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Fractures, hydrothermal alterations and permeability in the Soultz Enhanced Geothermal System

Fractures, altérations hydrothermales et perméabilité dans l'échangeur géothermique de Soultz

Béatrice Ledésert [a,*], Ronan Hebert [a], Albert Genter [b], Danièle Bartier [c], Norbert Clauer [d], Céline Grall [a]

[a] *Géosciences et environnement Cergy, université de Cergy-Pontoise, 5, mail Gay-Lussac, 95031 Cergy-Pontoise cedex, France*
[b] *Groupement européen d'intérêt économique exploitation minière de la chaleur, BP 38, 67250 Kutzenhausen, France*
[c] *Muséum national d'histoires naturelles, UMR 5143, 43, rue Buffon, 75005 Paris, France*
[d] *LHyGeS (Laboratoire d'hydrologie et de géochimie de Strasbourg) (CNRS/UDS), 1, rue Blessig, 67084 Strasbourg, France*

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ABSTRACT

Borehole studies of the Soultz-sous-Forêts granite are dedicated to deep geothermics. The hydraulic properties of the reservoir are mainly controlled by the occurrence of some altered cataclastic shear zones showing a low natural permeability characterized by the occurrence of brines. Those zones show a fracture cluster organisation with sealed fractures of various types (post-filled joints, sheared fractures, veins). The main hydrothermal deposits observed within the permeable zones are geodic quartz, carbonates, illite and more locally sulphides. The fracture wall–rocks are intensely transformed: dissolution of igneous minerals, crystallization of new minerals, porosity and permeability increase. It is important to characterize the newly-formed minerals in order to choose the reagents used to improve the permeability of the exchanger by chemical stimulations. This article represents a synthesis of the studies completed by the authors between 1990 and 2008 on the fracture networks, hydrothermal alterations and mineral crystallizations they induced and data about the flow pathways in the exchanger.

RÉSUMÉ

Le granite de Soultz-sous-Forêts est dédié à la géothermie profonde. Les propriétés hydrauliques du réservoir sont contrôlées par quelques zones broyées altérées montrant une faible perméabilité naturelle (caractérisée par l'écoulement de saumures) et regroupant des fractures de différents types : joints colmatés, fractures cisaillantes, veines. Les principaux dépôts hydrothermaux observés dans ces zones perméables sont des quartz géodiques, des carbonates, de l'illite et plus localement des sulfures. Les épontes des fractures sont intensément modifiées : dissolution des minéraux primaires du granite, développement de minéraux nouveaux, augmentation de la porosité et de la perméabilité. Il est indispensable de caractériser les minéraux néoformés afin d'adapter les réactifs utilisés pour accroître la perméabilité de l'échangeur par stimulations chimiques. Cet article présente une synthèse de travaux réalisés par les auteurs de 1990 à 2008 sur les

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* Corresponding author.
E-mail address: Ledesert@u-cergy.fr (B. Ledésert).

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réseaux de fractures, les altérations hydrothermales et les néoformations minérales engendrées, ainsi que sur les zones perméables de l'échangeur.

1. Introduction

It is planned that the Soultz-sous-Forêts granite will be used as an enhanced geothermal system (EGS). To this end, 5 deep boreholes have been drilled (Fig. 1): 2 were made initially to investigate the nature and structure of the rock (GPK1, ca.3600 m deep and EPS1, ca.2200 m deep) and 3 further for injection/production purposes (GPK2, GPK3, GPK4, around 5000 m deep each). Only EPS1 was entirely cored. GPK1 was partly cored but its deepening from 2000 to 3600 m was performed by destructive drilling. GPK2 to 4 were performed using destructive method.

The deeper Soultz granite is a 2-mica granite, while the rock above is a biotite and hornblende granite (Fig. 2). Both granites are crosscut by numerous fractures in which hydrothermal brines have circulated, creating hydrothermal alteration, and locally still circulate. Hydrothermal alterations are important to the EGS because: (1) they modify the mineralogy, porosity and permeability of the rock; (2) they provide an indication on the nature and temperature of natural fluids that flowed within the rock; and (3) they give an idea about the temporal and spatial scale of fluid circulations. In order to ensure the forced circulation of fluids between the three wells, it is necessary to describe in detail the fracture network and the properties of the granite in terms of permeability, together with porosity and mineral dissolution that can be assessed by petrographical studies.

The present article aims to provide an overview of the fracture network, hydrothermal alterations and permeable zones of the Soultz EGS. This study is mostly based on EPS1 comprising observation of the 800 m long granite cores and analysis of the hydrothermal alterations, fractal and structural analysis of the 3000 fractures and chemical analysis of the organic matter found near the bottom of the borehole. Recent work has also been performed on calcite sealing correlated with fracture network, flow pathways and illite content in the deepest sections of GPK2, GPK3

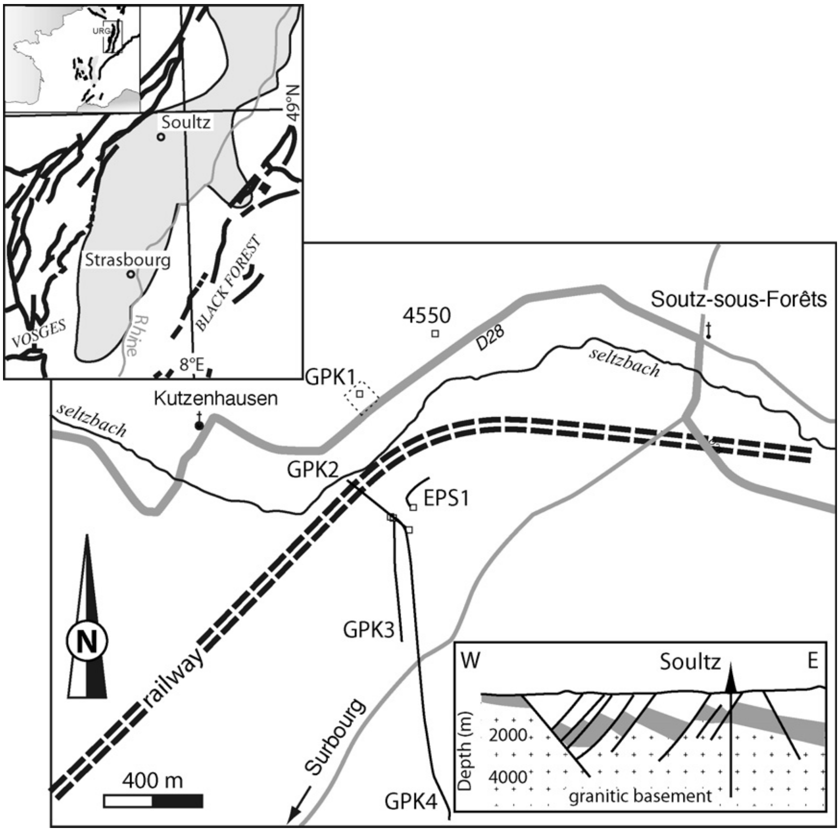

Fig. 1. Location of the Soultz site in the Upper Rhine graben (URG) and location of 6 drill holes in the Soultz area. The trajectories of boreholes EPS1, GPK2, GPK3 and GPK4 are indicated.

Fig. 1. Localisation géographique du site de Soultz dans le graben du Rhin supérieur (URG) et emplacement des six forages. Les trajectoires des forages EPS1, GPK2, GPK3 et GPK4 sont indiquées.

and GPK4, i.e. mainly between 4500 and 5200 m depths where the commercial exchanger is located.

This article is not an extensive review of all of the work performed on the Soultz granite, but it provides a synthesis of the studies made by the authors between 1990 and 2008.

2. Fracture network

The Soultz boreholes have intersected several thousands of pre-existing fractures and only some of them were naturally permeable during drilling operation. After hydraulic stimulation, a limited number of fractures were reactivated along the borehole and showed flow evidence. For example, in GPK1, between 2850 and 3600 m depth, about 6 main fracture zones supported flow (Evans et al., 2005). The geometry of the natural fracture network had to be studied carefully since it participates in the conduction of the injected fluids. It has been studied by the authors mostly in EPS1, since it was possible to characterize it with great accuracy using the cores, and in GPK1 by borehole imagery. In GPK2, GPK3 and GPK4, it has been studied by the authors only in relation with the location of newly-formed calcite as explained later.

2.1. EPS1

In EPS1, about 3000 fractures (Ledésert et al., 1993a; Genter et al., 1995) were identified between 1420 m (bottom of the sedimentary cover/top of the granite body) and 2230 m depth (bottom of the borehole). They are organized in clusters, in some of which brecciated areas were found. These clusters alternate with less fractured or unfractured zones. Fractures are organized in two main sets striking N005°E and N170°E with dips of 70°W and 70°E, respectively. These 2 sets are close to a conjugate fracture pattern of normal faults related to the formation of the Rhine graben (Villemin, 1986; Villemin and Bergerat, 1987). Within these 3000 fractures, less than 30 showed indicators of potential permeability such as geodic veins (Genter et al., 1995). All the other fractures are sealed by newly formed minerals because of hydrothermal alterations that will be described in detail in the next section. The fractures strike in a direction nearly parallel to the maximum horizontal stress favourable to the reactivation of sealed fractures by water injection.

Fractal analysis (Cantor's dust method) is a statistical method that allows the quantification of fracture distribution and a modelisation of fracture occurrence from available data. The data necessary for these calculations are either observed on 2D fracture images or are discrete fracture data obtained by logging in boreholes. It has been applied to the fracture network observed on the cores of EPS1. The fractal dimension of a fracture network is called D. Low D values are characteristic of clustered fractures while high D values are found for separated events. Fractal analysis of the 3000 fractures observed in EPS1 (Ledésert, 1993; Ledésert et al., 1993a) has been performed on the total fracture set, and on sub-sets that were sorted by thickness of newly-formed sealing (< 1 mm, 1 to 9 mm, > 9 mm) assuming the thickest were the most permeable. Only 97 large veins (thick sealing > 9 mm) were encountered. Fractal analysis shows that these large veins are clustered in zones all along the borehole, at about 1500 m, 1650 m and mostly between 2150 and 2170 m depths in a highly fractured and altered zone. Petrographic observation of both these sealings and alteration halos surrounding the large veins shows that they behave as major drains (details in "hydrothermal alterations" and "permeable zones" sections). Fractal analysis also provides a good tool for the prediction of fracture occurrence at depth. It shows that the probability of finding fractures never reaches 0 and that the probability is higher for clustered fractures such as the large drains described previously. In addition, fractal analysis was performed on a 3-D natural analogous system (block of granite from La Peyratte, Deux-Sèvres, France, sawn into parallel plates). It showed that large fractures characterized by a wide altered halo on both of their sides are the most efficient for fluid conduction, even though they are poorly interconnected (Ledésert et al., 1993b).

2.2. GPK1

GPK1 is located 500 m away from EPS1 (Figs. 1 and 2). The deepening of GPK1 from 2000 to 3600 m showed a clear relationship between the drilling rate and the physical properties of the granite (Genter et al., 1995). High drilling rates (6 m/h) indicated fractured zones with hydrothermal alteration, while the drilling rate fell to 3 m/h in unfractured and fresh granite. However, being destructive, the drilling provided only an indirect view of the fracture network by observation and analysis of rock chips (cuttings) and borehole imagery (Formation Microscanner Imager, FMI). FMI mostly allowed identification of the upper and lower limits of the altered and fractured areas, but seldom the individual fractures within these zones (Genter et al., 1995). Nine hundred and ninety-four fractures were recorded between 1960 and 3570 m in depth from FMI image interpretation (Genter et al., 1995). Among these 994 fractures, only 23 fractures were classified as having a large apparent electrical conductivity, which may indicate principal potential permeable pathways within the granite. The record of 994 fractures in GPK1 is significantly lower than the 3000 fractures observed on the 800 m long cores of EPS1. This difference is due to the indirect recording of fractures in GPK1, while the fractures were directly observed and measured on the EPS1 cores. However, the density of natural fractures imaged with borehole televiewer (BTHV) in EPS1 shows the same range as the records obtained by FMI in GPK1 (Genter et al., 1995).

2.3. GPK2, GPK3, GPK4

GPK2, GPK3 and GPK4 form the power system in which GPK3 is used for injection of fluids, while GPK2 and GPK4 are dedicated to production. Therefore, it is very important to make sure that the three wells are hydraulically connected. We did not study the fracture network in these 3 wells but we collected data from the literature for the interpretation of the analysis of mineral sealings (see hydrothermal alterations section).

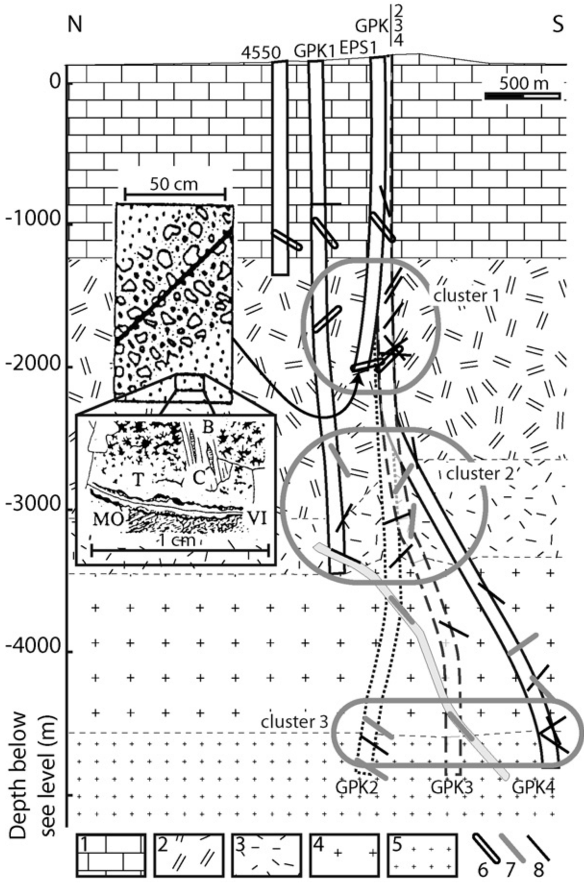

Fig. 2. Cross-section of the Soultz geothermal system showing 6 boreholes (modified after Genter and Dezayes, 2008): 4550 (oil drill hole); EPS1 entirely cored for scientific purpose; GPK 2 to 4 (geothermal exchanger, drilled in destructive conditions); GPK1 (scientific drill hole, destructive conditions, few core pieces). Small figure on the left shows a hydrothermalised zone developed on both sides of a fracture. Biotite (B) is altered and contains carbonate lenses (C). Plagioclased is replaced by tosudite (T) impregnated with organic matter (MO) lately transported by fluids circulating in a vein in which illite has precipitated (VI). Description of facies: 1 – sedimentary cover, 2 – standard porphyritic biotite-hornblende granite, 3 – standard granite with fractures and vein alteration, 4 – biotite-hornblende-rich granite becoming standard granite with depth, 5 – two-mica and biotite-rich granite, 6 – major fracture zone with massive mud loss showing a permeability during drilling, before injection, 7 – fractures with altered halo, showing more than 20% of fluid loss during stimulations, 8 – fractures with less than 20% of fluid loss during stimulations. Figure modified after Genter and Dezayes (2008), petrographic facies from Hooijkaas et al. (2006).

Fig. 2. Coupe des 6 forages du système géothermique (modifiée d'après Genter et Dezayes, 2008) : 4550 (forage de pétrolier) ; EPS1 entièrement carotté à des fins scientifiques ; GPK 2 à 4 (échangeur géothermique foré dans des conditions destructives) ; GPK1 (forage scientifique destructif et partiellement carotté). L'encart de gauche montre une zone hydrothermalisée développée de part et d'autres d'une fracture. La biotite (B) est altérée et contient des lentilles de carbonate (C). Le plagioclase est remplacé par de la tosudite (T) imprégnée de matière organique (MO) tardivement repoussée par les fluides ayant circulé dans une veine où a précipité de l'illite (VI). Description des faciès : 1 – couverture sédimentaire, 2 – granite porphyrique standard à biotite-hornblende, 3 – granite standard avec des fractures et veines d'altération, 4 – granite riche en biotite et hornblende devenant granite standard avec la profondeur, 5 – granite à deux micas riche en biotite, 6 – zone de fracture majeure caractérisée par une perte massive de boue et présentant une perméabilité lors du forage avant l'injection, 7 – fracture avec halo d'altération montrant plus de 20 % de perte de fluide lors des stimulations, 8 – fracture avec moins de 20 % de perte de fluide lors des stimulations. Figure modifiée d'après Genter et Dezayes (2008), faciès pétrographique d'après Hooijkaas et al. (2006).

In the lower reservoir (4.5 to 5 km depth) where the forced circulation is performed, the dominant orientation of fractures is north–south striking, with fractures dipping to the west or to the east (Genter et al., 1999; Valley, 2007). Dip angles are generally higher than 50°. Other fractures are subvertical and strike NW–SE. These results agree with studies made on the dataset of the shallow reservoir (Genter et al., 1995; Genter and Traineau, 1996; Dezayes et al., 2004; Valley, 2007). As a consequence, provided the results of fractal analysis of fracture distribution and thorough study of the fracture network are considered meaningful, it can be concluded that the fracture network in the shallow reservoir is representative of the whole network within the EGS.

East-dipping fracture zones dominate in the upper part of the basement, while west-dipping structures dominate in the lower reservoir (Dezayes et al., 2004). Recent studies (Jung et al., 1995; Genter et al., 1997; Evans, 2000; Sausse, 2002; Evans et al., 2005; Sausse et al., 2006) conclude that only a limited number of fractured zones contribute to fluid flow, as already shown by Ledésert et al. (1993a, 1993b).

3. Hydrothermal alterations

Two major kinds of alteration are encountered in the Soultz granite (Genter, 1989; Ledésert, 1993, 2000; Ledésert et al., 1996, 1999). In order of appearance, they are:

(1) a propylitic alteration, which occurred at the end of the crystallisation of the granite body. This weak alteration is characterized by the partial replacement of biotite and hornblende by chlorite, that of plagioclase by illite, and by newly formed epidote and hydrogarnet within the rock (Genter, 1989; Ledésert, 1993; Ledésert et al., 1996, 1999). This alteration is of little interest to the EGS, since it hardly modifies the mineralogy and porosity of the rock;

(2) a vein alteration found along fractures. It has been created by the interaction between the rock and natural fluids that flowed within the fracture network and sometimes are still flowing (Pauwels et al., 1993). Genter et al. (1995) have shown that the width of alteration zones on both sides of the fractures ranges between 0.2 and 28.5 m with an average of 3 m. An abundant literature is dedicated to this alteration (e.g. Dubois et al., 1996; Durst and Vuataz, 2000; Durst, 2002; Schleicher et al., 2006; Clauer et al., 2008) since it deeply modifies the properties of the granite as the density is lowered while porosity and P-wave velocity are highly increased (Ledésert et al., 1993a). The mineralogy is locally intensely transformed as the total dissolution of quartz, plagioclase, biotite and hornblende occurs leaving only K-feldspar preserved.

Table 1
Depth of tosudite occurrences (expressed in metres) for each of the 5 drill holes.

Tableau 1
Profondeur des occurences de tosudite (en mètres) pour chacun des cinq forages.

EPS1	GPK1	GPK2	GPK3	GPK4
1456		1420–2100 Not detected		
2159–2164 (Ledésert, 1993; Genter et al., 1997; Bartier et al., 2008)	**2510** altered zone (Genter et al., 1997)	2100–3880 huge fracture zone, total mud loss, no cuttings 3880–5088 not detected	Not detected all along drill hole Poor quality of cuttings (overcrushed)	Not detected all along drill hole Poor quality of cuttings (overcrushed)

Zones where tosudite was found are indicated in bold.

Several authors have shown that this results from the interaction between the granitic basement and fluids of sedimentary origin as attested by Cl/Br ratio, the chemistry and bulk chlorinity of the reservoir fluids (Pauwels et al., 1993) and the presence of organic matter (Ledésert et al., 1996). These fluids were locally enriched in Li and promoted the crystallization of a rather rare mixed layer clay mineral named tosudite (Ledésert et al., 1996, 1999; Bartier et al., 2008). In the tosudite-bearing zones, the combination of geochemical data, mass balance calculations and microthermometry on fluid inclusions showed that illite, and quartz precipitated from the dissolution of tosudite and biotite consuming protons provided by the maturation of organic matter in a fluid of decreasing temperature. Tosudite crystallization occurred at a temperature ≤ 350–$400\,^{\circ}$C; followed by quartz-carbonates-illite precipitation at around $140\,^{\circ}$C (Ledésert et al., 1999) similar to the present-day temperature of natural fluids (Pauwels et al., 1993; Dubois et al., 1996). Where it is found, tosudite replaces plagioclase and shows a honeycomb structure responsible for the 25% porosity of the altered rock. However, despite its impact on porosity (and likely peremeability) enhancement, tosudite cannot be considered as a major secondary mineral within the Soultz granite because of its scarcity (Table 1). As opposed to tosudite, quartz and carbonates reduce the bulk porosity of the granite as they precipitate within fracture planes and contribute to their sealing (Ledésert et al., 2009). Geochemical calculations (Pauwels et al., 1993; Komninou and Yardley, 1997) show that carbonates and quartz likely still precipitate from the natural fluids. Rabemanana et al. (2003) showed that calcite reactions dominate the quartz reactions in natural environments and that quartz reactions do not influence the characteristics of the reservoir. Tosudite has been neglected in these calculations but illite has been taken into account, which is important because of the permeability reduction by hairy particles in oil reservoirs (Wilkinson and Haszeldine, 2002). It can also be assessed that EGS reservoir properties might be modified by the massive injection of fresh fluids. The injection test made in September 1993 outlined a release of Mg, Ba, Si, F, SO_4 and CO_2 thus indicating dissolution (Pauwels, 1997), but no evidence of crystallization was reported, probably because of the short duration of interaction.

Salinities in the fluid inclusions of the carbonates and quartz crystals show large variations, from 3 to 23 wt.% NaCl (Ledésert et al., 1999; Dubois et al., 1996, 2000). The very low salinities (3 wt.% NaCl) might correspond to meteoric waters penetrating deeply and rapidly.The salinity of 10 wt.% eq. NaCl equals the present-day salinity of the fluids sampled in the granite and in the sedimentary cover. Salinities up to 23 wt.% eq. NaCl found in carbonate and barite veins probably correspond to deep sedimentary brines that penetrated the granite along open fractures. These variations in salinity could correspond to the mixing at constant temperature of sedimentary brines and meteoric waters.

Illite is a frequent alteration mineral found in the granite (Genter et al., 1995; Bartier et al., 2008). The relationship between fracture zones and high illite content was established from several detailed mineralogical studies based on core samples (Genter et al., 1995). With cutting samples, this relationship is more difficult to state clearly by a simple binocular on-site examination and even with controls (thin section, XRD). The recovery of illite is strongly dependent on the quality of cuttings that can be overcrushed or partly lost (accumulation in cavities, loss in permeable fractures). Illite precipitated as needles up to 20 μm long (Bartier et al., 2008; Ledésert, 1993) or flakes, either as alteration products of igneous minerals (biotite, oligoclase) or in veinlets. It was also found growing on tosudite crystals. It has a small impact on porosity reduction but, as shown by studies of oil reservoirs, it can reduce the permeability in a considerable way (Hamilton et al., 1989). Its abundance is expressed in comparison with the total amount of sheet silicates such as biotite, muscovite, chlorite (Fig. 3). Within highly altered and fractured granite, illite amount was estimated from bulk rock chemical analysis at 35 wt.% (Genter, 1989). In that case, illite was the unique clay mineral related to vein alteration. From well logging data in GPK1, it was also shown that about 100 m of altered granite occur between 1376 and 2000 m. This cumulative section of altered and fractured granite represents about 15% of the whole drilled granite length (Genter, 1989). In GPK2, where the cuttings are of good quality, illite is present mainly between 4500 and 4800 m (see Fig. 3, column GPK2). In both GPK3 and GPK4, its observation was very difficult. We assume that the clay minerals were completely crushed and lost within the drilling mud (Ledésert et al., 2009). Consequently, the presence of hydrothermally altered and fractured zones was very difficult to determine but fine microscopic

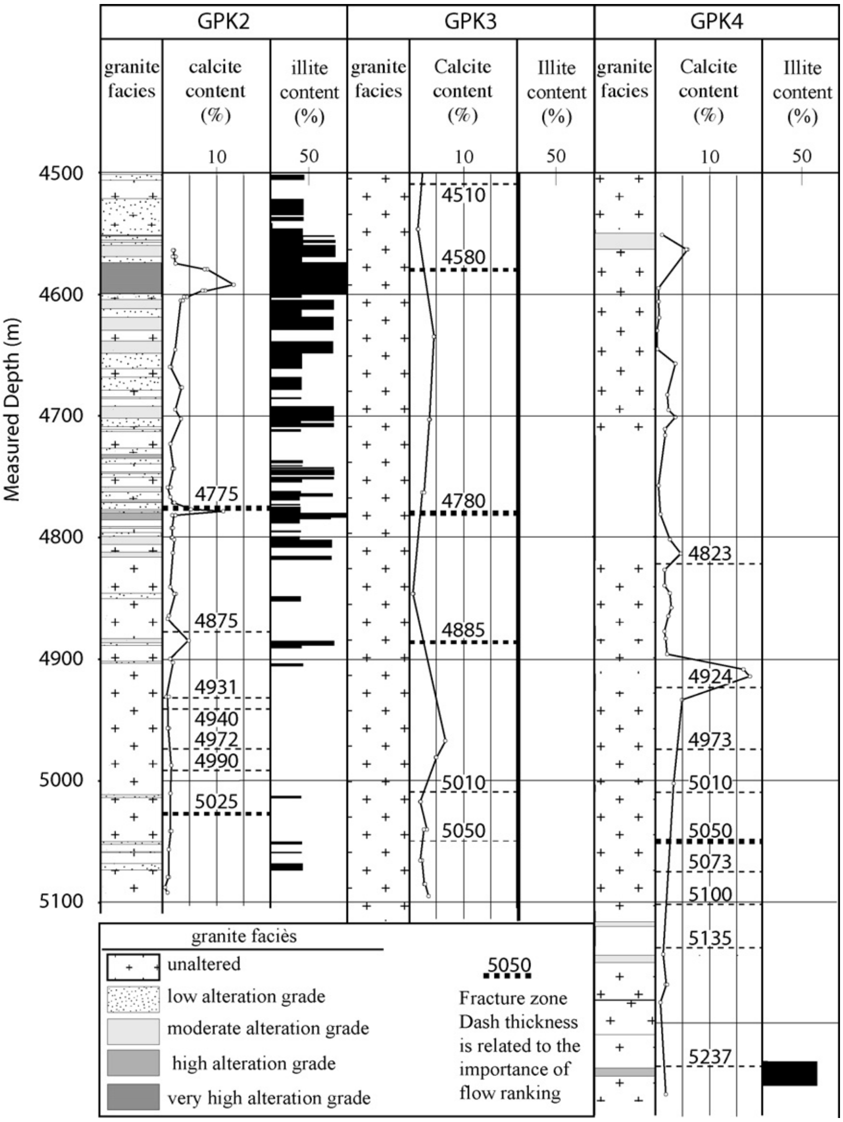

Fig. 3. Calcimetry data (calcite content) correlated with petrography (granite facies) determined from examination of cuttings with a binocular, illite contents when available and fracture zones with their flow ranking. Fracture zones are indicated with their depth. The thickness of dashed line increases with the ability of fractures to conduct fluids.

Fig. 3. Données pétrographiques « granite facies », calcimétriques « calcite content » et teneur en illite « illite content » en fonction de la profondeur pour GPK2, GPK3 et GPK 4. Les zones de fractures sont indiquées avec leur profondeur. L'épaisseur du figuré des zones de fractures augmente avec l'aptitude à conduire les fluides.

examination (Dezayes et al., 2005) allowed the determination of the degree of alteration of some fractured zones. In the fractured zones, the igneous biotite and plagioclase are obviously transformed into illite. Thus, illite is present but difficult to quantify. For GPK4, the occurrence of illite detected at 5237 m (Fig. 2) is due to the fact that the well had been cased just before that section improving the ascent of cuttings. Thus, the deepest on-site characterisation of the cuttings is only relevant between 5110 and 5260 m (Dezayes et al., 2005).

The K-Ar method was applied to date illite and K-rich illite-smectite mixed layers, as it is the only K-bearing mineral in the separated size fractions that was observed physically associated with tosudite in the studied granite volume (around 2160 m depth, EPS1). Tosudite is therefore not dated directly by this method as it does not contain K, but the SEM observations suggest a related genesis (Bartier et al., 2008). Also, no younger newly-formed mineral was observed petrographically, the younger K-Ar value might be considered at the end of illitization in the studied rock volume. The clay-rich fraction has been separated into 5 size-subfractions (< 0.1, 0.1–2, 2–5, 5–10 and 10–30 μm) by ultracentrifugation. The ages range from 62.9 ± 3.9 Ma for the coarser to 17.6 ± 1.5 Ma for the finer fraction, decreasing progressively with particle size (in Bartier et al., 2008). In previous K-Ar studies on illite of the same granite (Schleicher et al., 2006) and of overlaying sandstones (Clauer et al., 2008), the K-Ar results pointed to illite crystallization episodes during Permian, Triassic and Cretaceous times, in granite veins that they might have more or less sealed and in the sedimentary matrix and features. The 63 Ma age obtained here fits with the lowest K-Ar data obtained in the deep Triassic sandstones presently in the centre of the Rhine graben (Clauer et al., 2008), except that they were obtained on different size fractions: small in the sandstones, large in the granite vein. Both can be related and they record fluid migrations at about 63 Ma in fractures of the granite, where they grow into large particles, with some "escapes" into the overlaying sandy sedimentary rocks where they remind small. The younger K-Ar age at 18 Ma corresponds to the beginning of the local rifting activity (Bartier et al., 2008), and it looks like this event induced the latest generation of illite in the granite veins that could have been sealed by this crystallization. Such a two-step crystallization of illite-type minerals explains well in turn the progressive decrease of the K-Ar data from the oldest coarser particles to the smallest younger particles with the intermediate fractions consisting in a mixing of the 2 generations of illite (e.g., discussion in Clauer and Chaudhuri, 1995). Following Komninou and Yardley (1997), illite might crystallize also at present from the present-day fluids circulating in the granite.

4. Permeable zones

Production tests were performed in 2005 with an injection rate of 15 L/s in GPK3, which was entirely recovered in the production wells. However, an important discrepancy was observed between GPK2 (13 L/s) and GPK4 (2 L/s). Soultz is an open system allowing the production of native geothermal brines. Tracer tests confirmed that the brines produced compensate for the loss of the fresh water within the fractured basement (Sanjuan et al., 2006). The main problem is the very poor productivity of GPK4. As the main fracture orientations are rather similar in all the geothermal wells, this difference cannot be explained by the geometry of the fracture network itself only, but by the size and sealing of the fractures involved in forced fluid circulation. An extensive study of calcite deposition within the lower reservoir has been performed by Ledésert et al. (2009). Cuttings were analysed by mano-calcimetry to quantify the amount of calcite. These data were then compared for the three deep boreholes (Fig. 3) and correlated with available petrographic and flow pathway data. Calcite contents vary between 0.5 and 18 wt.% of the cuttings samples. They can be compared to the Fresh Granite Maximum Value (FGMV, dashed line at 1.8 wt.% of calcite) which, according to White et al. (2005) is the maximum value that can be observed in fresh granite. We can notice from Fig. 3 that most of the data are below or close to this FGMV while some calcite contents are very high. Then, values above FGMV must be definitely regarded as abnormal calcite contents, also called calcite anomalies, while values below or close to FGMV can be considered as normal calcite content for the Soultz granite.

From the study of calcite distribution (Ledésert et al., 2009), it appears that calcite is a good index of alteration, sometimes better than illite that may be lost by buoyancy in the cuttings. GPK2 (Fig. 3) shows high amounts of calcite (up to 13 wt.%) indicating that calcite is a major newly-formed mineral and that the use of well chosen chemical reagents may improve the behaviour of the well. In GPK3 (Fig. 3), the low measured amount of calcite indicates that the fractures are only slightly sealed and remain good pathways for fluids. GPK4 (Fig. 3) shows the highest amount of calcite and a very poor productivity before any stimulation. A general trend can be found as calcite contents higher than 10% are generally correlated with strongly altered zones in which sealing is extensive. It is also reported by Ledésert et al. (2009) that the higher the calcite content, the lower is the ability of the fracture network to drain fluids before stimulation, due to their sealing in which calcite undoubtedly plays an important role. However, it must be noted that cutting samples represent granite intervals of 3 to 6 m length and are sometimes of bad quality with loss of newly formed clay minerals and likely artificial concentration of calcite. Several acid systems such as hydrochloric acid (HCl), Regular Mud Acid (RMA or HCl-HF) and Organic Clay Acid ($C_6H_8O_7$–HF–HBF_4–NH_4Cl) were injected to dissolve minerals deposits in the GPK4 wellbore as well as filling materials of fractures in the vicinity of the well (Nami et al., 2008).

The transfer of fluids occurs along fractures, as deduced from the observations and analyses described previously. However, this does not explain the diffusion of fluids within the granite itself, shown for instance by the total transformation of plagioclase into clay minerals even far from the fractures (metre-scale altered halo), and their later impregnation by organic matter (Fig. 2). This small-scale diffusion is made possible by structures at the mineral grain scale (Sardini et al., 1997). The connectivity index gives a probability of the mineral phases being connected in 3D. The closer the index is to 100%, the higher is the probability that the phase is connected and beyond the percolation threshold in terms of permeability.

The high connectivity index obtained for plagioclase (69.7%) and quartz (62.1%) indicates that they form continuous interconnected skeletons throughout the rock. However, quartz is affected by microcracks, while plagioclase is subject to dissolution voids. The calculation of connected microcracks in numerous quartz crystals of different sizes never reaches 0, indicating that a fluid can go through the mineral, even the smallest grains, assuming that all the fractures are open which depends on their orientation within the stress field. The mean porosity of the plagioclase crystals is 4.3% in the fresh Soultz standard granite. It is approximately 20 times higher than that obtained for quartz. Combining the data of crystal connectivity and that of internal porosity, plagioclase can be considered as the main path for the fluid flow away from fracture planes. The permeability of 4×10^{-19} m^2 obtained by Sardini et al. (1997) during experiments on the fresh granite is due to the circulation of fluids in both the pore network in plagioclase and in the microcrack network in quartz. Biotite and orthoclase pore networks together with open grain boundaries also possibly contribute to the permeability, but this has not been quantified.

In the fractured and altered granite, the presence of immature organic matter 800 m below the top of the granite indicates a rapid circulation of fluids at a kilometre scale between the sedimentary cover and the granitic basement. The local impregnation of altered plagioclase with organic matter is also made possible by the intergranular microfracturation of the granite, the high degree of interconnection of plagioclase crystals, and their high porosity due to their replacement by clay minerals. These features show that several scales of discontinuities contribute to the high permeability of some zones within the EGS exchanger varying from μm-scale (alteration of plagioclase, impregnation of tosudite with OM) to km-scale (rapid migration of fluids attested by immature organic matter 800 m below the sediment/granite boundary, and by fluid inclusion data). The schematic view of the permeability network within the Soultz granite, from the top of the granite to the lower reservoir is given in Fig. 2.

5. Conclusion

The Soultz EGS exchanger shows a permeability from the μm to the km scale but few fracture zones are efficient for the Soultz EGS. The porosity of the rock is promoted by the dissolution of primary minerals and the crystallization of newly-formed phases along fractures, while its permeability may be reduced by the crystallization of hairy illite and calcite. Calcite appears to be an abundant and ubiquitous newly formed mineral within the Soultz EGS. Quantifying its abundance allows the identification of the zones where the fractures are sealed and gives a guide to the choice of reagents to be used for chemical stimulations. Illite is generally considered as a good indicator of alteration and possible permeability, but it has also been shown that it can be lost during drilling, while calcite is preserved. As a consequence, calcite amounts should be systematically quantified together with illite if new boreholes were to be drilled at Soultz.

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