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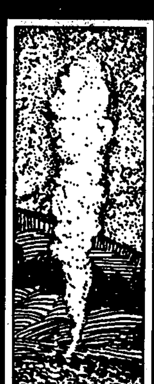

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HYDROTHERMALLY ALTERED AND FRACTURED GRANITE AS AN HDR RESERVOIR IN THE EPS-1 BOREHOLE, ALSACE, FRANCE

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ABSTRACT

As part of the European Hot Dry Rocks Project, a second exploration borehole, EPS-1, has been cored to a depth of 2227 m at Soultz-sous-Forêts (France). The target was a granite beginning at 1417 m depth, overlain by post-Paleozoic sedimentary cover.
Structural analysis and petrographic examination of the 800-m porphyritic granite core, have shown that this rock has undergone several periods of hydrothermal alteration and fracturing. More than 3000 natural structures were recorded, whose distribution pattern shows clusters where low-density fracture zones (less than 1 per meter) alternate with zones of high fracture density (more than 20 per meter).
Vein alteration, ascribed to paleohydrothermal systems, developed within the hydrothermally altered and highly fractured zones, transforming primary biotite and plagioclase into clay minerals. One of these zones at 2.2 km depth produced a hot-water outflow during coring, indicating the existence of a hydrothermal reservoir. Its permeability is provided by the fracture network and by secondary porosity of the granitic matrix resulting from vein alteration.
This dual porosity in the HDR granite reservoir must be taken into account in the design of the heat exchanger, both for modelling the water-rock interactions and for hydraulic testing.

INTRODUCTION

The objective of this European Hot Dry Rock (HDR) geothermal project is to develop an artificial heat exchanger within a granite covered by 1400 m of sedimentary cover. The site is located in the Upper Rhine Graben, on a marked thermal anomaly, giving a temperature of 140°C at 2 km depth in the former borehole GPK-1 drilled in 1987 (Kappelmeyer et al., 1991). Close to it a second exploration borehole, EPS-1, has been fully cored to a depth of 2227 m, providing 810 m of granite core.

Geologic investigations in HDR experiments are mainly concerned with describing the natural joint network that will be used to develop the artificial heat exchanger, and with gaining good understanding of the chemical and mineralogical features of the crystalline medium that will interact with the injected fluids. Continuous coring of the granite borehole EPS-1 provides an exceptional opportunity to achieve these aims.

FRACTURE STUDIES

About 3700 structures were recorded along the 810 m of granite-core sections (Fig. 1, 2). They were classified, according to their origin, into natural brittle fractures and artificial discontinuities induced by stress-release in the core. In this paper, only natural fractures are considered. These were created during the successive tectonic stages that affected this late-Hercynian granite.

Subhorizontal joints

These are mainly natural fractures without any indicator of movement, such as striation. They represent 4.5% of all natural fractures, are concentrated at the top of the granite, and their density decreases regularly with depth until 1700-1800 m (Fig. 2). Their average width is less than 0.5 mm. These joints seem to be related to isostatic unloading of the emerging granite during the Permian, under oxiditing conditions. They are sealed by iron oxides, but quartz, accessory calcite and clay minerals are also present as fillings.

Minor fractures

This is the most abundant type of structure recorded from the core sections, forming 69% of the total number of natural fractures. Their average width is about 0.5 mm, they dip steeply and are sealed by hydrothermal deposits of calcite, chlorite, quartz, sulfides, epidote and accessory hematite. Generally, the wall rocks in the area surrounding these minor fractures are not affected by alteration and show no evidence of movement. They are organized in clusters with zones of high fracture concentration where the maximum fracture density may exceed 20 per metre (Fig. 2).

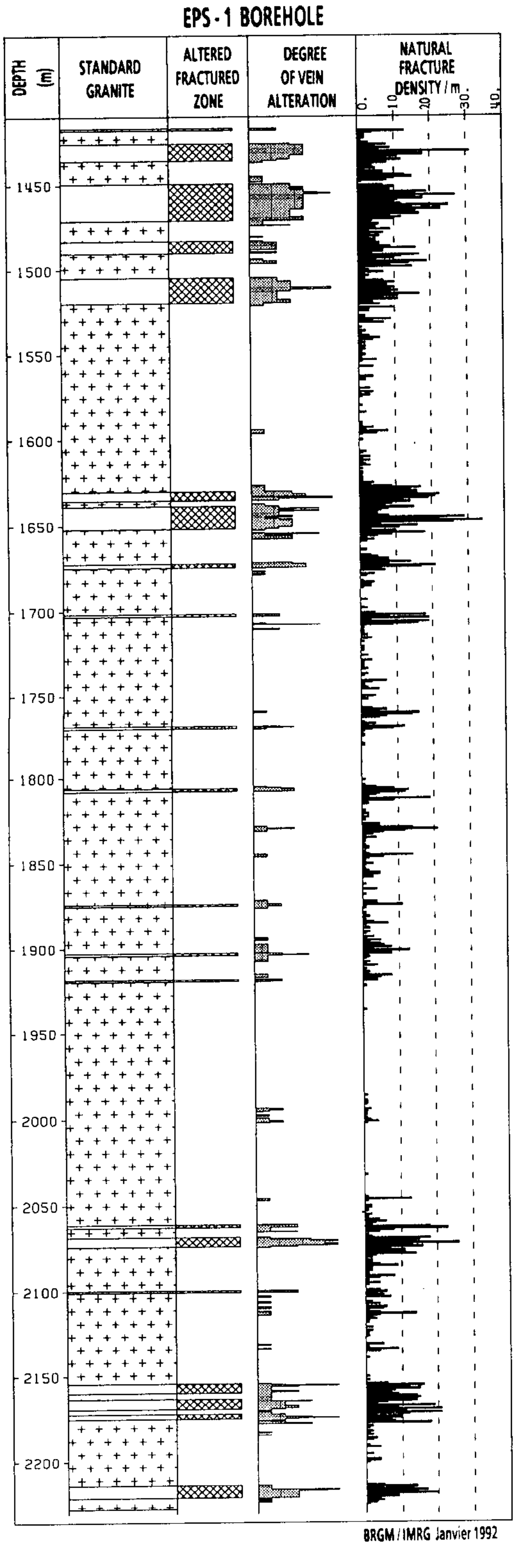

Fig. 1 : Composite petrographic log of borehole EPS-1 showing the relationship between petrography, vein alteration and density of natural fractures

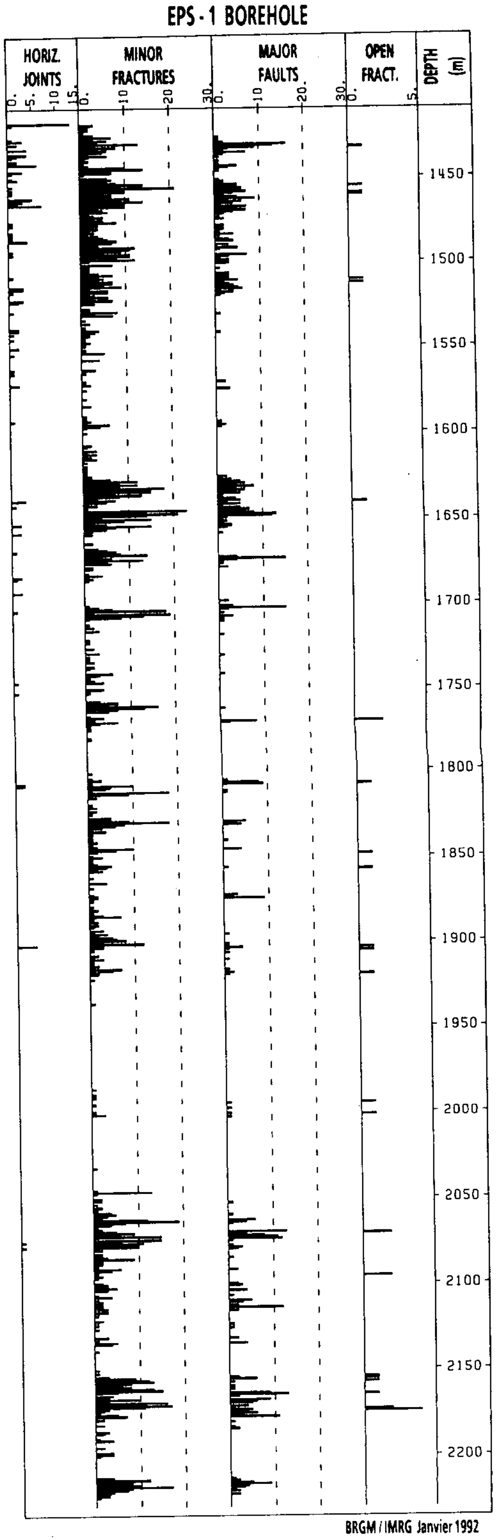

Fig. 2 : Density of different types of natural structures recorded in borehole EPS-1

Major faults
These are natural fractures showing presumed movement indicators and filled with mineral deposits. They represent 25% of the total number of fractures. Normal, reverse and shear faults were all observed. Although they were not formed during the same tectonic episode, these different types of major faults occur in the same depth intervals. Major fractures have an average width of 2.4 mm and typically have been filled by several successive hydrothermal deposits (quartz, clay minerals, carbonates, barite, sulfides). Their density distribution is virtually identical to that of the minor fractures (Fig. 2), so that together they form the main fracture zones in the granite, where they are associated with breccia, cataclastite and protomylonite.

Open fractures
About thirty natural discontinuities can be classified as open fractures, representing only 1% of the natural fractures identified on the core sections. These fractures show a moderate free aperture of 1.5 mm, but they have an average sealed width of 25 mm. The most common mineral fillings are quartz, calcite, clay minerals, barite and hematite. The thickest is a 250 mm-thick quartz-vein at 2175 m depth in the highly fractured zone that produced hot water during coring. The open fractures are mainly located within zones of high fracture density (Fig. 2), and their maximum density was recorded in the outflow zone.

Orientation of fractures
The core sections were not oriented during drilling; instead, we drew an arbitrary reference line. The core pieces in which structural features were present were photocopied using an unrolled photocopy machine which produces flatcore copies. The fracture traces were analysed and recorded by digitizer using BRGM software. Fracture-orientation data were then deduced from the comparison between cores and borehole imagery (Tenzer et al., 1991).

A stereonet of an oriented zone is presented in Fig. 3. The main vertical fracture sets strike N110° with a dip of 75°N and N165° with a dip of 80°E. Several secondary directional fracture sets exist locally. The set striking N165° is related to a paleostress field that probably was reactivated during the Oligocene E-W rifting activity of the Rhine Graben. As emphasized by Genter et al. (1991) in GPK-1 borehole, this structural set is also roughly parallel to the direction of present maximum horizontal stress measured in GPK1 borehole, which is N155° to N176° (Rummel and Baumgärtner, 1991).

PETROGRAPHY OF THE GRANITE AND HYDROTHERMAL ALTERATION

EPS-1 borehole intersected the same granite as GPK-1 borehole about 500 m away. This massif is fairly homogeneous and composed of a porphyritic granite with K-feldspar megacrysts, quartz, plagioclase, biotite, hornblende, and accessory titanite and magnetite.
Two main types of hydrothermal alteration were observed macroscopically in the cores: an early stage of pervasive alteration and subsequent vein alteration, as in borehole GPK-1 (Genter, 1989).

Pervasive alteration
This alteration took place on a large scale within the granite without visible modification of the rock texture. Low-grade transformation of biotite and plagioclase lead to the formation of chlorite, corrensite, calcite, epidote and white mica. In Fig. 1, zones affected by pervasive alteration and zones of massive unaltered granite are both included in the same "standard granite". Some of the joints sealed by calcite, chlorite, sulfides or epidote are related to this early stage of alteration.

Subsequent vein alteration
Vein alteration was closely related to fracturing along "fractured and hydrothermally altered zones" (Fig. 1), which are 1-15 m thick and represent about 10% of the total section. The intense fracturing created cataclastic granite, breccia, microbreccia and protomylonite; the primary texture of the granite may be destroyed in the most strongly fractured rocks, creating a fracture porosity partly sealed by hydrothermal products (quartz, calcite, illite, chlorite, sulfides, barite, hematite). Wall-rock alteration is intense in many places. Pre-existing biotite, hornblende and plagioclase have been partly dissolved and then transformed to dioctahedral mica inducing secondary matrix porosity.

An example of a "fractured and hydrothermally altered zone" observed between 2069 and 2075 m depth is given on Fig. 4, showing the relationship between cataclastic facies, degree of vein alteration (expressed as grade of transformation of primary minerals) and natural fracture density.

As illustrated on Fig. 4, the dip of such zones which concentrate steeply dipping fractures, is expected to be high.

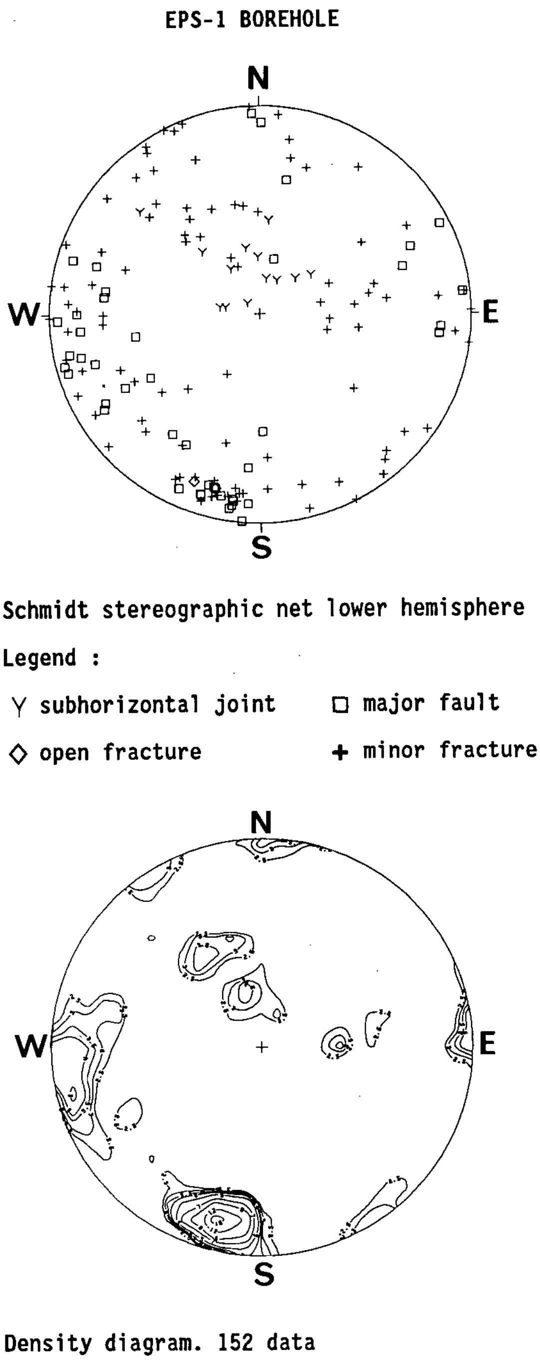

Fig. 3 : Poles of natural fractures from 1507 m to 1530 m depth

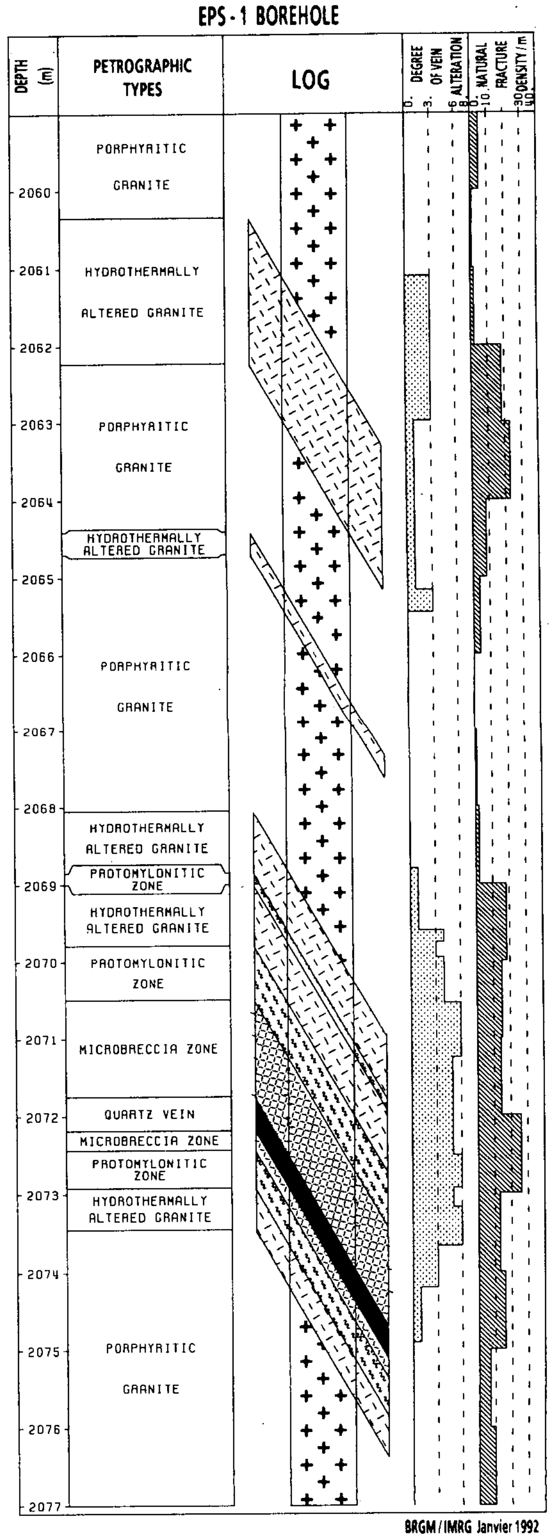

Fig. 4 : Detail of a fractured and hydrothermally altered zone developed within the Soultz granite as revealed by the examination of the EPS-1 core sections

The survey of all altered and fractured zones encountered on the core sections allows to define a general pattern for them, with from the centre to edge:

1) An inner zone of intense fracturing, with the formation of breccia zones and in places protomylonitic textures. Biotite and plagioclase are readily altered, K-feldspar megacrysts are intensely fragmented, and primary texture of the granite disappears. Fractures are commonly sealed by vuggy quartz veins up to 20 cm thick.

2) An intermediate zone where fracturing is less intense, with minor or major fractures, leading to the formation of cataclastic granite. Alteration is uniformly strong, and biotite and plagioclase have been transformed into clay minerals.

3) An outer zone where fracture density is close to zero, but alteration is intense. Biotite and plagioclase are readily transformed into clay minerals. This zone represents the proximal wall rock effect of a major fault zone, and the rock within it has been classified as hydrothermally altered granite.

These altered and fractured zones could be ascribed to paleohydrothermal systems developed within the granite. A hot-water outflow during coring showed that some of these fractured and hydrothermally altered zones are still active and related to a present-day hydrothermal system.
Their permeability seems to be provided both by the fracture network and by secondary porosity in the granite, as a result of vein alteration that partly dissolved pre-existing minerals (biotite, hornblende, plagioclase) and precipitated newly formed white mica.

IMPLICATIONS FOR HDR RESERVOIR DEVELOPMENT

The geologic characteristics of the HDR Soultz site are mainly controlled by its location within the Rhine Graben. Most of the natural fracture sets observed on the cores have been generated or reactivated by an E-W extensional regime during the Oligocene. The present stress field indicates extensional regime typical of a graben system with the present-day maximum horizontal compressional stress field (Sigma H), oriented N155° to N176° (Rummel and Baumgärtner, 1991). The natural subvertical structures, parallel to Sigma H, will have tendency to be open like tension gashes.

From the viewpoint of developing an HDR reservoir at the Soultz site, the granite environment can be classified into three main types: a) "standard granite" with a low natural fracture density, which corresponds to the standard model of the Hot Dry Rock reservoir; b) fractured and hydrothermally altered zones related to paleohydrothermal systems, similar to self-sealed fracture reservoirs observed in natural geothermal systems; and c) fractured and altered zones that are still active and related to a present-day hydrothermal system.
A relation between zones of vein alteration and fracture systems had already been identified in the investigations on cuttings from GPK-1 borehole (Traineau et al., 1991), but the examination of the EPS-1 cores greatly increased our understanding of these zones. They show a general pattern in which fracture density decreases from the centre to the margins. Intensity of vein alteration depends on this structural framework. The permeability of fractured and hydrothermally altered zones can be ascribed to a dual-porosity model, involving the fracture network and the dissolution-precipitation processes of vein alteration. This appears very important for modelling the fluid circulation and water-rock interactions during development of the future HDR reservoir. Furthermore, the orientation of fracture zones obtained from borehole imagery will enable us to predict the extent and geometry of the flow path within the granite.
As the main fracture sets within these zones are roughly parallel to the maximum horizontal stress, they constitute the most attractive target for development of a future Hot Dry Rock reservoir.

ACKNOWLEDGEMENTS
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