gamma ray measurements are variable. A lot of major fractured zones are visible on caliper data and P and S sonic slownesses (2980, 3100, 3180, 3250, 3350, 3400, 3510 m).

From 3510 down to 3800 m, both radioactivity and magnetic field are variable whereas caliper, ROP, P and S sonic velocities are stable. It suggests that some facies variations occur within a massive granite which is probably poorly fractured.

From 3820 down to 3880 m, no geophysical data are available. A cutting was collected at 3883 m (driller reference) and it shows a signature of highly altered and fractured granite facies.

4. BOREHOLE IMAGERY

4.1. Preliminary fracture analysis from UBI log

Acoustic full-oriented borehole imagery (UBI System of Schlumberger) enables continuous recording of planar discontinuities at the borehole surface and the collection of data about the borehole geometry. Fracture orientations (strike and dip direction) are obtained by the evaluation of the televiewer logs. The planar structures intersecting the borehole wall (and imaged as sinusoids) do not all have the same origin. A typology of planar discontinuities was therefore attempted in order to assess the geometry of the pre-existing fracture network and the role of drilling-induced fractures. The structures were classified into natural fractures, discontinuities with a segmental en-echelon appearance, and nearly-vertical induced fractures. This preliminary fracture analysis is expected to provide knowledge on the natural joint system, the active fault pattern, the alteration zones and the direction of the horizontal major stress component. Fracture orientations were determined as well as their frequency and the predominant orientation of five classes of different apparent apertures.

Natural fractures: these fractures are the most easily detectable on the borehole image. They are characterized by a continuous dark trace with a coherent sinewave (fig.5a).

Segment fractures: they correspond to discontinuous features appearing as half-sinusoidal traces. They occur in groups, which may or may not be spatially associated with natural fractures (fig.5b).

Vertical induced fractures: these structures are characterized by a subvertical dip and cut the borehole wall over several meters length (fig.6). They are well developed through massive granite and are associated with steeply dipping natural fractures. Their extension into the granite seems rather limited and they are interpreted as fractures induced by stress and/or thermal shock during drilling. The strike orientation of such a fracture is though to be parallel to the maximum horizontal stress direction.

About 400 fractures were identified on UBI log in order to determine the basic characteristics of the fracture network. Fractures are not homogeneously distributed but are organized in clusters. High density fracture zones are located at the top of the batholith (1900-2300 m), around 3100 m, and around 3500 m (annex). Other intervals with intermediate fracture density are observed around 1550, 2400-2500, 2600, 2750, 3100, 3250 and 3700-3800 m. The maximum recorded fracture density is 4 per meter at a depth of about 2250 m and 3120 m. Somes occurrences of open fractures are deduced from transit time and amplitude anomalies observed in UBI logs. The two main open fractures are located at 2110m and 3100m.

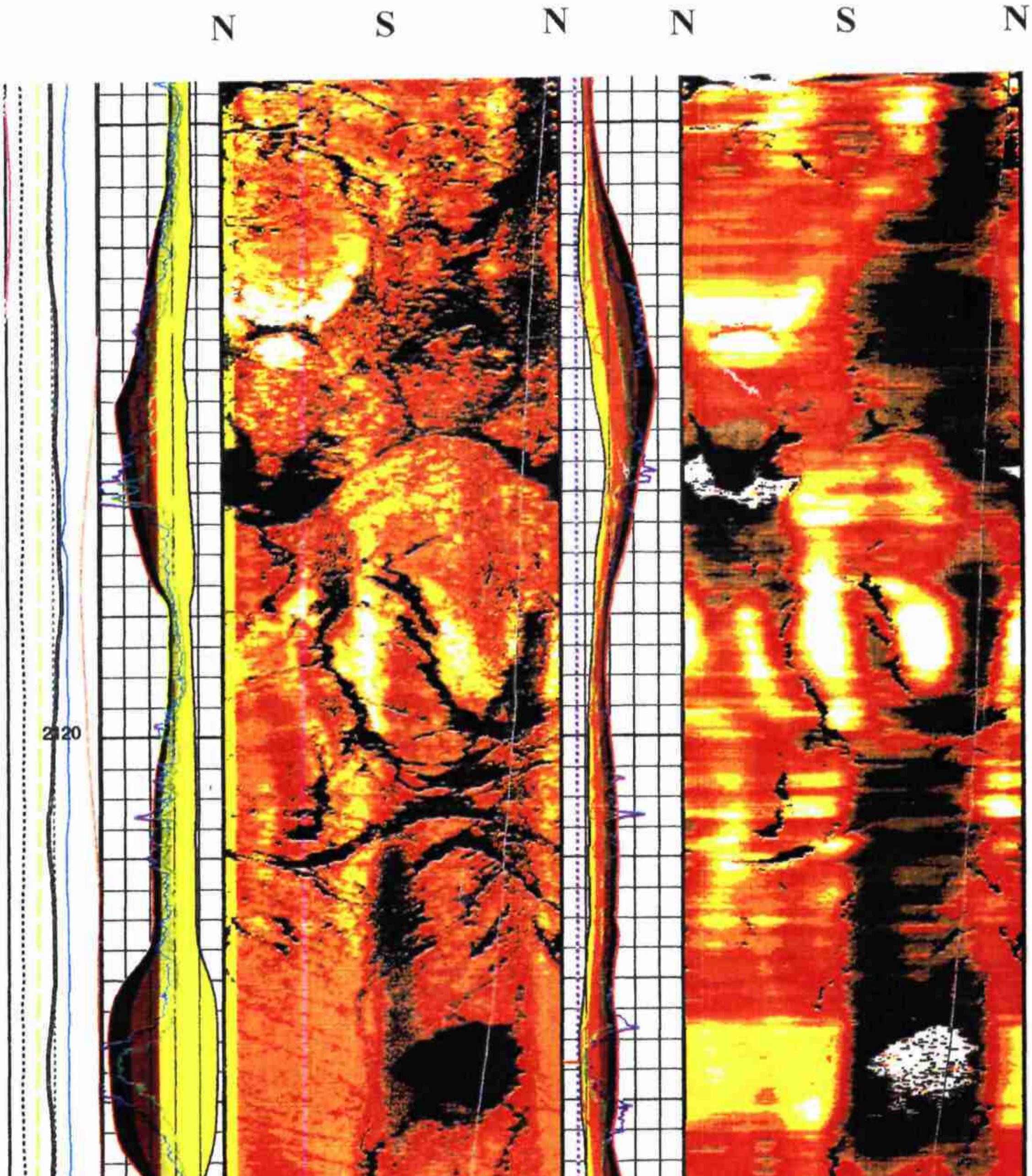


Figure 5a - Example of natural fractures on UBI image (Schlumberger log) in 8 1/2 section of GPK-2 well

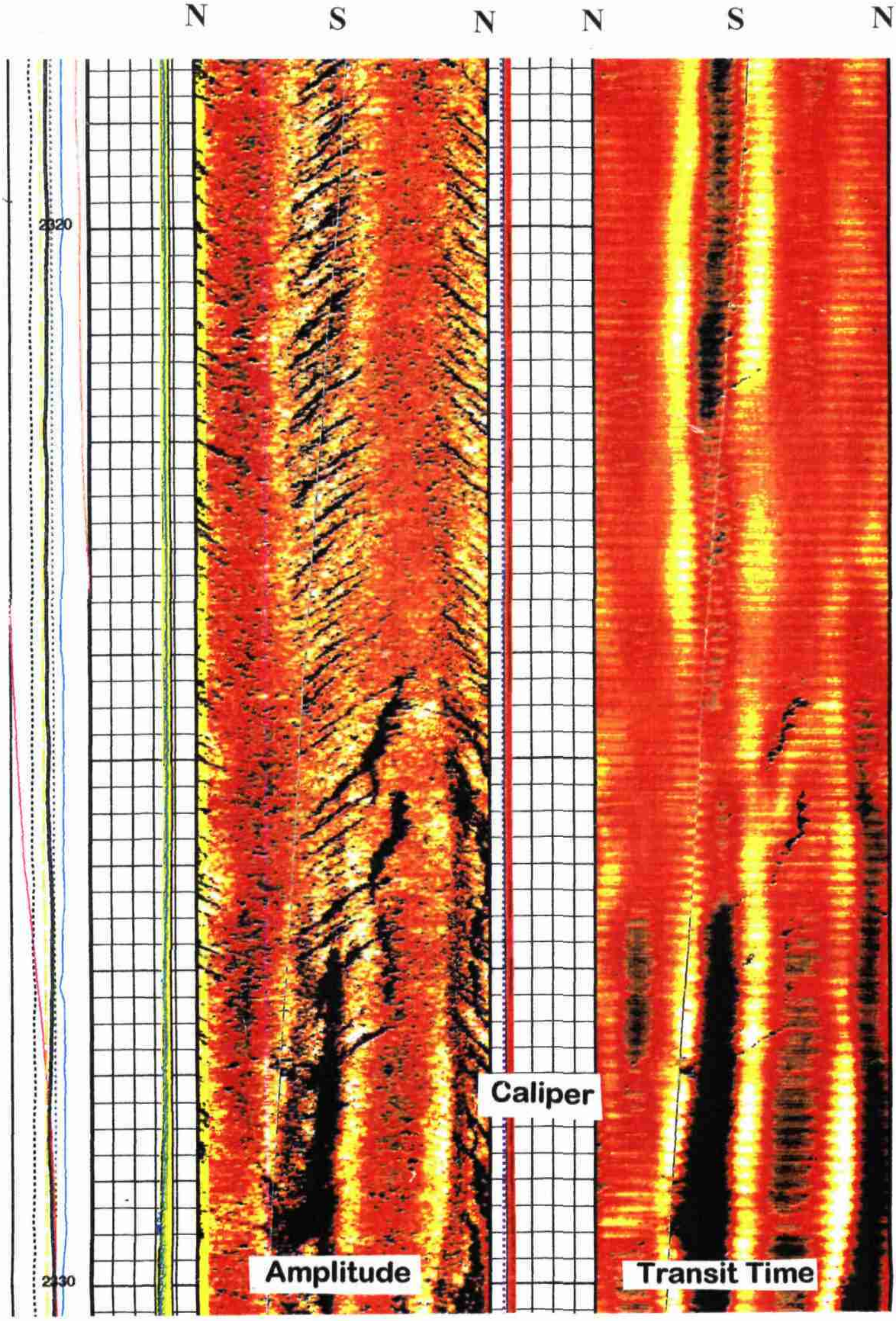


Figure 5b - Example of segmental en-echelon fractures on UBI image (Schlumberger log) in 8 1/2 section of GPK-2 well

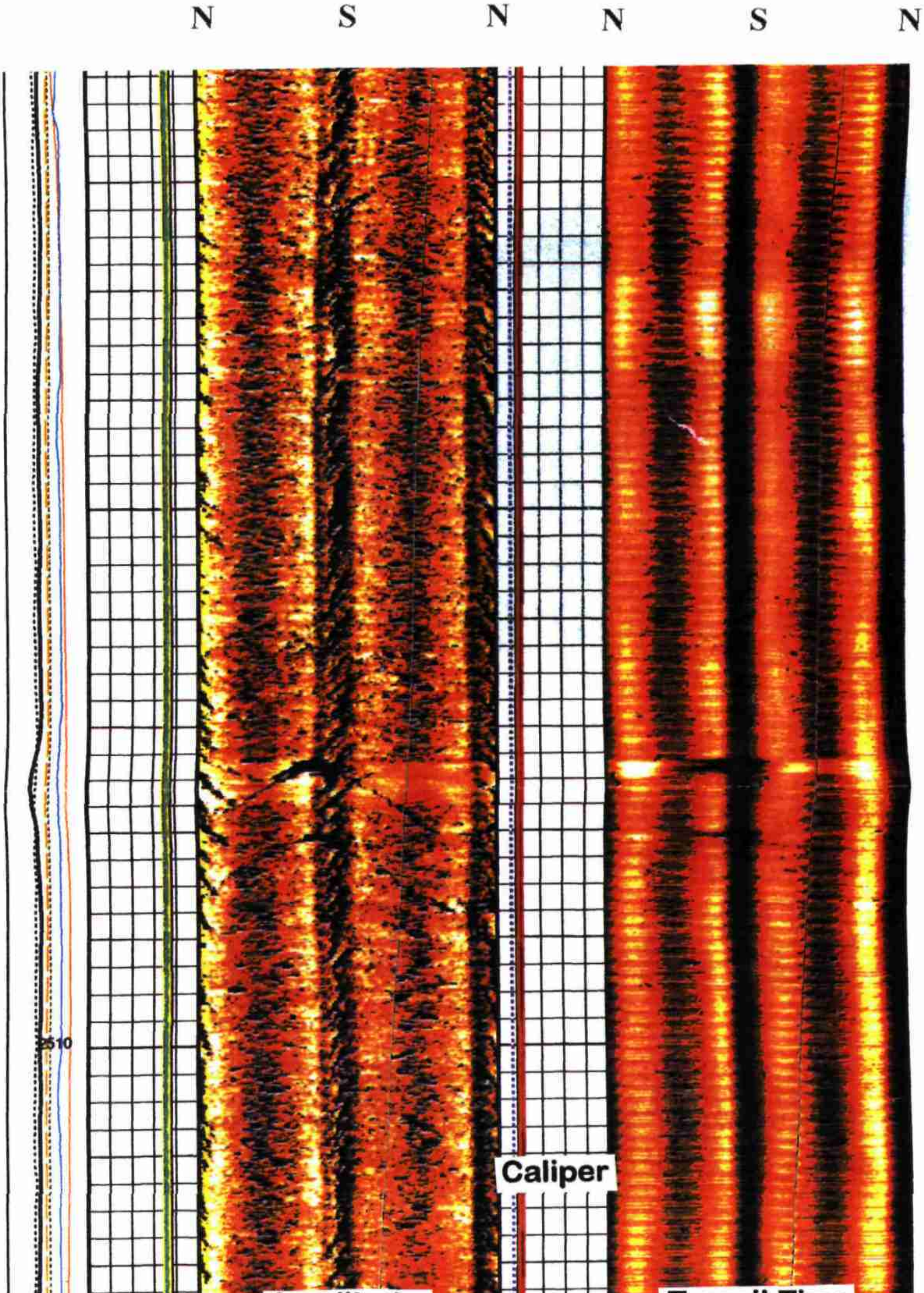


Figure 6 - Example of nearly-vertical fractures visible in transit time and amplitude images in GPK-2 well with the UBI system

4.2. Fracture orientation

4.2.1 Determination of strike direction

As no processed data file was available shortly after the logging programme, the orientation of the discontinuities was evaluated by overlays or with the help of a digitizer on the UBI imagery logs (fig.7). The devices and software package are installed at SWBU. In a first evaluation, only a log at a scale of 1:40 was available. On logs at 1:40 scale, the determination of dip angles less than 55° can be carried out with very poor accuracy in comparison to logs of 1:10 scale (compare amplitude on overlays at a scale of 1:40 and at 1:10 scale on figure 7). Generally, steep dipping discontinuities (60°-85° from horizontal) were observed. On the logs at a scale of 1:40, a total number of 406 clearly visible coherent planar discontinuities were determined.

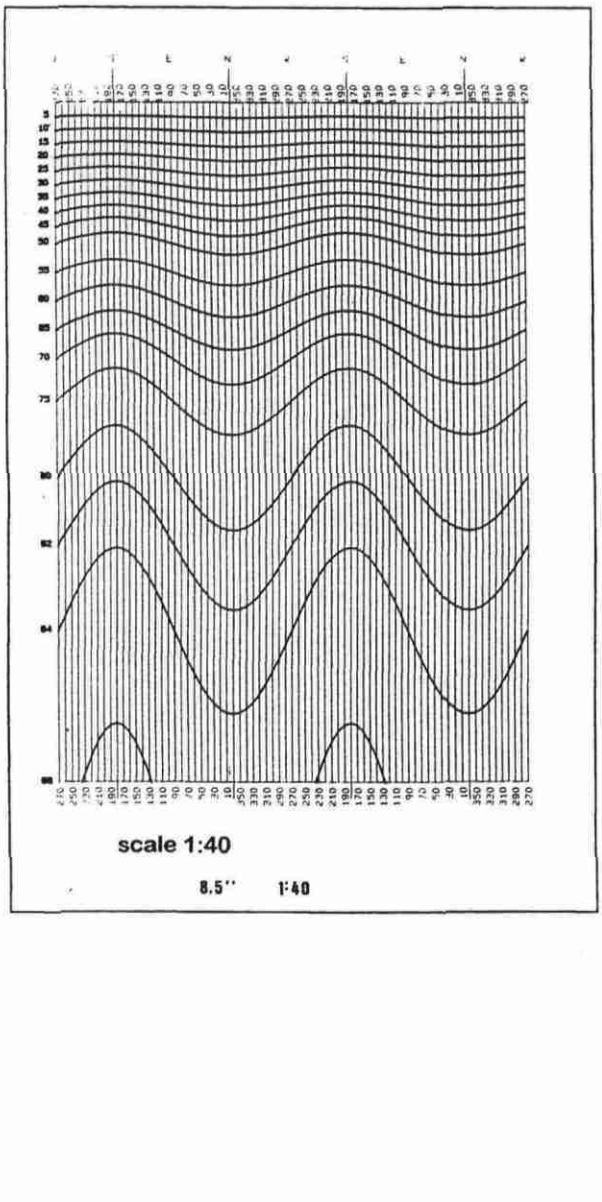
In the granitic section of GPK-2, highly dipping fractures are organized in a principal fracture set striking N005°E (25%) and two minor fracture sets striking N155°E (14%) and N170°E (9%) (fig.8). Sub-horizontal joints exist but they are present only at the top of the granite basement. They are interpreted as relaxation joints due to the uplift of the basement (Genter and Traineau, 1992).

The distribution of strike directions of planar discontinuities versus depth is presented in figure 9. The diagramme shows the preferred orientation of N5°E between 1850-2900 m and 3200-3800 m depth. Submaxima fracture set oriented N155°E is rather missing between 2450 and 2900 m depth.

The orientation of strike direction and frequency per meter of depth as well as the orientation of five classes of apparent apertures are presented in Figure 10. The average number of discontinuities per meter depth were identified on the logs at a scale of 1:40 as 0-1 joints per meter. In the vicinity of the major hydraulically active fault (2118 m) the frequency increases up to 2-3 joints per meter (1980-2075 m and 2109-2290 m depth). The classes of the apparent apertures are presented on figure 10 are listed in Table 3.

Color code	Apparent aperture size and class code
1. black	very small (K) and small size (T) apertures
2. violet	medium size apertures (U), mainly open joints
3. blue	large apertures (V), mainly open faults
4. green	very large apertures (W), open faults

Table 3 : Color and type code for fracture size evaluation used in Figure 10



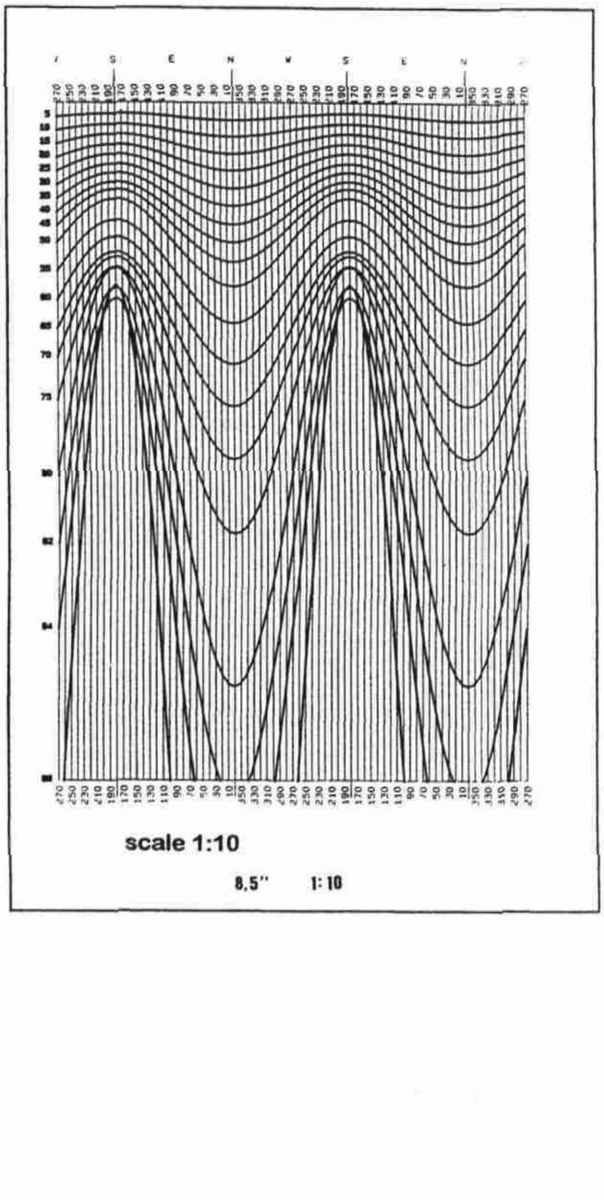


Figure 7 - Overlays used for evaluation of imagery logs at different scales (1:40 and 1:10)

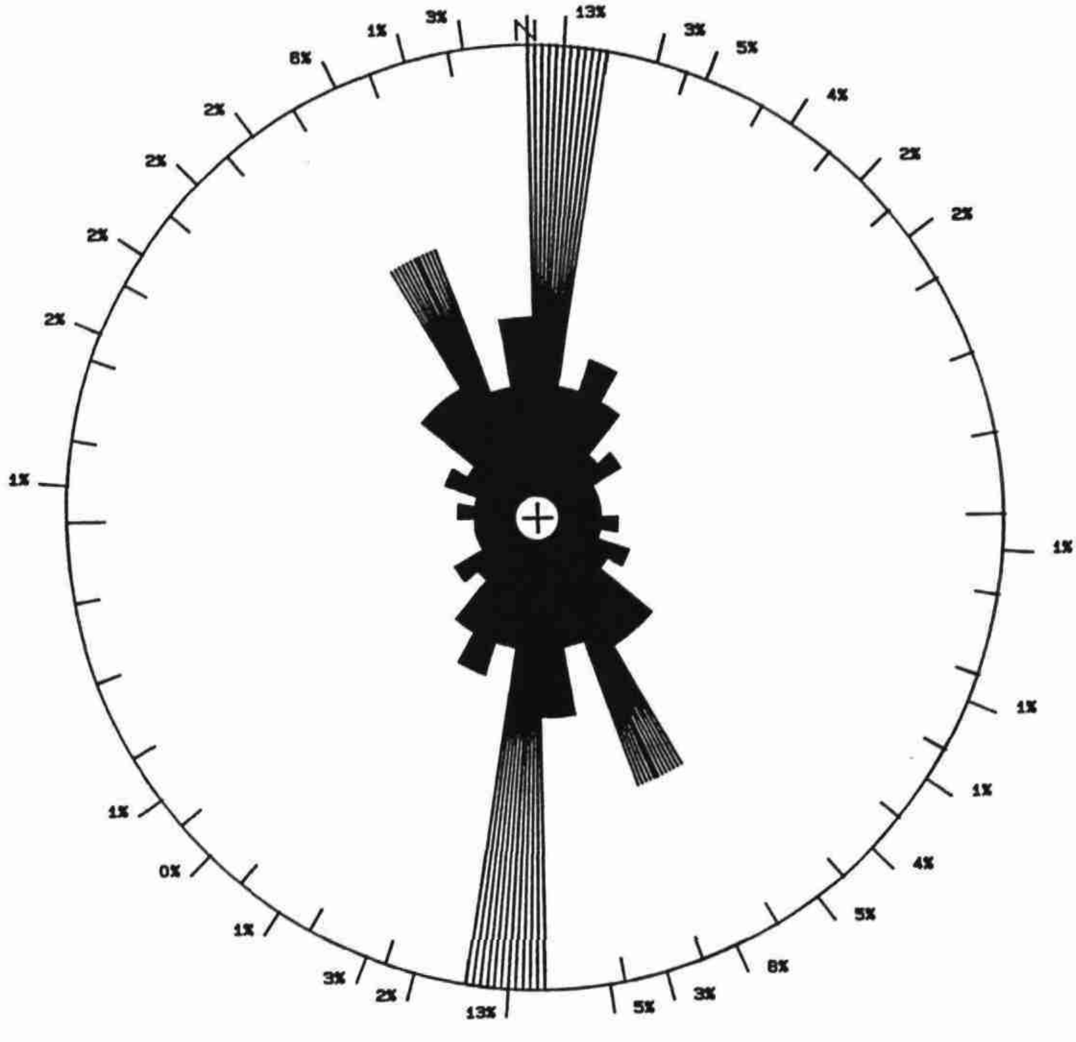


Figure 8 - Rose diagram of striking azimuth of fractures detected with UBI acoustic imagery in the GPK-2 well

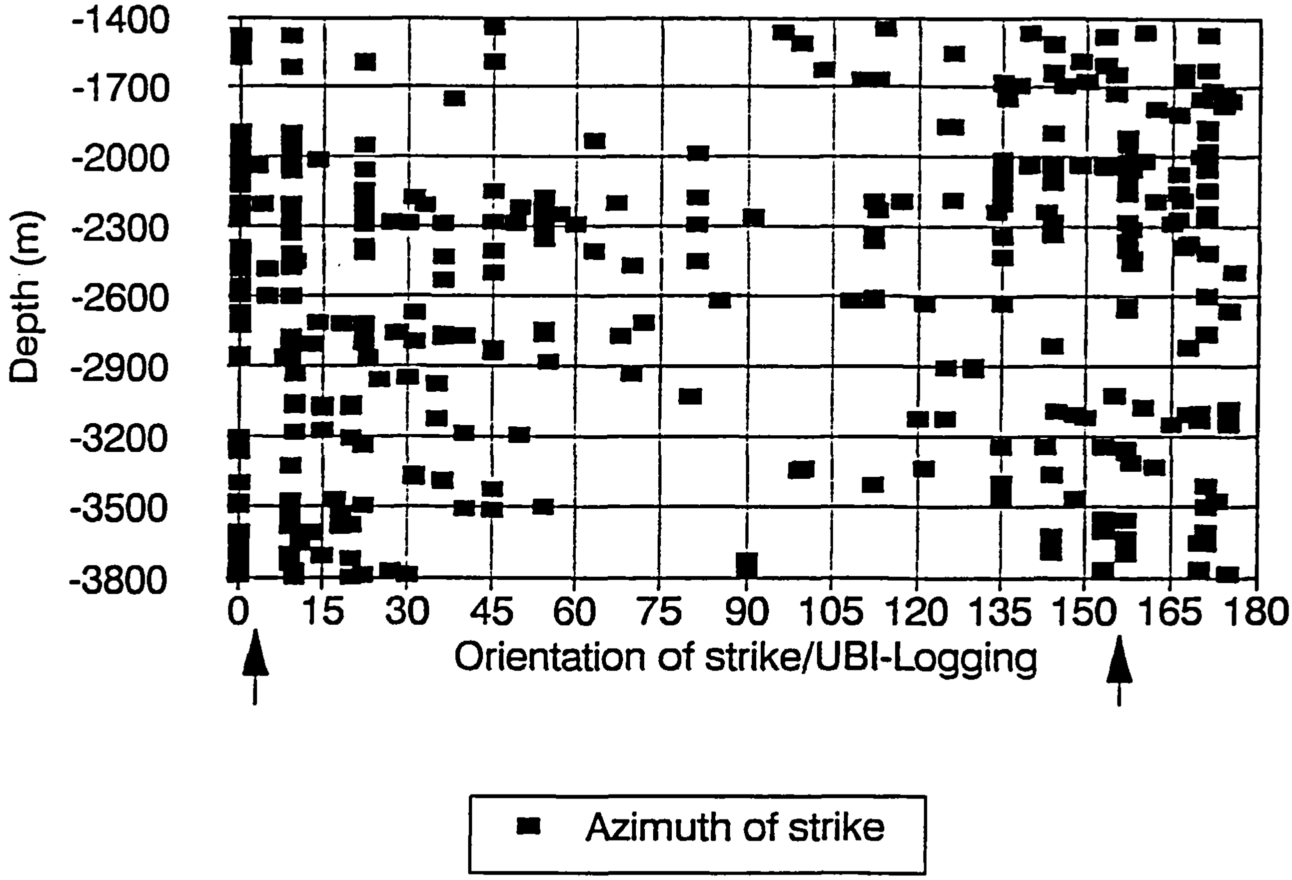


Figure 9 - Distribution of the striking azimuth of fractures versus depth in the GPK-2 well

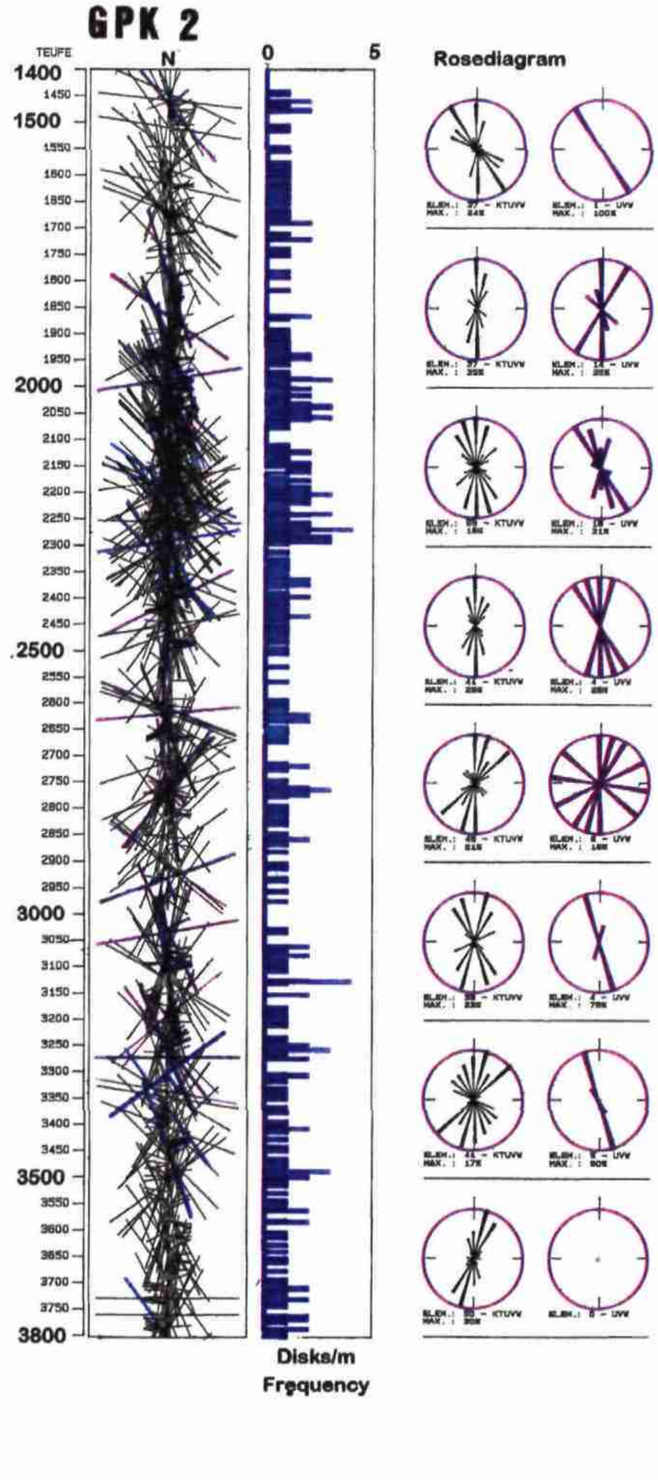


Figure 10 - Striking azimuth versus depth, fracture frequency and rose diagram of striking azimuth of fractures measured in the GPK-2 well

Figure 11 shows the orientation of three combined classes out of the total five classes of apparent apertures. The strike directions of fractues with very small and small size apertures is similar to th orientation of the major fracture sets shown in figure 8. The orientation of fractures with medium size aperture was also determined as N5°E and N155°E but with an additional submaxima at N85°E (fig.11a). In contrast to this, the orientation of large and very large apertures shows a major direction in N145°E with submaxima in N175°E and N75° E (fig.11 b,c). The orientation of a hydraulically open fault system at 2118-2125 m depth is N140-155°E with dips of 75°-85° to the East.

A composite log of the orientation of planar discontinuities and the results of the standard logging programme is shown in annex.

4.2.2 Determination of dip direction

Fractures dipping eastward (N95°E) are mainly encountered between 1900 and 2900 m, and between 3550 and 3700 m depth (fig.12a). Fractures dipping westward (N275°E) are mainly encountered between 1860 and 2600 m, and between 3300 and 3800 m depth. The submaxima of N65°E is mainly located between 2000 and 2400 m (permeable fault zone) and between 3050-3700 m depth. The submaxima of N245°E does not show a preferential concentration with depth. The major direction of dip is N95°E (12.8%) and N275°E (12.6%) with submaxima in N65°E (8.1%) and N245°E (6.7%) (fig.12b).

4.3. Fracture distribution in the deeper part of GPK-2 (3200 - 3800 m, 6 1/4" section)

Due to the casing shoe at 3211 m, the open hole section is between 3211 and 3883 m depth. Figure 13 shows the strike and dip direction in this open hole section. Between 3475 and 3800 m, the main strike direction is N5°E. Additionally, the submaxima of N155°E is shown between 3250 and 3325 m and from 3550 to 3760 m depth. In this deeper section, fracture dipping westward are dominating in two different depth intervals (3250 to 3550 m, and 3700 to 3800 m) and fracture dipping eastward are dominating between 3550 and 3700 m.

4.4. Vertical persistence of fractures

Between 1400 and 3800 m, fracture orientation was plotted in combination with the trajectory of the drill hole in depth sections of 300 m (fig.14). It is shown that over a horizontal distance of more than 100 m and a vertical distance of more than 2350 m, the main striking orientation of fractures is quite stable and nearly N-S.

4.5 Vertical induced fractures and major horizontal stress direction

In nearly vertical well, the detection of vertical fractures is quite easy with the UBI tool which permits a full borehole wall mapping. Evaluation the borehole imagery logs revealed a large number of nearly vertical fractures. Breakouts in a opposite angle of 180° were not detected in GPK-2. This could indicate a normal-faulting stress regime (Rummel and Bäumgartner, 1991; Klee and Rummel, 1993). Between 1430 and 3800 m depth, at least 395 m length contain

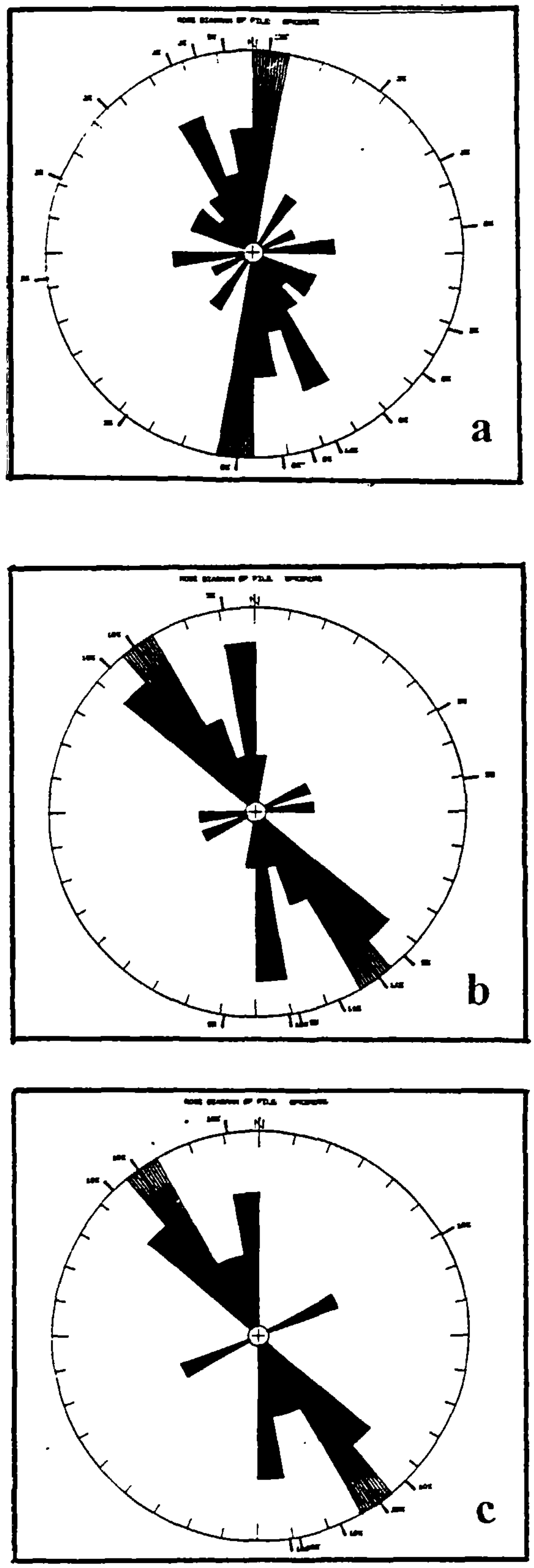


Figure 11 - Rose diagrams of striking azimuth of fractures detected with UBI acoustic imagery in the GPK-2 well for three different categories of fracture size aperture. (a) medium aperture, (b) large and very large aperture, and (c) very large aperture.

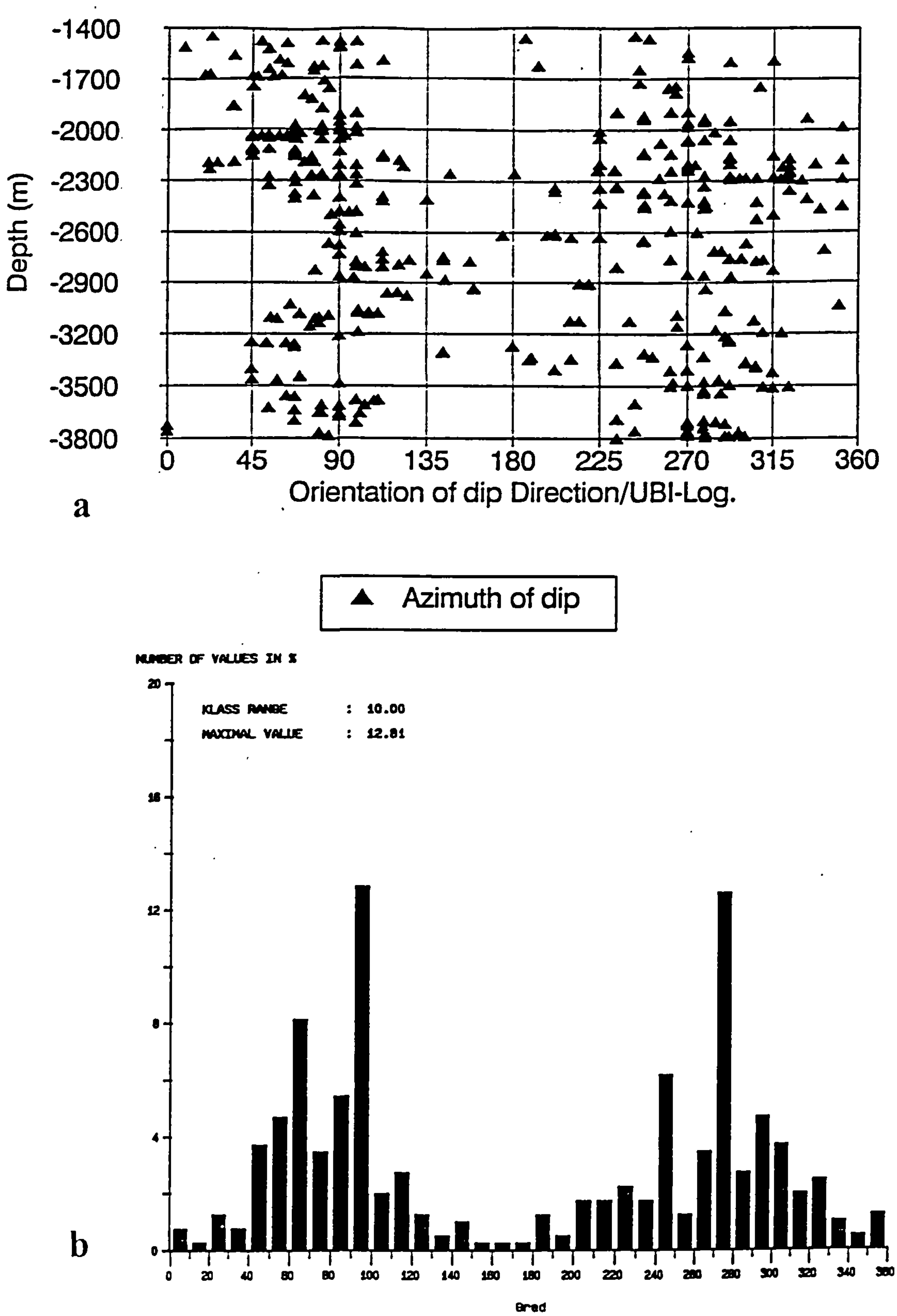
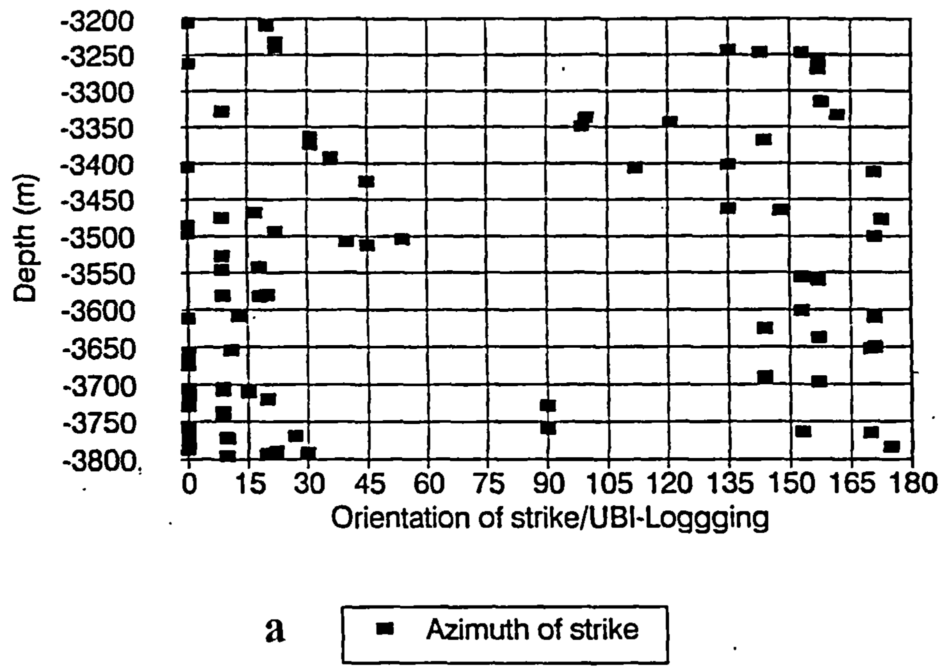


Figure 12 - Distribution of the dip-direction of fractures versus depth in the GPK-2 well (a), and histogram of fracture-dip direction between 0 and 360° for fracture population sampled in the GPK-2 well (b).



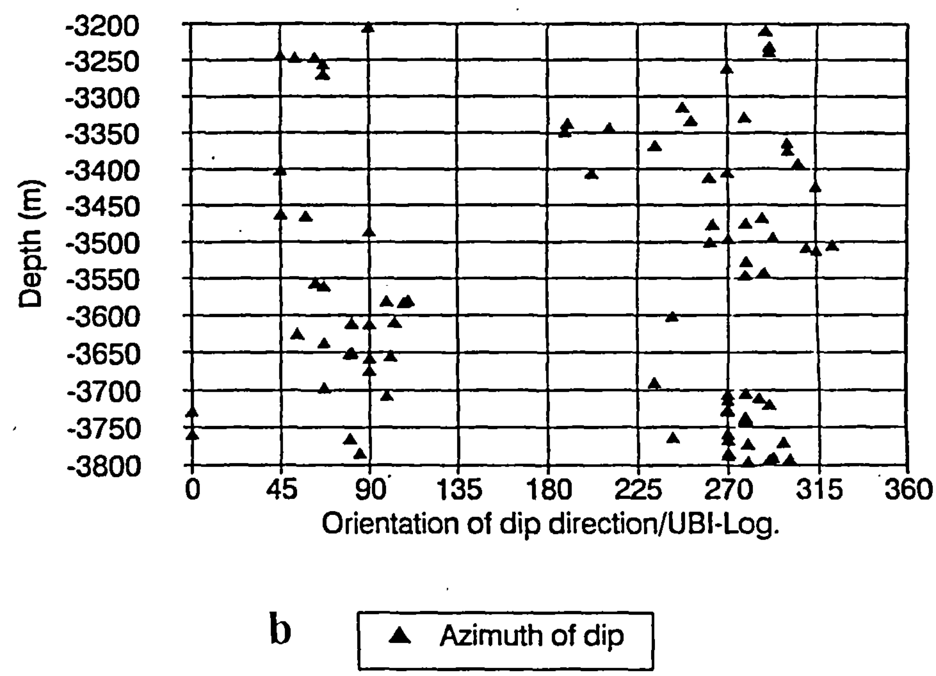


Figure 13 - Fracture distribution between 3200 and 3800 m depth.
(a) azimuth of strike and (b) azimuth of dip.

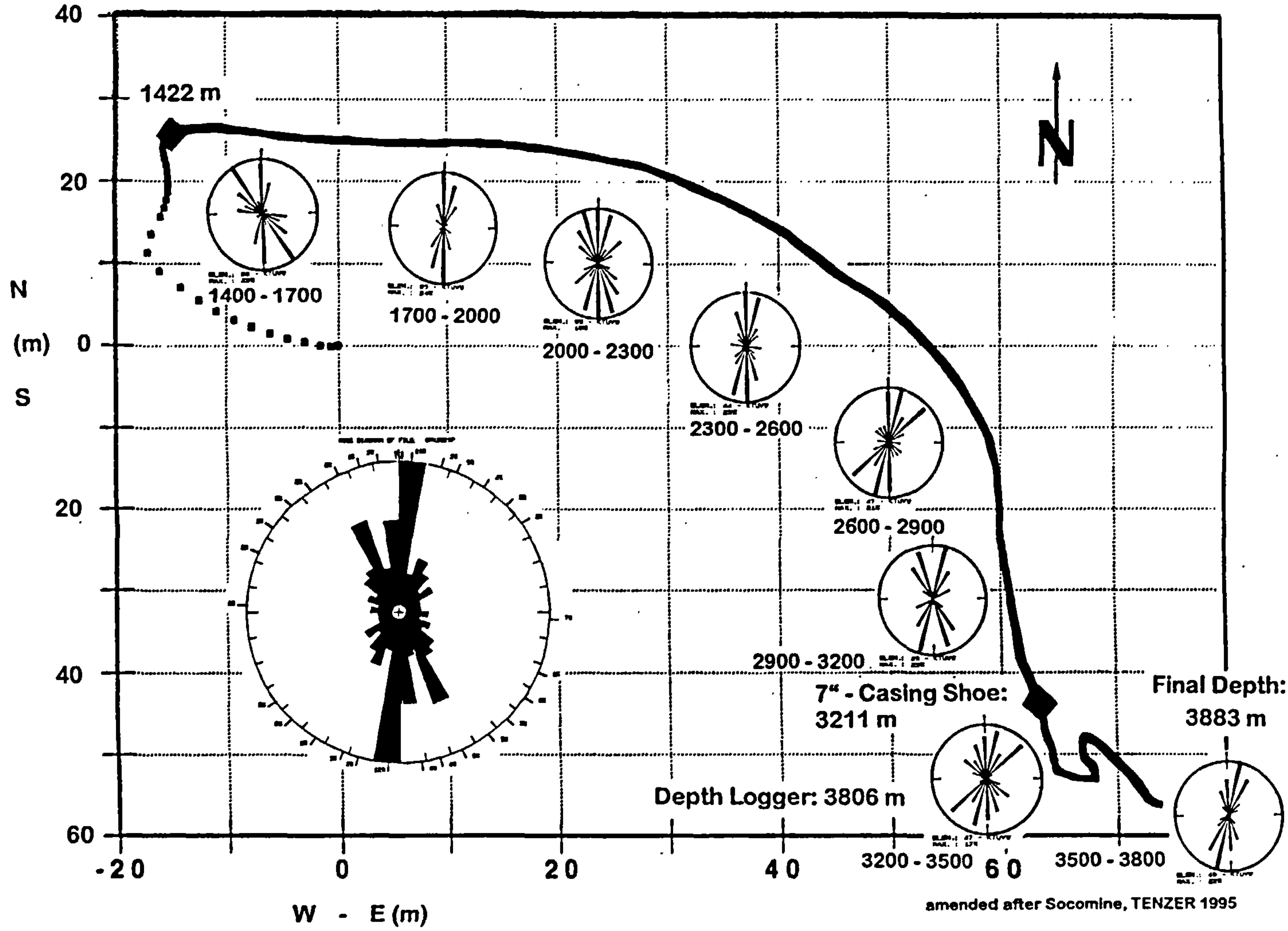


Figure 14 - Distribution of fracture orientation with depth plotted along the trajectory of GPK-2 well (map view).

vertical fractures which bisect the borehole and follow the borehole axis up to a few tens of meters. They are concentrated in the upper part of the well (1600 - 2000 m) and their orientation is mainly N-S (fig.16a). Assuming that the vertical fractures were hydraulically and thermally induced by drilling, they should have formed parallel to the maximum horizontal stress. Then, the orientation of the major horizontal stress direction should be determined as N175°E ± 17° (fig.16b).

4.6 Fracture system in drill holes GPK-2, GPK-1 and EPS-1

From core analyses or borehole imagery interpretation (Dezayes et al., 1995; Genter et al., 1991 and 1995; Tenzer et al., 1991 and 1992), the dominating nearly-vertical fracture system is characterised by two major striking fracture sets which are oriented NNE-SSW (N5°E-N10°E) and NNW-SSE (N170°E). The only slight difference can be found in the EPS-1 well from BHTV analysis with a dominating N30°E striking azimuth, i.e. +25° by comparing to the GPK-2 well (Table 4). Concerning the minor fracture set orientation, the data are more scattered and three main striking azimuth can be deduced, i.e. NE-SW (N50°E), ESE-WNW (N100°E) and NW-SE (N150°-N155°E). The orientation of vertical fractures is in good agreement between GPK-2 and GPK-1 (around N170°E) and in the upper vertical part of the EPS-1 well (1420-1850m).

Drill hole	Main set	SMinor set	Vertical fractures	Method	Réf.
GPK-2	N5°E	1. N155°E 2. N170°E . 3. N15°E	N175°E ± 17°	UBI	this report
GPK-1	N170°E	1. N150°E 2. N120°E 3. N10°E	N169°E ± 11°	BHTV	Tenzer et al. 1991 Tenzer et al. 1992
EPS-1	N30°E	1. N50°E 2. N10°E 3. N180°E 4. N100°E	1. N140-160°E 2. N20-30°E (below 1850 m depth)	BHTV	Tenzer 1995
EPS-1	N10°E N170°E			Core	Genter et al. 1995

Table 4 - Comparison of fracture set striking orientation at Soultz recorded in drill holes GPK-2, GPK-1 and EPS-1.

4.7. Application to HDR technology

As a preliminary conclusion for fracture analysis in GPK-2, the dominating fracture set which is striking N-S, is rather stable with depth in terms of orientation. Deeper fractures are dipping westward (3250-3550m, 3700-3800m) as the main fault located at 3500 m depth in the GPK-1 well (Genter and al., 1995). Such a fractured zone could be hydraulically connected at the scale of the HDR geothermal doublet during the further stimulation experiments.

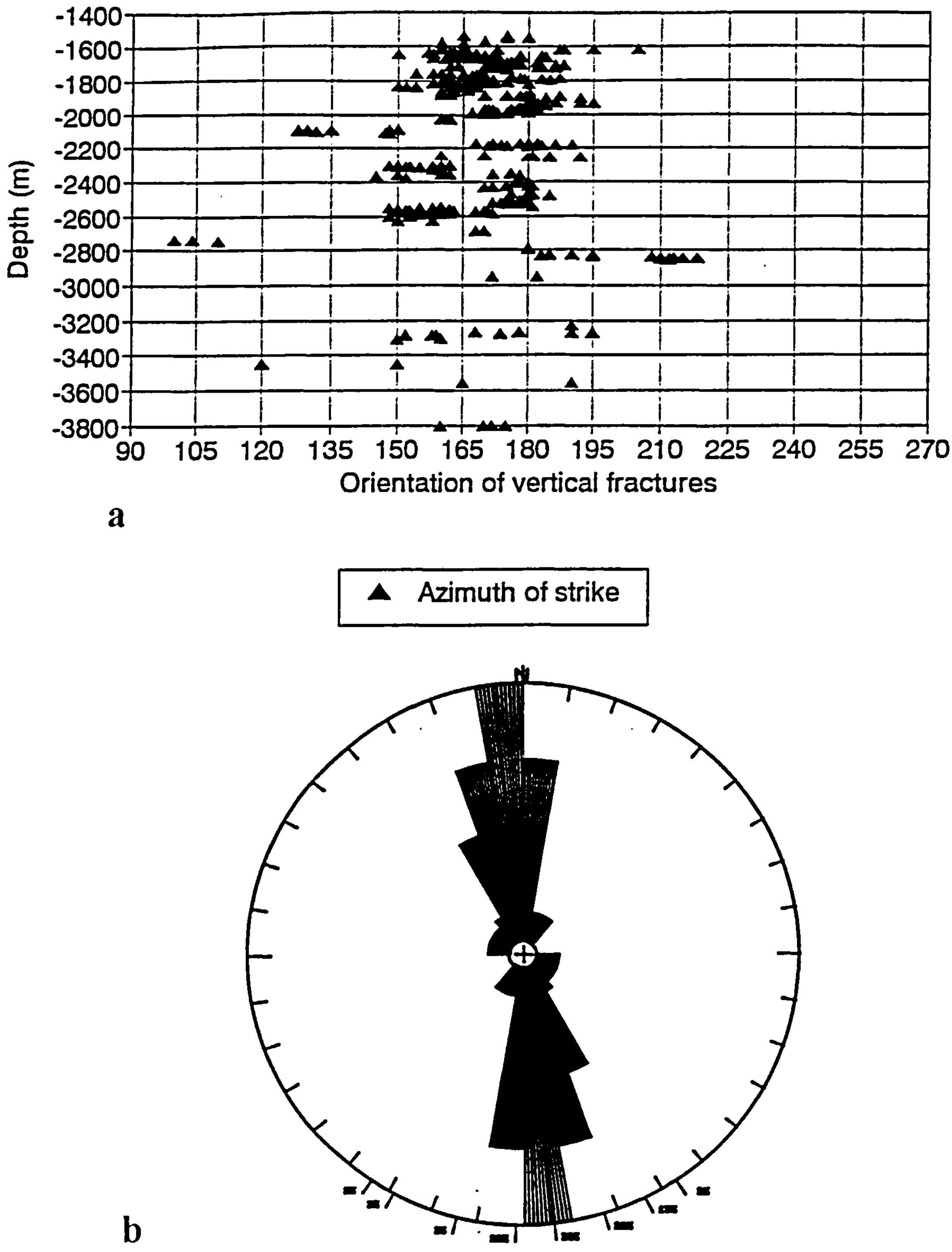


Figure 15 - Distribution of the striking orientation of vertical-induced fractures with depth in the GPK-2 well (a), and rose diagram of their striking azimuth (b).

Between the GPK-1 and GPK-2 wells, the orientation of the maximum horizontal stress is rather stable at the scale of the heat exchanger horizontal axis (N170°E). The geometry of the pre-existing fracture system strikes in a direction nearly parallel to the maximum horizontal stress. In this favorable situation, hydraulic injections will tend both to reactivate natural fractures at low pressures, and to create a geothermal reservoir. These results will aid the further development of Hot Dry Rock technology.

For a better characterisation of the potential hydraulic fractured zone at depth, a combination between borehole imagery technique and flowmeter, and temperature logs should be useful for detected at depth the connected fracture system.

At Soultz, the granite massive is overlain by 1.4 km of sedimentary cover which is mainly composed of well-known regional aquifers (Muschelkalk limestones, Buntsandstein sandstones). For a better understanding of large-scale fluid flow through the multiple fractured granite, natural fracture characterization will be included within a more general development of deep fractured rocks (deep jointed sedimentary rocks, HDR fractured crystalline reservoir).

5. CONCLUSION AND FURTHER DEVELOPMENTS

The evaluation of the geological profile from chip samples examination has been realised on-site during the deepening of HDR GPK-2 borehole between 1420 and 2110 m and providing daily petrographic logs.

This geological characterisation of a deep granite dedicated to HDR experiments, mainly based on previous experience of EPS-1 cores and GPK-1 cuttings, confirms the occurrence of a lot of hydrothermally altered and fractured zones at depth.

Conventional well logs and acoustic borehole imagery (UBI system) were supervised on-site and preliminary compared with the synthetic petrographic log and geological results from closer deep wells (EPS-1, GPK-1).

From a petrographical point of view, fractured and altered zones represent basically the only significant feature which disrupt the relative homogeneity of the granite massive encountered in GPK-2 well. However, some facies variations occur (biotite rich granite) and well-logs responses are not so clear to fully characterize the deep petrography of GPK-2 well in the 6 1/4 section, especially below 3510 m. An additional Gamma ray spectral well-log (U, Th, K content) would be very useful for a better understanding of the deep geology of GPK-2.

From a structural point of view, fracture network geometry is characterized by a principle nearly-vertical N005°E orientation which is similar to those deduced from closer deep Soultz wells. Vertical thermal-induced fractures revealed from acoustic borehole televiewer show a mean striking orientation of N175°E, which mainly corresponds to the striking azimuth of principal horizontal stress as it was still mentioned in closer deep wells.

Combination of standard well logging interpretation, borehole imagery analysis and geological data lead to propose a synthetic composite log of GPK-2 between 1420 and 3800 m.

Acknowledgements

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ANNEX

**Synthetic petrographic log of the GPK-2 borehole from chip samples examination.
Depth: 1400 to 2150 m (Soultz-sous-Forêts, France).**

EXPLANATION OF HEADINGS

Depth: Depth of the borehole from DATALOG.

Drill Rate: Drilling Rate (meter/hour) provided by DATALOG.

Petrographic Variation: Petrographic variations deduced from cuttings (variation of biotite and K-felspar contents).

Standard Granite: Porphyritic granite with K-felspar megacrysts, in accordance with previous data acquired on GPK-1 and EPS-1 core sections.

Fracture zones: Fractured and altered granite facies deduced from cuttings. [Illitisation of biotite and plagioclase is an effective index of hydrothermal alteration related to fractures].

Biotite content: Estimated percentage of biotite from binocular microscopic examination.

Choritisation: Degree of chloritisation of biotite, indicator of pervasive alteration. (0: very weak; 1: weak; 2: moderate; 3: strong).

Illitisation: Degree of illitisation of biotite and plagioclase, indicator of vein alteration (same scale).

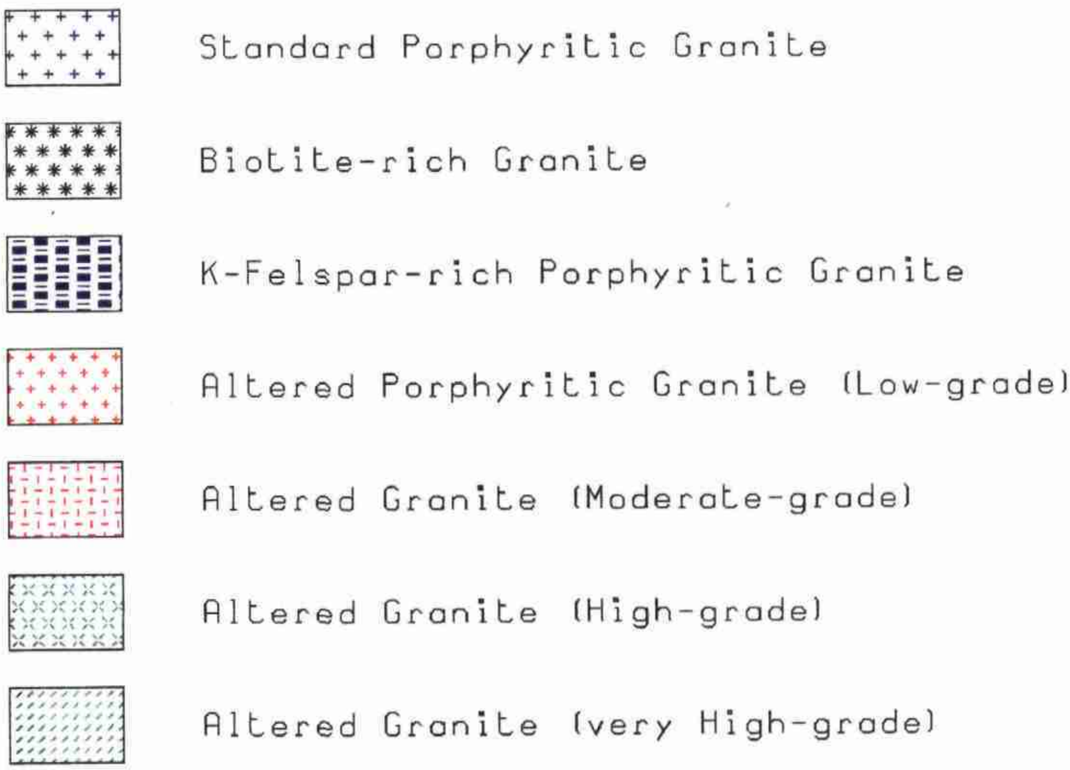
Hematisation: Degree of hematisation of primary minerals, and hematite hydrothermal filling (same scale).

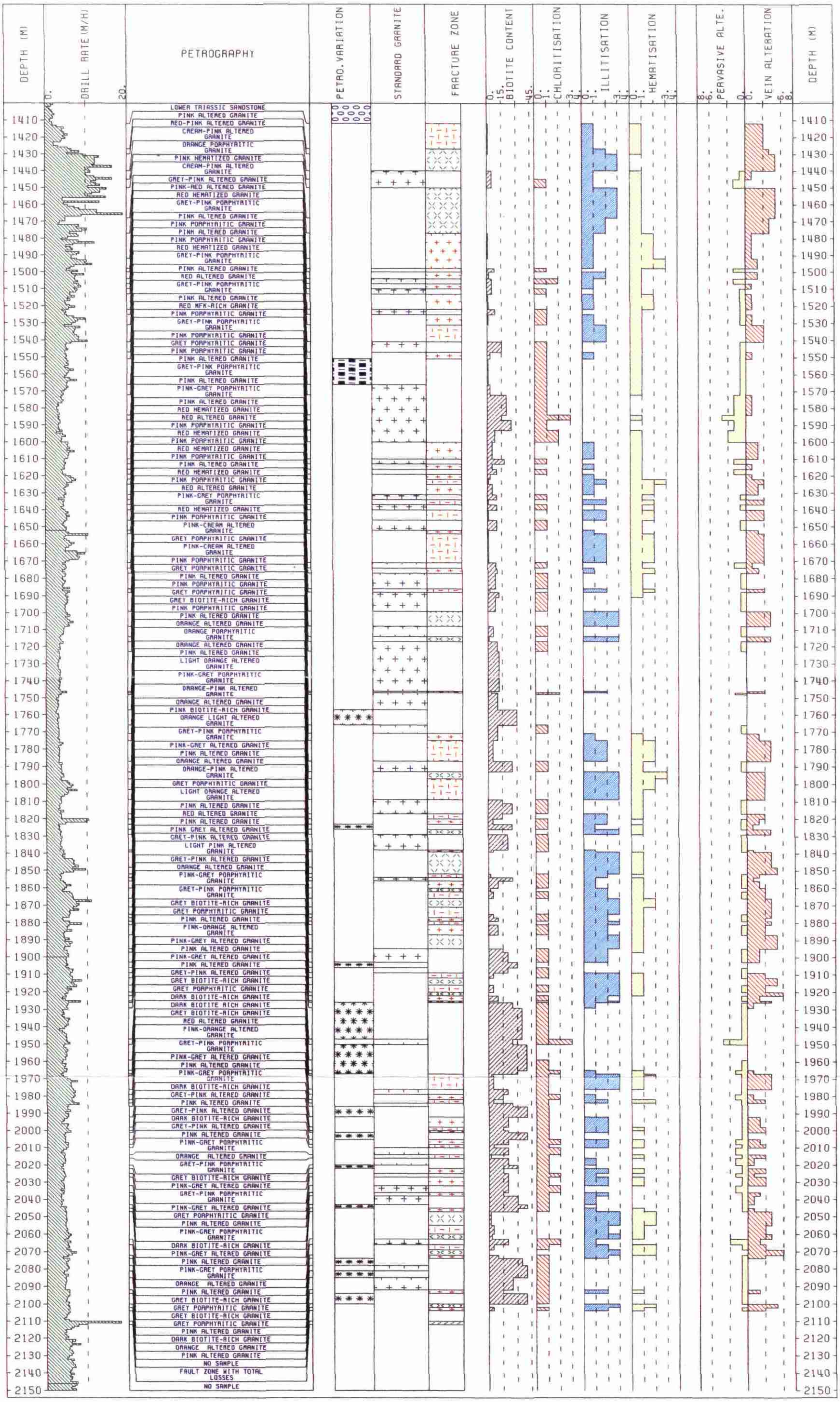
Pervasive alteration: Degree of pervasive alteration within the granite massif, such as chloritisation of biotite. (0: very weak; 2: weak; 4: moderate; 6: strong).

Vein alteration: Degree of vein alteration, restricted to fracture zones and expressed as illitisation in cuttings samples. (0: very weak; 2: weak; 4: moderate; 6: strong).

HDR BOREHOLE GPK-2

Patterns of the petrographic log




DEPTH (M)
DRILL RATE (M/H)
PETROGRAPHY
PETRO. VARIATION
STANDARD GRANITE
FRACTURE ZONE
BIOTITE CONTENT
CHLORITISATION
ILLITISATION
HEMATISATION
PERVASIVE ALTE.
VEIN ALTERATION
DEPTH (M)