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Chapter 3

CALCIMETRY AT SOULTZ-SOUS-FORÊTS ENHANCED GEOTHERMAL SYSTEM: RELATIONSHIPS WITH FRACTURE ZONES, FLOW PATHWAYS AND RESERVOIR CHEMICAL STIMULATION RESULTS

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ABSTRACT

The results of a calcimetry performed on cuttings from the 3 wells of the Enhanced Geothermal System of Soultz-sous-Forêts (France) are compared to other available data of petrography, mineralogy, fracture zones, flow pathways and so on. The relationship between flow ranking and calcite content for the fracture zones of GPK3 and GPK4 is opposite to that of GPK2 (the better the fluid flow, the lower the calcite content). This suggests that the fracture zones of GPK2 are different from those of GPK3 and GPK4, and that the connectivity to the fracture network may be different too. The results of this study provide also some explanation for the effects of the chemical stimulations performed in the 3 wells, as well as some information for future chemical stimulations that could be aimed to improve the connectivity between the wells and the fracture network.

INTRODUCTION

The economic success of the exploitation of an enhanced geothermal system (EGS) depends on many parameters, but firstly on the features of the geothermal reservoir. A good geothermal reservoir must be made of rocks with very low porosity and permeability affected by a fracture network with a good geometrical connection as well as a good and efficient hydraulic connection, that is, the existence of natural or/and created open fractures acting as

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flow pathways for the circulation of deep and hot fluids. These are crucial conditions to complete a circulation loop between production well(s), where hot fluids exit and are used for electricity production, and an injection well returning used fluids to the reservoir.

It is not rare that the flow pathways of the system are sealed or filled by natural or induced mineral precipitation. This inhibits the fluid circulation and thus finally lowers the possibility of heat extraction. In order to increase the connectivity between the wells and the fracture network of the reservoir, it is possible to perform some hydraulic or chemical stimulations. Hydraulic stimulation consists of pumping a fracturing fluid into a well at a sufficient pressure so that it can generate and extend cracks into the reservoir. The major problem of this technique is the associated induced micro-seismicity that can raise public concern. Chemical stimulation consists of the injection of acid at a pressure below hydraulic stimulation. It is aimed to remove as much material (precipitated minerals and drilling wastes mainly) as possible that seal or fill fractures and/or wellbore permeability. It is therefore very important to have a good knowledge of the mineral species that hinder the connectivity between the wells in order to choose most suitable chemical component to perform most effective stimulation as possible. It is also very important to know how these minerals are distributed in order to determine an appropriate technique for the chemical stimulation.

The geothermal reservoir of Soultz-sous-Forêts (France) is affected, like many other EGS in the world, by these problems of poor hydraulic connection between an injection well and some production wells. Hydraulic and chemical stimulations have been performed in order to enhance the connectivity between the wells and the reservoir fracture network. These stimulations did not have the same effect on the three wells. Further to these stimulations, a study of the relationships between fracture zones, flow pathways and mineral precipitation has been performed (Ledésert et al., 2009; Hébert et al., 2010). Despite some common points, the three wells show different features that allow to better understand the different results of the chemical stimulations in particular.

THE ENHANCED GEOTHERMAL SYSTEM OF SOULTZ-SOUS-FORETS

Geological Setting

The EGS of Soultz-sous-Forêts (France; figure 1) is located in the Upper Rhine graben (URG) where a thermal anomaly occurs (Ziegler, 1992; Dèzes et al., 2004). The temperature at 5 km depth is estimated at around 200°C (Hurtig et al., 1992; Genter et al., 2004). The geothermal pilot plant is made of three boreholes (GPK2, GPK3 and GPK4). The geothermal reservoir is made of a palaeozoic granitic basement. The Soultz granite is composed of several types of granite (mainly a porphyritic monzo granite and a two mica granite) and some sub-facies recently described in detail and updated by Hooijkaas et al. (2006). The granitic basement, which is overlain by about 1400 m of Mesozoic and Tertiary sediments (mainly carbonates and sandstones), is strongly fractured (Ledésert et al., 1993; Genter and Traineau, 1996; Sausse, 2002; Valley, 2007) and also affected by hydrothermal alterations. Indeed, the granite underwent an early pervasive alteration stage, which is widespread, and later vein alteration has developed into the fracture system (Genter, 1989; Traineau et al., 1991; Genter et Traineau, 1996; Ledésert et al., 1996, 1999; Dubois et al., 2000; Bächler &

Kohl; 2005; Hooijkaas et al., 2006). Quartz, carbonates (in particular calcite) and clay minerals (primarily illite) are the major sealing phases observed in the main fracture zones (Genter, 1989; Traineau et al., 1991; Ledésert, 1993; Genter & Traineau, 1996; Ledésert et al., 1996, 1999; Dubois et al., 2000), but their distribution gives a random character to the overall permeability of the system (Portier et al., 2009).

Geothermal water injected into GPK3 is pumped from GPK2 and GPK4. A deep fluid circulation is supported by a network of permeable fractures in the granitic basement where water is heated up to approximately 200°C (Hettkamp et al., 2004). Based on a binary geothermal power plant, the extracted heat is converted into electricity from a 1,5 MWe turbine (Genter et al., 2009).

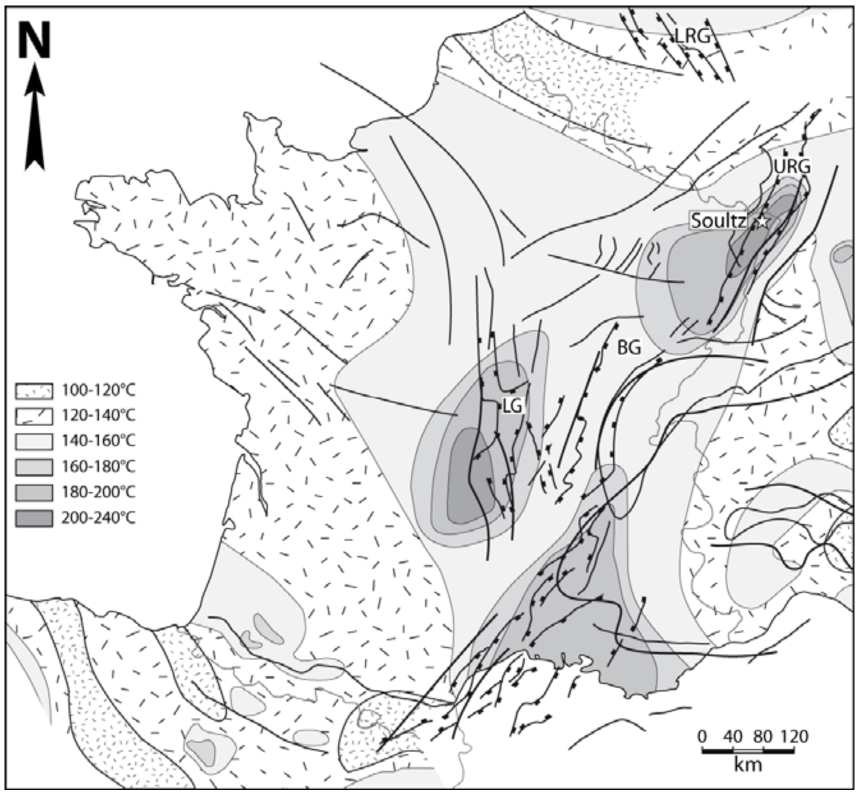

Figure 1. Map of extrapolated temperatures at 5 km depth and location of some major structural structures (modified after Hurtig et al., 1992 and Dèzes et al., 2004). LRG: Lower Rhine Graben; URG: Upper Rhine Graben; BG: Bresse Graben; LG: Limagne Graben.

The Soultz fracture network is structured at different scales, from microcracks in minerals to regional faults (Ledésert et al., 2010). Both scale discontinuities are responsible for the high permeability of some zones through the geothermal reservoir. The two dominant sets of fractures (~60% of the whole network) are orientated around N-S with dipping towards the east or the west. The strike of these two main sets remains constant with depth, but the partitioning between the dominant dip orientations varies. In the deep part of the reservoir at 4800-5000 m TVD (True Vertical Depth), the fracture set dips dominantly to the West. Two additional sets of subvertical fractures orientated NW–SE and NE–SW are frequently observed. Dezayes et al. (2010) have classified the fracture zones into three different categories (or levels) on the basis of their relative scale and importance as fluid flow paths. Level 1 corresponds to major fracture zones, which were permeable prior to any stimulation operation (Figure 2) and were subject to important mud loss during the drilling operation. Fracture zones of level 2 are characterized by at least one thick fracture with a significant hydrothermal alteration halo. They showed a flow indication higher than 20% of fluid loss during stimulation. Fracture zones of level 3 show a poorly developed alteration halo and a fluid loss below 20% during stimulation.

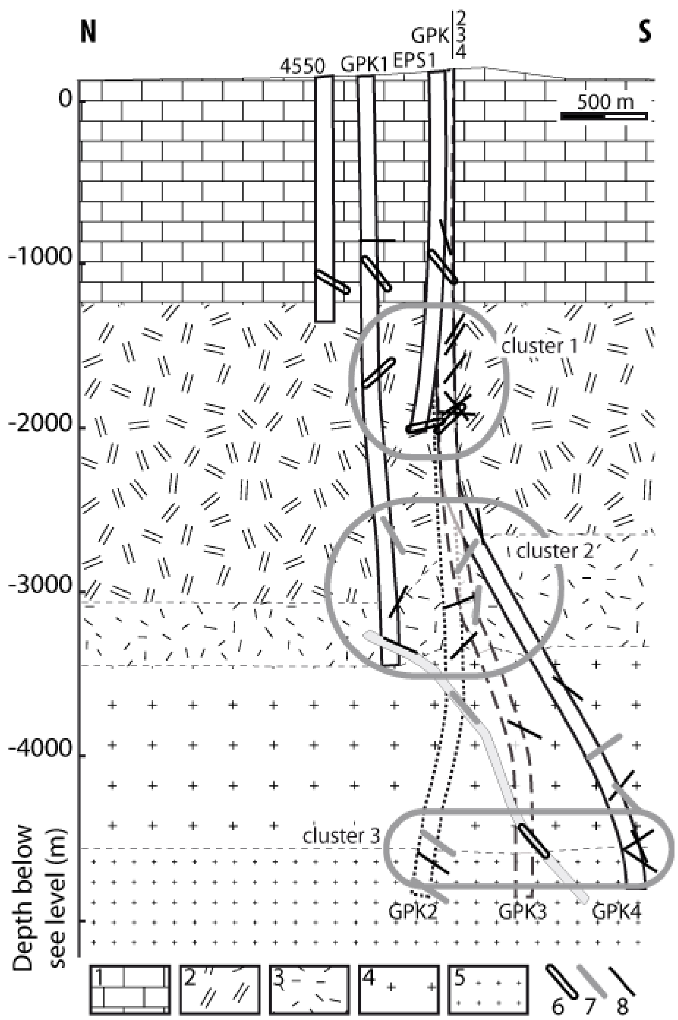

Figure 2. Cross-section of the Soultz geothermal system: 4550 (oil drill hole); EPS1 (cored scientific hole); GPK1 (scientific hole, destructive conditions, few core pieces). 1: sedimentary cover, 2: standard porphyritic Bt-Hbl granite, 3: standard granite with fractures and vein alteration, 4: Bt+Hbl - rich granite becoming standard granite with depth, 5: two-mica and Bt-rich granite, 6: Level 1 fracture, 7: Level 2 fracture, 8: Level 3 fracture. Figure modified after Dezayes and Genter (2008), petrographic facies from Hooijkaas et al. (2006), mineral abbreviations according to Kretz (1983).

On the basis of their spatial distribution (i.e. depth), fracture zones through the three wells have also been divided into three clusters (Figure 2; Dezayes et Genter, 2008; Dezayes et al., 2010). Cluster 1 is located between 1800 and 2000 m TVD in the unaltered granite. It includes several major fracture zones of level 1with permeable zones. Cluster 2 (3000–3400 m TVD) occurs in a zone where the granite shows evidences of high pervasive alteration related to a dense network of small-scale fractures. Cluster 3 occurs in the deep reservoir (4500–5000 m TVD) where the granite is massive and characterized by a low alteration degree (i.e. low permeable matrix). Many fracture zones have been identified in this cluster and they are listed in table 1, but only few of them are characterized according to the different levels defined by Dezayes et al. (2010). There is only one major fracture zone (GPK3-FZ4775; Table 1) of level 1 in this part of the exchanger. This major flow pathway is located in GPK3 at around 4775 m MD (measured depth) (Dezayes et al., 2010) and it is suspected to connect to GPK2 well at higher level (3900 m MD; Figure 2). There are two fracture zones (GPK2-FZ4780 and GPK2-FZ5050; table 1) of level 2, and both are located in GPK2 respectively at 4780 and 5055 m MD. Finally there are four fracture zones of level 3, and one is in GPK2 (FZ4885) and the others being in GPK4 (GPK4-FZ4973; GPK4-FZ5010 and GPK4-FZ5100). To sum up, the fracture network of the deep reservoir is heterogeneous. GPK3 is crosscut by a highly conductive fracture zone (with a strong alteration halo) of level 1. In contrast, GPK4 is characterized only by poorly conductive fracture zones (with poor alteration halo) of level 3. Finally, GPK2 contains levels 2 and 3 fracture zones, indicating the occurrence of poorly and moderately conductive fracture zones.

Low-pressure circulation tests, having been performed after drilling completion at around 5000 m prior to any stimulation, indicated an initial poor hydraulic connectivity between the wells and the reservoir with initial productivity rates of 0.02 $L.s^{-1}.bar^{-1}$ in GPK2, 0.2 $L.s^{-1}.bar^{-1}$ in GPK3 and 0.01 $L.s^{-1}.bar^{-1}$ in GPK4 (Nami et al., 2008). This poor hydraulic connectivity is due to a poor geometrical connectivity and/or the more or less complete sealing of fractures by naturally or induced precipitated minerals such as quartz, carbonates (in particular calcite) and clay minerals (primarily illite) for the major phases as observed in the main fracture zones (Genter, 1989; Traineau et al., 1991; Ledésert, 1993; Genter & Traineau, 1996; Ledésert et al., 1996, 1999; Dubois et al., 2000). The distribution of these minerals gives the impression of a random character to the overall permeability of the system (Portier et al., 2009; Hébert et al., 2010).

HYDROTHERMAL ALTERATIONS

As previously indicated, the Soultz granite presents evidence of hydrothermal alterations. Firstly, a propylitic alteration took place at the end of the magmatic crystallisation. It is characterized mainly by the partial replacement of silicates (chloritisation of biotite and hornblende, illitisation of plagioclase) as well as the formation of epidote and hydrogarnet (Genter, 1989; Ledésert, 1993; Ledésert et al., 1996, 1999). This alteration is of little interest to the Soultz EGS, since it hardly modifies the mineralogy and porosity of the rock. The second hydrothermal alteration evidence is made of vein alteration observed along fractures. It results from the interaction between the granite and some natural fluids that flowed, and sometimes are still flowing, within the fracture network of the reservoir (Pauwels et al., 1993). This alteration, which produces possible thick alteration zones on both sides of the fractures (0.2 m to 28.5 m, 3 m on average; Genter et al., 1995), may deeply modify the granite properties. For exemple, it lowers the density and increases the porosity as well as the P-wave velocity (Ledésert et al., 1997). Mineralogical transformations may be important, especially for silicates. Primary quartz, biotite and hornblende are generally strongly affected leaving only K-feldspar preserved. Plagioclase is totally dissolved. The mineral transformations result from the interaction between the granite and fluids of sedimentary origin (Pauwels et al., 1993; Ledésert et al., 1996) and meteorotic waters (Dubois et al., 1996, 2000; Ledésert et al., 1999). Main secondary minerals are quartz, calcite and illite (Genter et al., 1995; Bartier et al., 2008; Ledésert et al., 2010) and they may be likely still precipitating at present from natural fluids (Pauwels et al., 1993; Komninou and Yardley, 1999). Tosudite, a Li-bearing mixed-layered clay mineral, is an additional secondary mineral but it is not considered playing a major role on the reservoir properties because of its scarcity (Ledésert et al., 2010). Quartz and calcite reduce the porosity of the granite as they precipitate within the fracture planes and contribute to their sealing (Ledésert et al., 2009). On the opposite, illite does not reduce the porosity of the rock but it can reduce its permeability (Hamilton et al., 1989; Wilkinson and Haszeldine, 2002).

Hydraulic and Chemical Stimulations

As the initial productivity rates of the wells were very low, hydraulic and chemical stimulations have been performed in order to improve the connectivity between the wells and the fracture network (Figure 3).

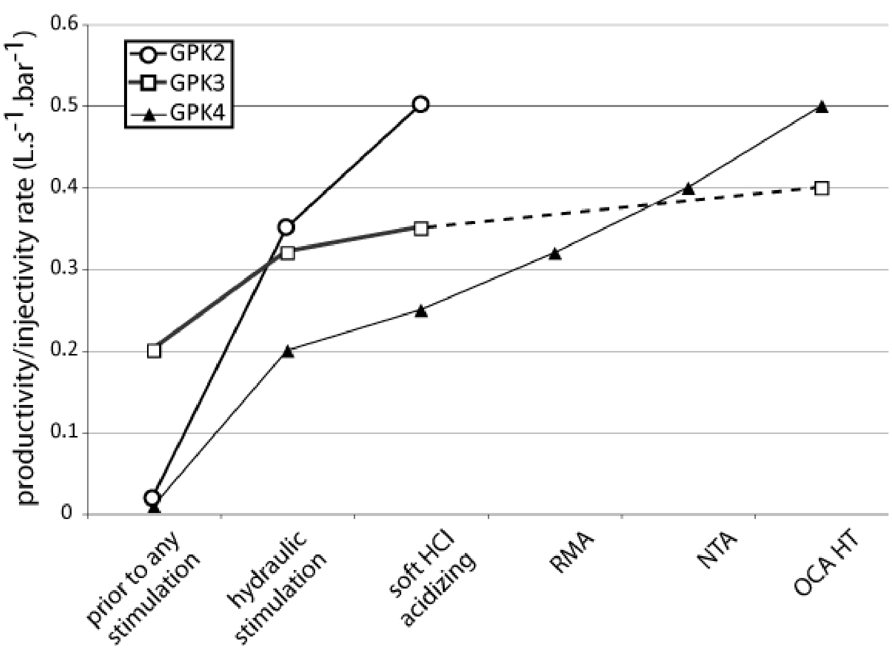

Figure 3. Evolution of the productivity/injectivity rate as function of the chronological stimulations (Hébert et al., 2011).

Hydraulic stimulations started first. The productivity rate of GPK2 and GPK4 was improved significantly and approximately by a factor of 20 (respectively 0.4 -0.3 $L.s^{-1}.bar^{-1}$ and 0.2 $L.s^{-1}.bar^{-1}$; Nami et al., 2008; Portier et al., 2009), whereas that of GPK3 increased only by a factor 1.5 (0.32 $L.s^{-1}.bar^{-1}$; Tischner et al., 2007; Nami et al., 2008). Chemical stimulations took over the hydraulic stimulations that had to be stopped because of induced micro seismicity and public concern. Chemical stimulations differ from a well to another, and once again with different results. GPK2 underwent just a limited and soft HCl acidizing but it had a significant impact on the productivity rate of the well which increased to 0,5 $L.s^{-1}.bar^{-1}$ (Nami et al., 2008; Portier et al., 2009). GPK3 underwent an initial HCl acidizing in 2003 followed by stimulation with OCA HT (Organic Clay Acid for High Temperature) in 2007. The final injectivity rate of GPK3 was estimated at around 0.4 $L.s^{-1}.bar^{-1}$, which is regarded as a weak impact after these two stimulations (Portier et al., 2009). GPK4 underwent a series of 4 different chemical stimulations. It first started with a soft HCl acidizing which improved the productivity rate of the well from 0.2 $l.s^{-1}.bar^{-1}$ to 0.3 $l.s^{-1}.bar^{-1}$. The second stimulation, which was made with RMA (Regular Mud Acid) had an estimated enhancement of about 35%. Then a NTA treatment (chelating agent) took place. The GPK4 productivity rate increased to 0.4 $l.s^{-1}.bar^{-1}$. The last stimulation was made with OCA HT, which allows reaching a final 0.5 $l.s^{-1}.bar^{-1}$ productivity rate for GPK4.

To sum up (Figure 3), hydraulic and chemical stimulations had an efficient impact on GPK2 and GPK4 productivity rates. The hydraulic stimulation was the most efficient because the enhancement was of one order of magnitude. Both stimulations had very little effect in GPK3 in comparison to GPK2 and GPK4.

MATERIAL AND METHOD

Material

The material consists of cuttings that are the main source of direct data in the Soultz deep wells. They are crushed rock chips resulting from destructive drilling. 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 of the original rock (i.e. before any stimulation) for a given level. Detecting variations covering less than 3 m is difficult because the standard spacing of sampling is of 3 to 6 m intervals for the three wells. GPK2 cuttings are fine-grained, averaging less than 1 mm and are of rather good quality. GPK3 and GPK4 cuttings are of poorer quality compared to GPK2 because of grain size (0.1 to 1 mm due to overcrushing that makes the description and identification difficult) and because of problems encountered during the drilling process (refer to Ledésert et al., 2009 for complete discussion).

As the chip samples are very fine-grained, the identification of the altered primary minerals (biotite, K-feldspar, and plagioclase) as well as the quantification of the relative abundance of clays within the samples was very difficult. Hydrothermal minerals (chlorite, illite, hematite, and epidote) were classified into four levels of abundance (absent, low, medium, and high). Calcite, which is the ‘focus’ mineral in this study, occurs as veins and in altered primary minerals. It is easily observed in cuttings under an optical microscope.

In GPK4, the geological characterization is rather poor except between 5105 and 5260 m depth because the upper part of the well was cased before drilling this interval. Then, the ascent of the samples was regular and they did not show any biotite enrichment. Therefore, the analysis of cuttings in this zone is of better quality and more reliable.

To sum up, the cuttings used in this study have been collected during drilling and therefore they represent the initial state of the granitic reservoir prior to any stimulation. The GPK2 cutting sample quality is very good compared to that of GPK3 and GPK4. For this reason, GPK2 is used as a reference well for deriving some guidelines from sample studies. The sample quality is mainly related to GPK2 drilling conditions that provided not only coarse cutting samples but also limited the crush of the granite.

Methods

Petrography, Mineralogy, Well-Logging Data

Complete petrographic data of granite chips are available in Genter et al. (1999) and Dezayes et al. (2003, 2005). Illite, which has been shown to be characteristic of hydrothermal vein alteration (Genter et al., 1999; Ledésert et al., 1999; Bartier et al., 2008), is expressed in terms of relative abundance among all the sheet silicates (mainly biotite, chlorite, and illite). It is important to remind that illite data are only reliable in GPK2. Despite being petrographically observed and supported by spectral gamma-ray data within the three wells (Dezayes et al., 2003, 2005), illite quantification was hindered in GPK3 and GPK4 because of the poor quality of cuttings (overcrushing and drilling problems, affecting mainly minerals with high buoyancy such as illite; Ledésert et al., 2009). The flow pathways were determined in each well by measurement of flow and temperature anomalies within the injected fluid (for more details see Evans et al., 2005). The results of petrography and XRD were finally correlated with well-logging data (ultrasonic borehole imagery (UBI), flow and temperature log at different injection rates, and gamma-ray spectrometry) in order to locate flow pathways in each well and characterize the alteration halos (Sausse et al., 2007).

Manocalcimetry

The carbonate content was measured on 200 mg of the powdered part of cuttings using a Meliere manocalcimeter (Dunn, 1980) at the Muséum National d'Histoire Naturelle de Paris (see Ledésert et al., 2009 for more details about the apparatus and the measurement). The precision of the measurement is estimated at around ± 0.5 wt.%. In order to check the reproducibility of the results, two analyses were systematically performed for each sample. The reproducibility is considered good when the difference between the two results is lower than 0.5 wt.%, i.e. within the precision interval.

RESULTS

Recently, Ledésert et al. (2009) and Hébert et al. (2010) performed manocalcimetry on random and focused sampling of cuttings from the three well-bores in order to assess the influence of calcite on the permeability of the flow pathways (complete and detailed method available in Ledésert et al., 2009 or Hébert et al., 2010). The results of calcimetry are presented in synthetic logs (Figures 4, 5 and 6) in addition to available data, i.e. petrography, illite content, fracture zones, fracture zone levels, flow ranking and well-logging data such as ultrasonic borehole imagery (UBI), flow and temperature log at different injection rates, gamma-ray Spectrometry.

Table 1. Fracture zone and calcite anomaly features in the three wells. Grey rows are for calcite anomaly matching with no fracture zone or fracture zone with no analyzed sample. (Data from Dezayes and Genter, 2008; Dezayes et al., 2010; Ledésert et al., 2009 and Hébert et al., 2010)

Well	**Fracture zone**	**level**	**Dip Dir.**	**Dip**	**Thickness (m)**	**Flow ranking**	**Fluid flow (%)**	**Sample depth (m MD)**	**Calcite content (wt%)**	**Associated anomaly**
GPK2	FZ-4510					5		4510	1.7-2.0	
GPK2	FZ-4580					2		4579	7.8 –8.3	A1
GPK2								4592	13.0	A1
GPK2								4677	3.4	A2
GPK2								4702	3.4	A3
GPK2	FZ-4780	2	250	65		1		4780	11.2	A4
GPK2	FZ-4885	3	250	65		2		4885	4.8	A5
GPK2	FZ-5010					5		5011	1.5	
GPK2	FZ-5050	2	250	65		6		5055	1.2	
GPK3								4096	5.6	A1
GPK3								4383	2.8-2.9	A2
GPK3								4467	3.0-3.2	A3
GPK3								4635	4.5-4.7	A4
GPK3	FZ-4775	1	234	64	15	1	63-78	4776	2.8-3.0	A-4776
GPK3	FZ-4875					4	2	4875	1.5	
GPK3	FZ-4931					6	0	4933	12.4-12.6	A-4933
GPK3	FZ-4940					7	2-4	4946	10.9	A-4946
GPK3	FZ-4972					3	4	4965	6.6	A5
GPK3	FZ-4990					5	4	4980	4.8-5.0	A-4980
GPK3	FZ-5025					2	10-15	5036	2.7-3.2	A6
GPK3								5093	3.5	A7
GPK4								4562	5.7-5.9	A1
GPK4								4659	3.5	A2
GPK4								4707	3.5	A3
GPK4	FZ-4823		271	80	2	7		4822	4.6	A4
GPK4	FZ-4924		279	73	2	7		4919	17.8	A5
GPK4	FZ-4973	3	276	81	2	7				
GPK4	FZ-5010	3	257	85	15	7		5015	6.0-6.2	A-5015
GPK4	FZ-5050		78	74	2	1		5045 5060	3.2 3.5-3.7	A-5045 A-5060
GPK4	FZ-5073		61	63	12	7				
GPK4	FZ-5100	3	255	69	10	7		5105	4.0	A-5105
GPK4	FZ-5135		275	67	6	7		5147	1.5	
GPK4	FZ-5237		288	75	2	7		5231	4.2	A-5231

According to White et al. (2005), the calcite content of a fresh granite is 0.252 wt.% on average and does not exceed 1.8 wt.%. The basic value of the calcite content of the Soultz granite is consistent with that of White et al. (2005), even if it is very often closer to the upper value. Therefore we consider in our study that any manocalcimetry measurement over 2 wt.% can be regarded as a calcite anomaly. Calcite anomalies are named according to their well and depth (e.g., anomaly GPK2-A4592 corresponds to the calcite anomaly measured in GPK2 from a sample collected at 4592 m MD) and their features are given in Table 1.

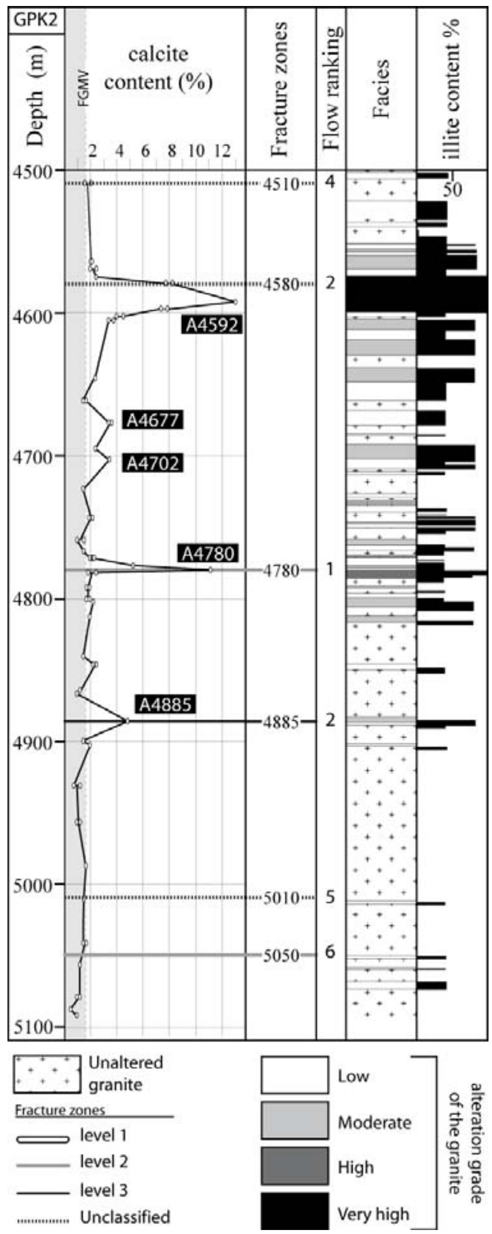

Figure 4. GPK2 open-hole synthetic log (modified after Hébert et al., 2010). Fracture zones (from Gentier et al., 2005; Sausse et al., 2007), flow ranking (from Sausse et al., 2007), petrographic facies and illite content (from Genter et al., 1999). FGMV grey zone corresponds to the fresh granite maximum value of calcite (White et al., 2005).

GPK2

Five main calcite anomalies can be distinguished on Figure 4. GPK2-A4592 is the peak (13.5 wt.%) of a large calcite anomaly that occurs between 4574 and 4605 m MD and that also contains several other samples with high calcite content (samples: 4579 (8%); 4592 (7.5%); 4602 (~4.3%); 4605 (~3.6%)). This large zone, whose peak is the highest calcite content measured in GPK2, is characterized by a very high alteration grade of the granite and a very high illite content (100%), the occurrence of a fracture zone (GPK2-FZ4580) that is considered as rather conductive (ranking 2 of 6). GPK2-A4677 and GPK2-A4702 are minor anomalies. They both contain around 3.5 wt.% of calcite and do not match with any of the identified fracture zones. Nevertheless they differ slightly from each other in terms of the alteration grade of the granite (respectively low and moderate) and in the illite content (40% and 80%) points of view. GPK2-A4780 is a narrow anomaly with a high calcite content (11.5 wt.%), high alteration grade, and high illite content (100%). It fits with the most conductive fracture zone of the well (FZ4780, flow ranking 1 of 6, level 2). The last calcite anomaly is GPK2-A4885. It is moderate (5 wt.%), with moderate alteration halo and a high illite content (80%). This anomaly matches with the fracture zone FZ4885 that is one of the most conductive of the well (flow ranking 2 of 5) but not so much efficient (level 3).

To sum up, in GPK2, calcite contents higher than 5% are associated systematically with a flow pathway, and an illite content higher than 40%. However, illite contents of 40% and more do not systematically fit with fracture zones and/or flow pathways and high calcite amounts. Three fracture zones identified respectively at 4510, 5010 and 5050 m MD, corresponding to the less conductive of GPK2, do not show any calcite anomaly. Note also that among these three fracture zones, only one (FZ5050) is classified according to fracture levels defined by Dezayes and Genter (2008) and Dezayes et al. (2010). GPK2-FZ5050 is of level 2, same as GPK2-FZ4780 except that the latter is the most conductive of the well and highly mineralised by calcite.

GPK3

Eight calcite anomalies and 7 fracture zones are identified in the open-hole of GPK3 (Figure 5). GPK3-A4635 (~4.5 wt%) and GPK3-A5092 (~3.5 wt.%) do not fit with any fracture zones or flow pathways. The low anomaly GPK3-A4776 (3.0 wt.%) corresponds to the most efficient fracture zone GPK3-FZ4775 in terms of the fluid flow (ranked 1 of 7, and accommodating 63–78% of the fluid flow; level 1; Dezayes et al., 2010). This low calcite content suggests a poor mineralized zone that must be geometrically connected very well to the permeable fracture network, which is consistent with the interpretation that this fracture zone is directly connected to GPK2 at higher level. A series of four calcite anomalies (A4933, A4946, A4965 and A4980) describe altogether a large anomaly zone extending from 4875 to ~5000 m MD. The peak of this anomaly zone is made of GPK3-A4933 (calcite content of 12.6 wt.%). It matches with the fracture zone at 4931 m MD that is ranked 6 of 7 with a fluid flow considered zero. This suggests that the low conductivity of this fracture zone could be the result of abundant calcite mineralization. A bit deeper are anomalies GPK3-A4946 (10.5 c wt.%), GPK3-A4965 (6.7 wt.%) and GPK3-A4980 (~ 5.0 wt.%). None of these anomalies is located right on a fracture zone, but there is always one very close for each of them, maximum in a ten of meters. These three fracture zones (FZ4940, FZ 4970 and FZ4990) all have a very low conductivity (ranked respectively 7, 3 and 5 of 7, and fluid flow at 4%). This large anomaly zone is made of a cluster of fracture zones, which are rather highly mineralised by calcite. Anomaly GPK3-5036 is low (3.2 wt.%). It is close to a fracture zone (GPK3-FZ5025), which is supposed to be the second, more efficient flow pathway of this well (ranked 2 of 7, and accommodating 10-15 % of the fluid flow).

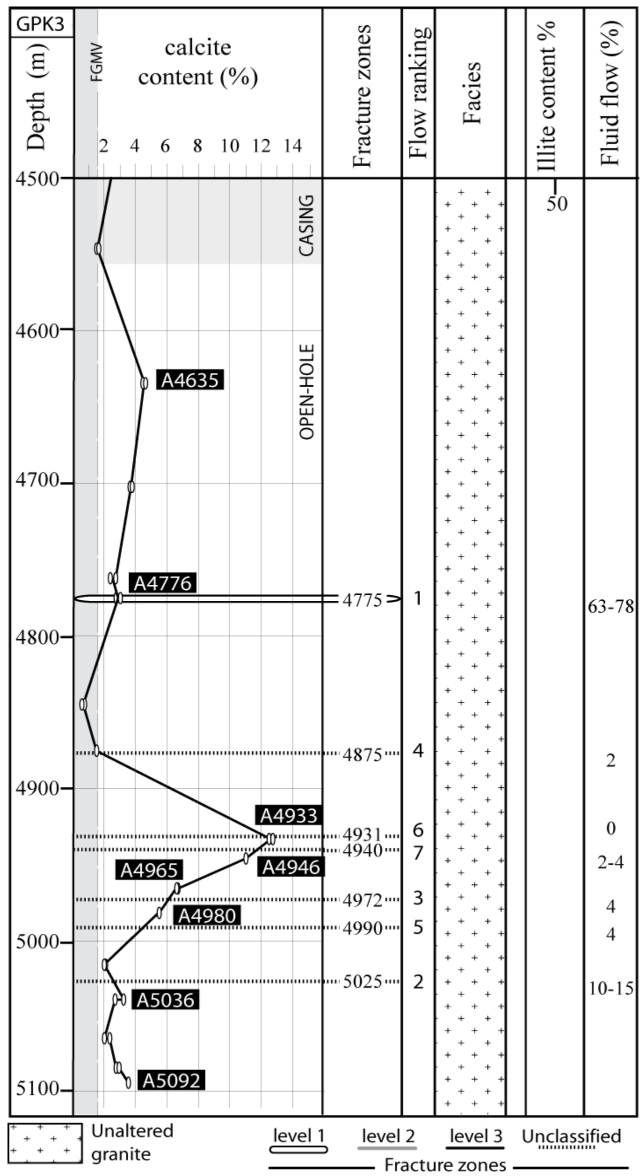

Figure 5. GPK3 open-hole synthetic log (modified after Hébert et al., 2010). Fracture zones (from Gentier et al., 2005; Sausse et al., 2007), flow ranking (from Sausse et al., 2007), petrographic facies and illite content (from Genter et al., 1999). FGMV grey zone corresponds to the fresh granite maximum value of calcite (White et al., 2005).

The fracture zone GPK3-FZ4875 (ranked 4 of 7; very low fluid flow of 2%), which corresponds to the upper limit of the large anomaly zone, does not show abnormal calcite content. The occurrence of the fracture zone at 5025 m MD accommodating 10 to 15 % of the fluid flow suggests that the poor connectivity of the large anomaly zone may rather be the result of the important mineralisation of calcite within the cluster of fracture zones than only due to the occurrence of the fracture zone of level 1 at 4775 m MD which is directly connected to GPK2 and drives most of the fluid.

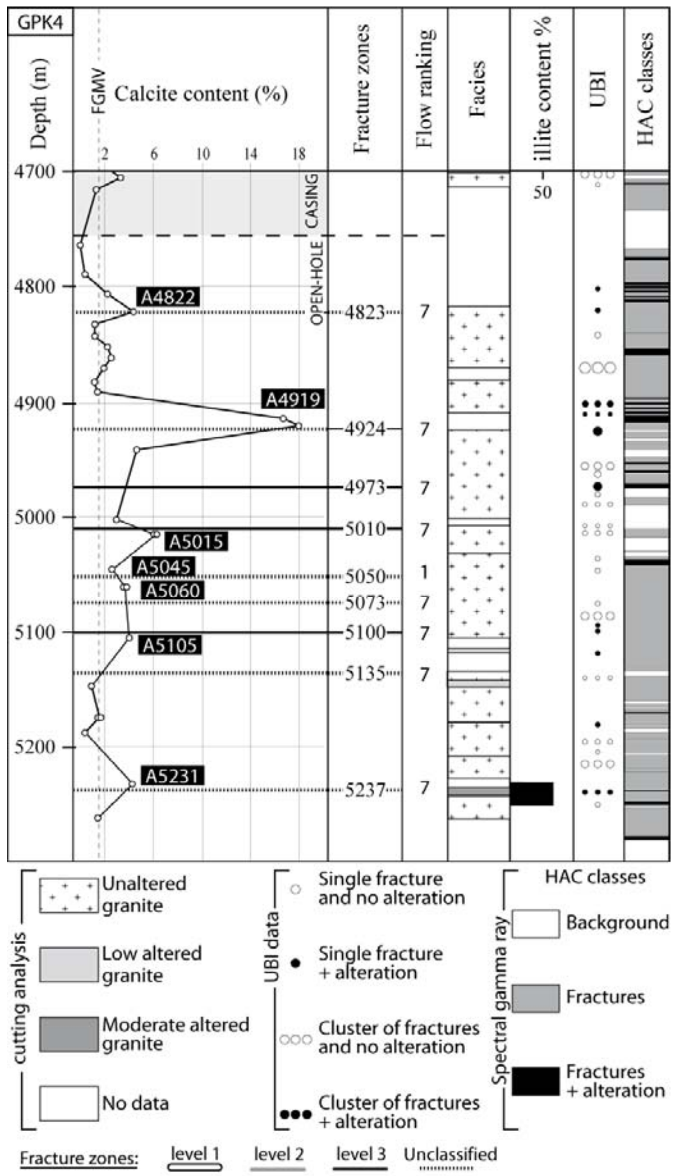

Figure 6. GPK4 open-hole synthetic log (modified after Hébert et al., 2010). Fracture zones (from Gentier et al., 2005; Sausse et al., 2007), flow ranking (from Sausse et al., 2007), petrographic facies and illite content (from Genter et al., 1999). FGMV grey zone corresponds to the fresh granite maximum value of calcite (White et al., 2005).

GPK4

GPK4 open-hole is characterized by the occurrence of 9 fracture zones (Figure 6) of which one (GPK4-FZ5050, flow ranking 1 of 7) is very conductive compared to the others (all ranked 7 of 7). Three fracture zones are of level 3, the others being not classified from that point of view.

Anomaly GPK4-A4822 is low (4.6 wt.%). It fits with a fracture zone at 4823 m MD with a low conductivity (Sausse et al., 2007). GPK4-A4919 is the major peak of a large anomaly (18 wt.% of calcite) that occurs between 4894 and 4931 m MD. This zone is characterized by the existence of several clusters of fractures that are not efficient flow pathways even if associated with alteration. The poor connectivity is consistent with an important mineralisation of calcite hindering fluid flow.

Anomaly GPK4-A5015 is moderate (~6 wt.%). It is very close to a GPK4-FZ5010 that is interpreted as a single fracture with a very low flow ranking (7 of 7) and of level 3. Anomalies A5045 and A5060 (respectively 3.2 and 3.6 wt.%) are the lowest calcite values measured in this well. They frame the GPK4-FZ5050 that is the most efficient flow pathway in GPK4 so far (1 of 7). It suggests that this fracture zone is little mineralised and probably rather well hydraulically connected. GPK4-A5105 (4 wt.%) and GPK4-A5231 (4.3 wt.%) are moderate. They lie close to fracture zones (GPK4-FZ5100 and GPK4-FZ5237) that show a similar and low conductivity (all ranked 7 of 7), suggesting a poor geometrical connection with the hydraulic system as all the other fracture zones have the same flow ranking of 7.

DISCUSSION

We can distinguish two main groups of fracture zones in GPK2. The less conductive zones (FZ4510, FZ5010 and FZ5050) are characterized by low alteration facies, moderate illite content and low calcite content (below 2 wt.%) resulting likely from the early pervasive fluid alteration. It suggests that these fracture zones are poorly hydraulically connected to the fracture network of the geothermal reservoir. On the opposite, the fracture zones with the best conductivities (FZ4780, FZ4580, FZ4885) match with high to moderate calcite anomalies (respectively 11, 8, ~5 wt.%), high to moderate alteration grade and high illite content. This suggests massive precipitation of calcite from later fluid circulations within the fractured zone. Thus, the calcite content seems possibly proportional to conductivity. Note that the illite content is correlated clearly with the alteration grade.

In GPK3, the less conductive fracture zones are concentrated in a zone that extends from ~ 4875 to ~ 5000 m MD, where they correlate with a large and high calcite anomaly zone. The main fracture zone (FZ4775), which accommodates 63–78% of the fluid flow, has the lowest calcite anomaly (2.9 wt.%) of all the fracture zones of this well. Except for A4635 and A5092, all the moderate calcite anomalies occur in the vicinity of fracture zones. In this well, regarding the fracture zones data and the calcite anomalies, it seems that the more calcite is, the less fluid flow becomes. Therefore calcite plays a major role in the reduction of the conductivity of the fracture zones of this well. This statement does not apply to fracture zone FZ4875 (very low conductivity and low calcite content) that is probably connected very poorly to the fracture network. On the opposite FZ4775 is a very conductive zone of several meter thick visible on different geophysical logs. It is particularly well connected hydraulically to GPK2 and the calcite precipitation is not abundant enough to hinder or reduce the fluid circulation. Thus, in GPK3, the maximum fluid flow and significant calcite deposit are not correlated with each other as it is observed in the open-hole section of GPK2.

All the fracture zones of GPK4 were sampled within a distance of 1 to 5 m except for FZ4973 for which no cutting was available (Figure 6). Fluid flow is mainly accommodated via FZ5050 which is framed by anomalies GPK4-A5045 and GPK4-A5060 in addition to the anomalies with the lowest values measured within the open-hole of GPK4. All the other fracture zones are considered to have a similar low fluid flow (all ranked 7 of 7). They all are close to moderate or high calcite anomalies. Therefore it seems that in GPK4, the higher the fluid flow is, the lower the calcite anomaly becomes.

Figure 7 depicts the relationship between calcite content and flow ranking for the fracture zones of the three wells. Flow ranking can be divided into three domains. Low values (1 and 2) correspond to very conductive fracture zones, moderate values (3 and 4) to moderatly conductive fracture zones, and flow ranking above 4 corresponds to poorly or not conductive fracture zones. In the same manner, we can distinguish three main parts in figure 7 with respect to the calcite content. Below 2 wt. % of $CaCO_3$, there is no precipitation of calcite due to hydrothermal alteration. The low calcite content which remains within the the range of possible values for a fresh granite could be due to the pervasive propylitic alteration. Above 10 wt.%, there is a very important precipitation of calcite, and between 2 and 10 wt.%, calcite precipitation may be low to moderate. This partitioning of the diagram allows a characterization of the fracture zones in term of hydraulic connectivity as well as the estimation of the role of calcite precipitation with respect to fluid flow. The distribution of the data for the three wells shows two different and opposite trends: the higher the flow ranking is, the lower the fluid flow becomes, and vice versa. In GPK2, the fracture zones with the best fluid flow correlate with the highest anomalies, whereas the less conductive zones do not show abnormal calcite content. Alteration correlates also quite well with these observations (Figure 4). Calcite is abundant within the best conductive fracture zones but does not seal them, suggesting that the fracture zones have a possible wide aperture and are hydraulically well connected to the reservoir. Fracture zones with a low calcite content correlate with a low fluid flow. In this case, calcite precipitation cannot explain the poor conductivity which suggests that such fracture zones are hydraulically poorly connected to the fracture network, and if not, other minerals may be responsible for their sealing. According to the GPK2 data, it seems that the amount of calcite in fracture zones could be fluid flow dependent. Unfortunatley GPK3 and GPK4 are very different from GPK2.

GPK3 and GPK4 show some similarities. That is, the most efficient fracture zones in terms of fluid flow correlate with the lowest calcite anomalies, whereas the less efficient zones correlate with moderate to very high anomalies. In these two wells, fluid flow seems to be inversely proportional to calcite content, which is opposite to that of GPK2. The fracture zones with high fluid flow are little sealed by calcite (~3 wt.%), suggesting a (very) good hydraulic connection, which is not hindered by the occurrence of other mineral precipitations either. Calcite seems to play a major role in the low fluid flow of GPK3 fracture zones as well as for one of the fracture zones of GPK4. The other poorly conductive fracture zones of this well display either moderate to insignificant calcite content. Nothing can be said about fluid–rock interactions and possible occurrence of alteration halos around fracture zones in GPK3 and GPK4 because of the lack of petrographic data (Figures 5 and 6). However, the highest fluid flow zone in GPK3 at 4775 m is clearly a thicker fracture zone visible on borehole acoustic logs. In GPK4, all the fracture zones show no evidence of alteration except for FZ5237, which suggests a possible alteration halo for this zone.

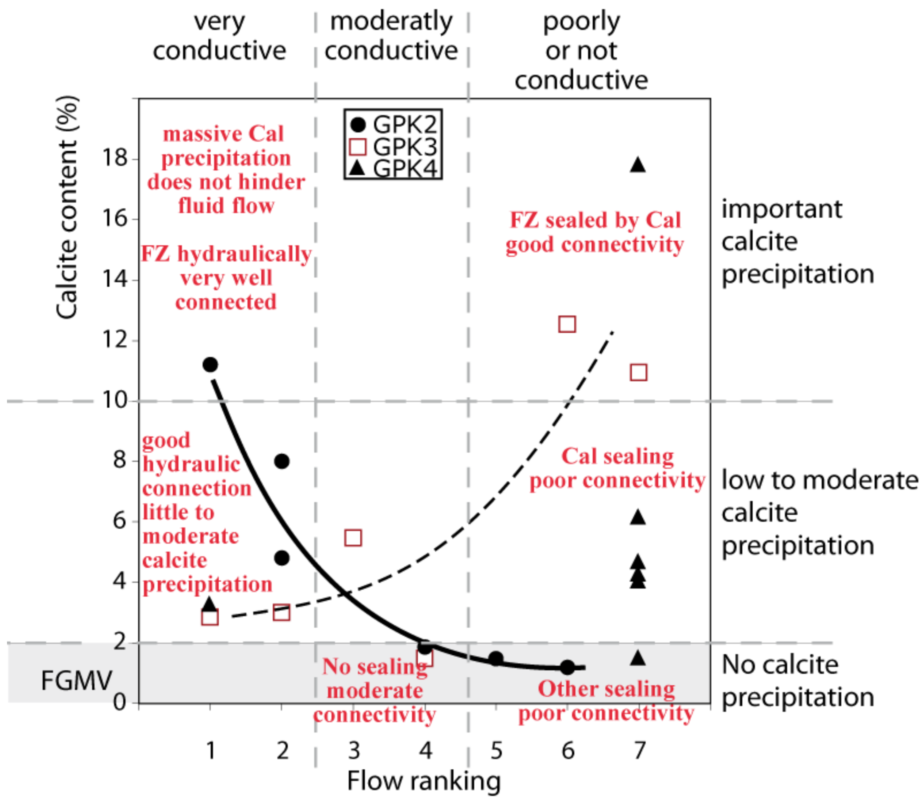

Figure 7. Calcite content vs. flow ranking for the different fracture zones of the three wells (modified after Hébert et ., 2011).

The results of manocalcimetry provide some information concerning the way the chemical stimulations acted. GPK2 just underwent a soft HCl acidizing (Figure 3). The pretty good result of this stimulation can be explained by the fact that acidizing has dissolved large amounts of calcite that were preferably located in the most conductive fracture zones. Therefore it improved significantly the production rate of the well. Nevertheless, these highly permeable fracture zones are also characterized by the abundant presence of illite, which suggests that additional improvement of the connectivity could be achieved in stimulating GPK2 with RMA in order to remove these clay minerals. After hydraulic stimulation, GPK3 underwent a soft HCl acidizing and later a stimulation with OCA HT (Figure 2), resulting altogether in a disappointing enhancement of the injectivity rate. According to Portier et al. (2009), the weak impacts of chemical stimulations are mainly due to the major FZ4775 of level 1, which connects to GPK2 at higher level and accommodates most of the fluid flow (63-78%), hindering any chemical stimulation to reach deeper zones. This is indeed embarrassing as several fracture zones with high calcite content occur below 4775 m MD. Thus a focused chemical stimulation with HCl around 4933 m MD performed between packers or using temporary diverters (e.g. Petty et al., 2011) should improve the injectivity rate of this well.

GPK4 is the well that underwent the largest number of varied chemical stimulations (Figure 3). They all contributed to the significant improvement of the productivity rate of the well. Soft HCl acidizing had probably only effect on the less conductive fracture zones as they are moderately to highly sealed by calcite, i.e. all the fracture zones except the most conductive one. Indeed, FZ5050 shows the lowest calcite anomaly. The conductivity of this fracture zone may have been improved either by the hydraulic stimulation or the others chemical stimulations in case it would be sealed by silicates such as illite. It is also likely that these and/or other fracture zones contained clay minerals that were removed by RMA, NTA and OCA HT, but this remains an hypothesis as these minerals are not very well documented in this well.

CONCLUSION

This study addresses and discusses the results of manocalcimetry measurements performed on random and selected sampling of cuttings from the 3 wells of the Soultz-sous-Forêts EGS. The Soultz granite shows, at least in the deeper part of the geothermal exchanger, an average content of calcite which is relatively high but remains in the range of accepted values for a fresh granite (<1.8 wt.%). Several abnormal calcite contents (i.e. above 2.0 wt.% = calcite anomalies) occur in the three wells. They may reach very high values such as ~13 wt.% in GPK2 and GPK3, and 18 wt.% in GPK4. Similar low and moderate anomalies are also present in the 3 wells. The relationship between flow ranking and calcite content for the fracture zones of GPK3 and GPK4 is opposite to the one of GPK2 (the better the fluid flow, the lower the calcite content). This suggests that the fracture zones of GPK2 are different from those of GPK3 and GPK4, and that the connectivity to the fracture network may be different, too. This difference of behaviour between the 3 deep wells has already been illustrated by the study of induced microseismicity for events having a magnitude higher than 1 (Dorbath et al., 2009). GPK2 is characterized by a rather compact and well structured network of medium-scale fractures, whereas GPK3 and GPK4 are characterized by more localized and discrete fracture zones. This study also illustrates that it is very challenging to generalize what we learnt from a given well and apply it to the whole fractured crystalline rock mass.

Nevertheless some problems still remain. First, some calcite anomalies do not correlate with any identified fracture zones. We can wonder whether these anomalies could correspond to completely sealed fracture zones where no fluid flow can be detected. Second, some fracture zones have no abnormal calcite content. According to Sausse et al. (2007), these fracture zones have a low or very low fluid flow. As they are not sealed by calcite or surrounded by calcite-rich alteration halos, we can suspect that they are poorly connected to the fracture network or/and they are sealed with other secondary minerals (illite, quartz, etc.). Finally, some fracture zones remain poorly or not at all documented (calcimetry, fracture zone level).

The results of this study also provide some explanation for the effects of the chemical stimulations performed in the 3 wells, as well as some information for future chemical stimulations that could be aimed to improve the connectivity between the wells and the fracture network.

This study finally demonstrates that calcimetry is a very simple and low cost analytical method that should be performed prior to any chemical stimulation in order to choose the most efficient treatment.

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