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CHARACTERIZATION OF FRACTURE CONNECTIVITY AND FLUID FLOW PATHWAYS DERIVED FROM GEOLOGICAL INTERPRETATION AND 3D MODELLING OF THE DEEP SEATED EGS RESERVOIR OF SOULTZ (FRANCE).

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ABSTRACT

This study presents a 3D interpretation of the fracture connectivity and the resulting permeability derived from the study of the geophysical logs run after the drill of three wells at 5 km depth in the framework of the Soultz European EGS geothermal project.

The major fracture zones encountered in these wells are located through examination of borehole image logs, classical geophysical well logs and cutting samples. These large-scale fracture zones could be 10m thickness and are characterized by sealed core and a peripheral damage zone that is highly porous and/or fractured and therefore highly permeable. However, two scales of fracture networks are present in the granite: a highly connected network consisting of fractures with small apertures that maybe represents the far field reservoir, and another network that contains these isolated and wide fracture zones which develops an anisotropic permeability in the rock and allow the hydraulic connection of the wells. This hierarchy of flow is strongly dependant on the petrophysical properties of the rock and especially is directly linked to the intensity of the granite hydrothermal alteration.

A 3D model of the Soultz exchanger is constructed with the gOcad code (Earth Decision, Paradigm). The model is enclosed in a 3D regular grid extending in the open part of the heat exchanger between 4000 and 5200 m true vertical depth. The grid axes fit on the directions of the maximal anisotropy of the microseismic cloud observed during the different stimulation tests. The grid is aligned with a global N170°E direction and represents a total volume of 1.5 109 m^3. The fracture database of the three wells (GPK2, GPK3 and GPK4) is integrated in the model and some statistical analysis of the fracture connectivity is performed with the FracaFlow code (Beicip-Franlab). The fracture network permeability is estimated taking into account different parameters such as apertures, extensions and porosity derived from petrophysical criteria. Main fluid flow pathways are identified and compared to the occurrences of fluid losses during the well stimulation tests.

Finally, the 3D model is used to match the Soultz granite lithology, geophysical and hydraulic characteristics. The statistical treatment of the Spectral Gamma Ray logs shows that specific anomalous K_2O contents due to illite precipitation could indicate the presence of altered zones. These zones correspond to zones where large fluid losses occurred during injection tests, and often match with thick altered fractured zones.

The 3D model of the Soultz granite could be used as a geometrical basis for fracture quantification of fracture porosity and permeability determination in the EGS reservoir.

INTRODUCTION

Soultz-sous-Forêts, located in the Upper Rhine Graben, hosts one of the few deep geothermal 'Enhanced Geothermal System' test sites in the world. At its current state of development, the EGS site consists of three boreholes: GPK2, GPK3 and GPK4, the European geothermal pilot plant which extends to more than 5000 m depth, GPK1 a first hydraulic test well which extends to 3600 m and a reference hole EPS1 which has been fully cored down to 2230 m (Figure 1).

In deep enhanced geothermal systems (EGS), natural or forced fluid circulation takes place through the fracture networks in crystalline rocks characterized by low matrix porosity. The connection between fractures and the consequent anisotropic permeability are then crucial to insure the efficiency of the geothermal exchanger and to recover sufficient fluid temperatures at surface.

The objective of this paper is therefore an attempt to reconstruct and quantify a 3D network of connected, permeable fractures within the target rock volume between the wells and to achieve a better understanding and prediction of the hydraulic response of the granite respecting the structural observations of fault and fracture organizations and petrophysical criteria. An important database of borehole image logs, classical geophysical well logs and cutting samples (Dezayes et al., 2005) is used to reconstruct the 3D model of the fractured reservoir.

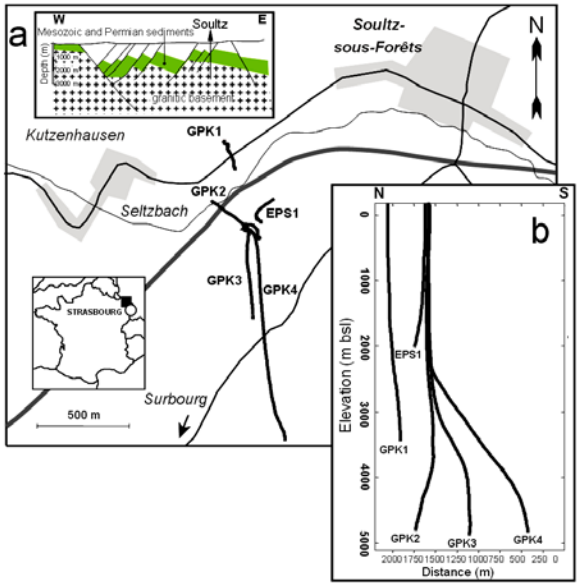

Figure. 1. Schematic geological map of the Rhine Graben and location of the Soultz-sous-Forêts EGS site (a). Location and traces of the Soultz deep geothermal wells; solid lines correspond to well traces (a and b). (Modified after Dezayes et al., 1995, 2005).

GEOLOGY AND GEOPHYSICS

The Soultz granite is a Hercynian monzogranite characterized by phenocrystals of alkali feldspars in a matrix of quartz, plagioclase, biotite and minor amphibole. The granitic basement at Soultz has been strongly altered by flowing fluids (vein and pervasive alterations). Fluid circulation takes place through two fracture networks that create scale-related flow: the first is a closely-connected network of small-aperture fractures that may represent the far-field reservoir, and the second is a set of local, wide-aperture fractures that result in an anisotropic permeability system connecting the injection and production wells hydraulically (Sausse and Genter, 2005). This hierarchy of flow is strongly dependent on the petrophysical properties of the rock and is directly linked to the intensity of the granite hydrothermal alteration (Sardini et al., 1997; Ledésert et al., 1999; Sausse, 2002; Géraud et al., 2005; Sausse and Genter, 2005; Hooijkaas et al., 2006).

The French Geological Survey (BRGM) collected geological and well logging data to characterize the Soultz fractured granite reservoir in terms of petrography, hydrothermal alteration and natural fracture network; well data were acquired by the Schlumberger and Geoservice companies. The main well logging in the three deepest wells (GPK2, GPK3 and GPK4) data consisted of the gamma-ray spectral log. Fracture geometrical properties and their spatial relationships were analyzed based on amplitude and transit time anomalies derived from acoustic image logs (Ultrasonic Borehole Imager; UBI). The fractures can be identified with high accuracy and measured in orientation and in dip by these borehole imagery techniques. Other flow and/or temperature logs were run in the different deep wells during injection and production tests since 2003 and some interpretation of the main fracture and permeable zones are described by Dezayes et al. (2005). These flowing fractures could correspond to isolated fracture, series of thin parallel fractures and large-scale fracture zone. These large-scale fracture zones could be 10 m thickness and are characterized by sealed core and a peripheral damage zone that is highly fractured and therefore highly permeable (Genter et al., 2000). Geometrical and hydraulic parameters such as fracture orientations, their relative contribution to flow are available in the open holes for the three deepest wells (Dezayes et al., 2005; Sausse et al., 2007).

These different types of fractures appear in an altered granitic matrix. Sausse et al. (2006) have recently showed that the deepest zones of the wells are characterized by local anomalous Gamma Ray values that could match with high permeabilities values.

This paper tries therefore to precise this result using a complete 3D model of the Soultz reservoir fracture network matched in details with the Soultz granite lithology, geophysical and hydraulic characteristics.

3D GEOMETRICAL MODEL OF THE DEEP WELLS

Fracture orientations

The main fractures are modeled by planar discs centered on the wells and respecting the fracture orientations (Table 1). Most of the fractures appear to be members of a nearly-vertical conjugated fracture set with a symmetry axis striking NNE-SSW consistent with the Rhine Graben tectonics.

Fracture extensions

The major issue for reconstructing the 3D geometry of the Soultz fracture network is the question of the fracture extensions. In a first approach, we define and correlate the fracture extensions according to the importance of flow observed on flow log runs during the injection and stimulation tests in the wells. Extensions are variable, fixed with an arbitrary correlation between the fracture disc object diameter and the importance of flow registered on flow logs.

Maximal extensions of 600 m are fixed in order to respect one unique criterion: a fracture plane that cuts one well cannot intersect the others if no information indicates the presence of such fracture zone on the UBI images.

However, the presence of kilometric fault is well known in the Soultz Graben site. Indeed, one of the fracture zones was specifically treated and was assumed to be the most important in the reservoir. This fault zone intersects the well GPK3 at 4775 m depth (MD) and corresponds to a huge cave and to a casing leak in GPK2. Moreover, this fracture zone doesn't cut the well GPK4. The fault plane is located around 90 m below the bottom of the hole. Tracer tests performed between 2000 and 2005 in the Soultz wells (Sanjuan et al., 2006) demonstrate that 2 types of circulation are developed between the wells. These tests gave evidence of a fast and relatively direct hydraulic connection between GPK3 and GPK2 (short loop) but also indicated the existence of another larger and slower hydraulic connection between GPK3 and GPK4 (large loop). The absence of direct connection between the open hole of GPK4 and the fault plane could explain these two types of hydraulic behaviors.

The assumption of the presence of large fault zone in the deep reservoir is therefore done and a final extension of 2000 m was fixed for this fracture.

Fracture types	WCO_A	WCO_B	CO_A	CO_B	DCO_A	DCO_B	ZF_A	ZF_B
mean dip azimuth	232	18.4	42.6	262	270	63	263	61
mean dip	70	67	68	70	69	75	76	72
Average True spacing (m)	271	785	192	82	26.5	39	250	1140
nb data at wells	11	7	26	44	149	96	15	5
distribution length	log norm.	log norm.	log norm.	log norm.	log norm.	log norm.	log norm.	log norm.
Mean length (m)	40	40	10	10	1	1	100	100
Apertures (m)	0.08	0.08	0.01	0.01	0.001	0.001	0.1	0.1

Table. 1. Main parameters used to stochastically modeled the fracture networks with the Fraca® code. The GPK3 fault zone is not included in the stochastic generation of the fracture networks. WCO (Wide Connected Open Fractures, CO (Connected Open Fractures, DCO (Discontinuous Open Fractures). A and B types of fractures correspond respectively to 90-100° and 210-240° dip directions of fracture planes.

Fracture apertures

A fracture is usually defined as two smooth and parallel planes separated by a constant hydraulic aperture. This approach is generally used in the case of regular fracture networks with smooth and widely open fractures. In this case, the fracture permeability corresponds to global and often maximal conductivities controlled by the cubic law. However, in the case of the Soultz fracture zones, where clusters of thin, hydrothermally altered conjugated fissures and fractures intersect each other to produce a highly cataclased zone, the choice of realistic values of apertures is therefore complex. Apertures of the different sets of fractures used in the model are higher than classical values used in parallel plate models. This assumption wants to takes into account the clustering phenomena of fracture zones at Soultz. The fracture zone aperture consists of the addition of thinner fracture apertures organized in clusters.

By this way, maximal values of apertures ranging between 8 cm and of 10 cm are computed for the systematic sets of fractures (Table 1). This ratio between fracture extension and aperture gives only a hierarchy of relative apertures in the model. Fracture apertures are assumed to be the effective aperture available for fluid flow i.e. that fix the fracture real conductivity.

3D HYDRAULIC MODEL OF THE DEEP RESERVOIR

Discrete Fracture Network modeling

Several fracture networks are taken into account in the model. After a structural statistical analysis, derived from the UBI image analysis, several sets are described. First, a fracture classification takes into account the opening and types of opening of fractures that can be defined from the UBI images (amplitude versus transit time). The main fracture zones (significant flow losses on flow logs, Dezayes, 2005) define a first type of fractures (ZF in Table 1). Then 3 categories of fractures corresponding to moderate or minor flowing fractures are described and characterized as WCO (Wide Connected Open Fractures), CO (Connected Open Fractures, DCO (Discontinuous Open Fractures). Then, the final sets of fractures are defined using these categories and structural criteria: two main orientations are observed with subvertical fractures with dip directions of 90°-100° and 210°-240° (Table 1, fracture types A and B). Their lengths, extensions, main orientations (strikes and dips weighted by Fisher coefficients), main spacings, main apertures are the base parameters of a Fraca® (BeicipFranlab, IFP) Discrete Fracture Network modeling (DFN (Figure 2). Numerous, high density fractures are modeled in the granite representing a highly connected network of thin fractures. The recognized intersections of fractures with the wells are preserved.

The fault zone in GPK3 (4775 m depth MD) is individually treated and imported in the 3D model using a deterministic approach. The fault zone corresponds to one single plane characterized by a most important extension and aperture than the others.

The output of the model is a synthetic 3D set of rectangles populating a grid volume around the wells in the open hole sections (4500-5000 m depth, Figure 2).

Fracture conductivities

The final fracture network geometry (fracture location, orientation, length, extension) as well as fracture properties (aperture, conductivity) come from stochastic generation of local 3D models using the previous fracture set characteristics.

Synthetic fracture integrated conductivities respecting the modeled network and observed data are calculated respecting equation 1 derived from the Poiseuille Law (Cacas, 1989):

$$c = g \cdot a^3 \cdot l / 12 \cdot \nu \qquad (1)$$

with a, the fracture aperture, c, the fracture conductivity in mD.m, g the acceleration due to gravity, l the length of couple of fracture intersections and ν *the fluid kinematic viscosity.*

The fracture conductivity is supposed to be uniform over a given fracture surface but it can vary from one fracture to another. For example, the fracture conductivities range from 0.42 to 30 mD.m around the GPK3 well.

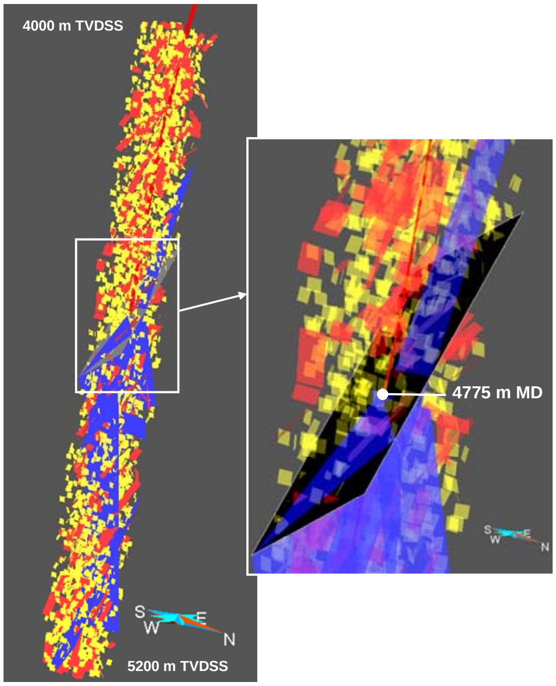

Figure. 2. A) Example of the GPK3 discrete fracture networks generated from the geometrical parameters presented in Table 1 (gOcad® representation). Colors correspond to the different sets of fractures. B) Focus in the zone where the main fault zone intersects the GPK3 well at 4775 m.

Fracture conductivities were propagated in each well grid model via a property interpolation using the gOcad® DSI tool (Earth Decision, Paradigm, Mallet, 1989 and 2002). This interpolation and propagation of the 3D property allows to define the main zones of fracture occurrences and high conductivities corresponding to clusters of fracture intersections. The final global conductivity model was then compared to the geophysical signal recorded during the well GPK3 logging.

FRACTURE HYDRAULIC BEHAVIOR AND PETROPHYSICS

Statistical study of Spectral Gamma Ray

Spectral gamma ray ranges vary from one well to another. GPK3 and GPK2 (upper part of the reservoir) show highest values with two modes observed respectively at 195 and 205 GAPI in comparison with a lower modal value of 160 GAPI observed for GPK4 logs (Figure 3).

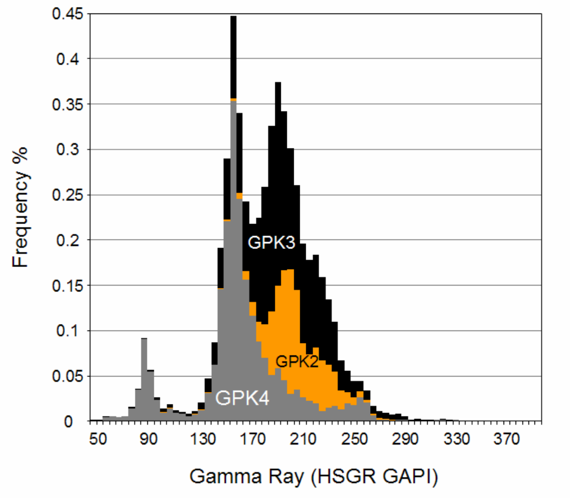

Figure. 3. Frequency histograms showing the distributions of the spectral Gamma ray values for the Soultz three deep wells.

Figure 3 shows that GPK4 is less radioactive than GPK2 and GPK3. This shift of the gamma ray values could indicate a lesser degree of alteration.

A statistical study of the Spectral gamma ray logs was performed on GPK3 and GPK4 geophysical logs using Hierarchic Ascendant Classification (HAC) methodology. GPK2 was not included in this statistical study because of a lack of data in the deepest part of the reservoir. 6 classes of Gamma Ray electrofacies were determined corresponding to groups of logging depths characterized by low intra and high inter variances of the spectral Gamma ray group of variables. The 6 classes show gradual values of Potassium content and more sparse ones for Thorium and Uranium contents (Figure 4).

Genter et al. (1998) show that water-rock interactions in the fractured zone of the granite have resulted in the leaching of primary minerals and the precipitation of secondary minerals (quartz, clays, carbonates, sulfides) within the fractures and on their walls. Potassium is present in clay minerals such as illite and at Soultz is indicative of fractured, altered zones (Sardini et al., 1997; Ledésert et al., 1999; Sausse, 2002; Sausse and Genter, 2005). Potassium is also found in K-feldspar and biotite, minerals that are easily altered into K-enriched clay minerals.

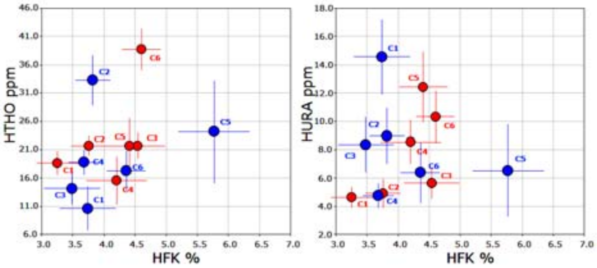

Figure. 4. Frequency histograms showing the distributions of the spectral Gamma ray values for GPK3 (red circles) and GPK4 (blue circles)

Uranium is present in some accessory minerals such as sphene, apatite and oxides, but it is a mobile element that can easily be leached and removed from the rock matrix by fluids circulating through fractured zones.

GPK3 electrofacies class C5 seems to be marginal because it corresponds to simultaneous high ranges of Potassium and Uranium contents in the rock. This class could therefore characterize a localized granitic facies variation instead of a fractured altered zone that could not match with high Uranium contents. In a same way, the electrofacies class C6 is characterized by simultaneous high Potassium and Thorium contents. Sausse et al. (2006) show that K and Th are characteristic of altered fracture zones in the granite, while changes in U content could reflect variations in the rock matrix. However, isolated Th anomalies are rare and could indicate higher amounts of zircon and/or monazite in the rock matrix.

GPK3 electrofacies classes C5 and C6 could therefore correspond to lithological variations of the rock matrix.

Spectral gamma Ray values in front of fracture conductivities (GPK3)

The matching between spectral gamma ray values and fracture conductivities shows that the highest conductivities are observed for high Potassium contents in the rock (GPK3 electrofacies class C3, C4, C6). Class C5 corresponds to such high Potassium contents but this class is characterized by systematic low conductivity that assesses the fact that this class could correspond to localized facies variations. GPK3 electrofacies class C1 and C2 show lower conductivities corresponding to lower Potassium contents (Figure 5).

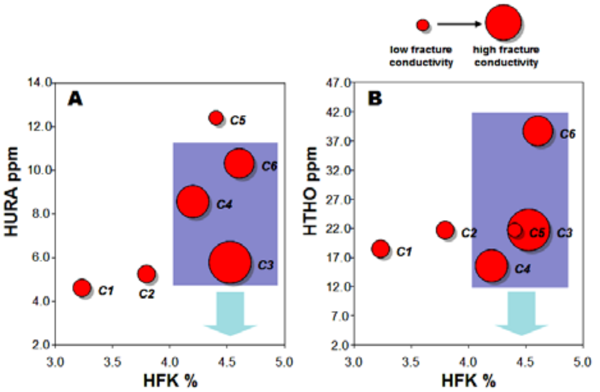

Figure. 5. Cross-plots A) Uranium (HURA ppm) – Potassium (HFK %) and B) Thorium (HTHO ppm) – Potassium (HFK %). Sizes of the dots are proportional to fracture conductivities. Red squares shows the Potassium ranges where high fracture conductivities are observed.

Spectral gamma Ray values in front of fracture conductivities (GPK4)

The 6 classes of HAC electrofacies defined in GPK4 were superimposed in the Uranium-Potassium and Thorium-Potassium cross-plots (Figure 6).

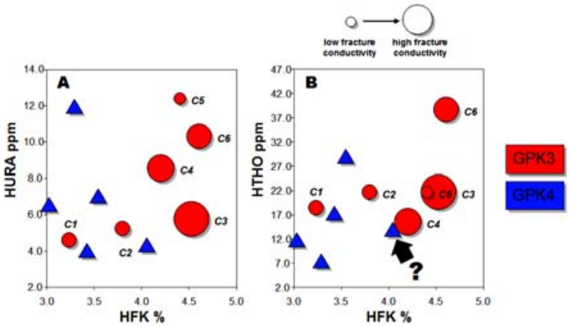

Figure. 6. Cross-plots A) Uranium (HURA ppm) – Potassium (HFK %) and B) Thorium (HTHO ppm) – Potassium (HFK %) for GPK3 electrofacies (red circles) and GPK4 electrofacies (blue triangles). Sizes of the dots are proportional to fracture conductivities.

Figure 6 shows that the main GPK4 electrofacies classes do not match with the Potassium high content classes of GPK3. Only one GPK4 electrofacies is plotted near the GPK3 C3 electrofacies in the Thorium-Potassium cross plots. This equivalent Potassium and Thorium content could correspond too to high conductivity fracture zones (Figure 6B). This class corresponds to the GPK4 C6 electrofacies (Figure 4).

However, Figure 7 shows that this GPK4 electrofacies doesn't match with such high conductivity.

Indeed, in GPK4, the most important conductivities correspond to electrofacies C3 and C1 that match with low Potassium contents.

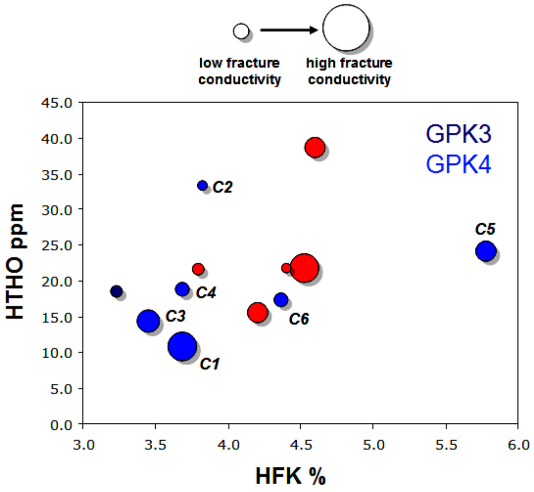

Figure. 7. Cross-plot Thorium (HTHO ppm) – Potassium (HFK %) for the two wells GPK3 and GPK4. Sizes of the dots are proportional to fracture conductivities.

The conclusion of a good matching between conductivities and Potassium content observed in GPK3 could not be applied in the case of GPK4.

GPK4 shows less alteration of the granitic matrix than GPK3. Higher conductivities are derived from the Discrete Fracture Network modeling. GPK4 shows numerous fractures in its open hole section: 285 instead of 132 fractures for GPK3. This fact implies a highest connectivity in the vicinity of the well and higher consecutive conductivities.

The fracture network connectivity must therefore be taken into account and superimposed to the petrophysical criteria before to try to propose a generalized hydraulic model of the reservoir.

FRACTURE NETWORK CONNECTIVITY

The 3D Fraca® hydraulic model allows to define the different connections between the fractures and the wells (flow tubes). The connected fracture network is illustrated by the display of the existing flow tubes in the Fraca® camera. Indeed, Figure 8 shows that GPK3 develops large and channelized fracture connectivity around the main fault zone observed at 4775 m depth (MD).

The mapping of the flow percentage on the tubes shows that the main permeability is observed for the fault plane that connects other important structures around the well (first left image of GPK3, Figure 8). Then the flow propagates in channelized, well defined pathways. On the opposite, GPK4 shows more numerous flow tubes than GPK3 but mainly developed in the vicinity of the well. Some connectivity exists between the main structures in the well but they mainly make sorts of shortcuts of flow, connecting the well with itself (white arrow, figure 8). The high density of fractures observed in GPK4 is therefore not directly linked to the well permeability. GPK4 shows more numerous fractures than GPK3 but is characterized by a lesser degree of alteration and a consecutive lower permeability.

These two different hydraulic behaviors could explain the difference of well responses during the tracer tests. The absence of direct connection between GPK3 and GPK4 could be mainly due to the difference of fracture connectivity development in GPK4.

DISCUSSION

Discontinuities such as fractures are potential sites for fluid circulation and have important implications for the hydraulic properties of rocks. The matrix permeability of igneous rocks is generally small and, consequently, the global permeability is mostly controlled by the fracture and crack networks. Therefore, the quantification of the fractured rock hydraulic properties strongly depends on the knowledge of the geometrical parameters of fractures (orientation, extension, aperture, density).

The Soultz site is the object of various and numerous studies since 1987. The knowledge of the fracture distribution in wells is optimal thanks to numerous structural and geophysical studies. The Soultz fracture database is now a chance to test the various modelling approaches that wants to simulate the 3D fractured deep geothermal reservoir. The recent VSP survey (April 2007) performed at Soultz in the deep wells will probably help too to improve the 3D model of the deep fracture zones developed within the Soultz EGS reservoir.

The main results of this study are the assessment that permeability is linked to the alteration of the rock mass. The fluid flows through the granite matrix results in the dissolution of some primary minerals and the precipitation of secondary phases. Hydrothermal alteration may create secondary porosity in the rock and resulting higher permeabilities.

The modeling approaches must take into account these observations and petrophysical criteria to define the input parameters of model. In this study, high values of apertures are used to define the different fracture sets. Define a fracture aperture of 10 cm is not realistic in in situ lithostatic pressure conditions. However, the cluster organization of fractures at Soultz implies that thinner apertures cannot be realistic too. Whatever the value of apertures used to model the fracture hydraulic behavior, the main important point stays that the aperture hierarchy between fracture sets plays the main role. This aperture could be easily recorded from UBI images.

Then, the extension of fractures can be derived from the aperture. In the Soultz case, such assumptions of an extension aperture ratio allows to propose a first 3D Discrete fracture Network in the reservoir and around the wells.

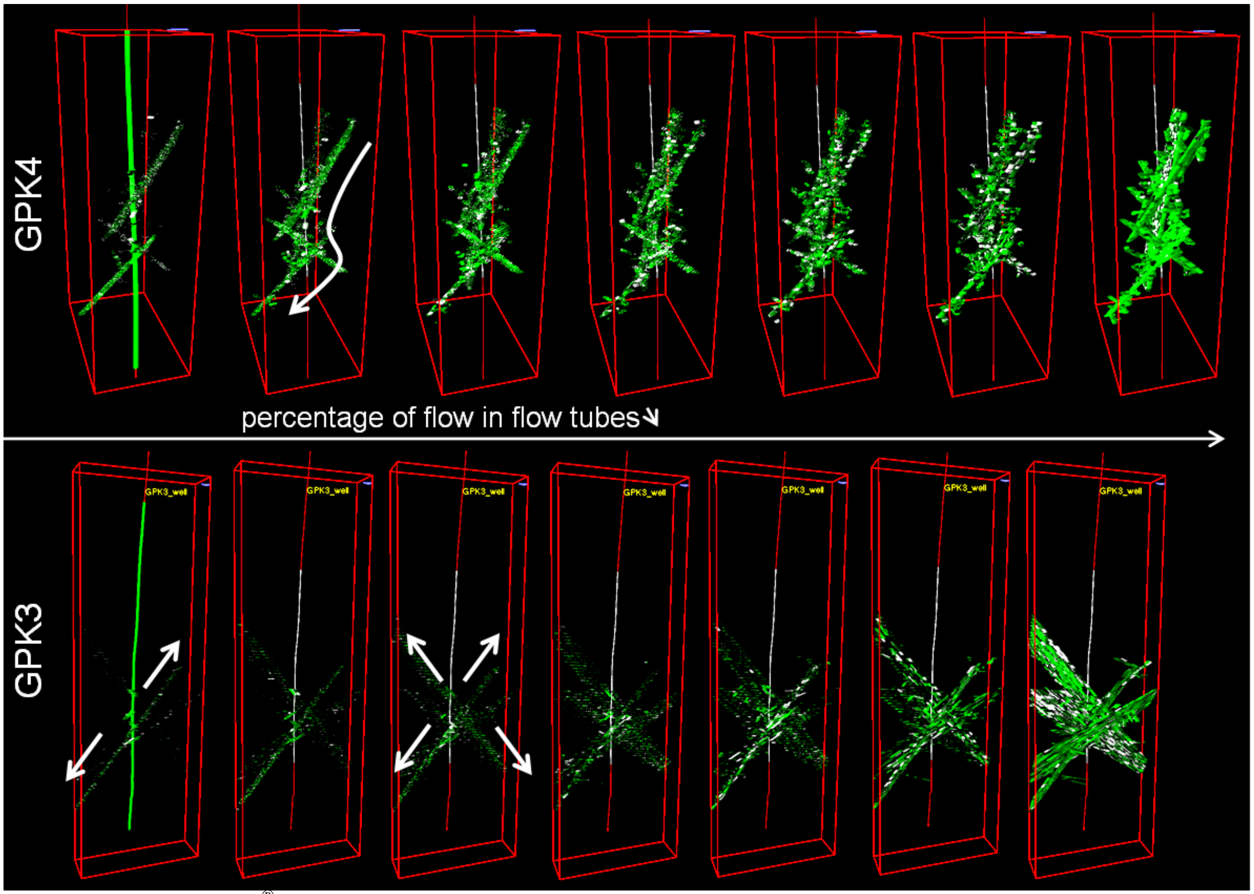

Figure. 8. Fraca® representations of GPK3 and GPK4 wells showing the flow tubes existing between the connected networks of fractures. Each 3D model corresponds to a certain range of the flow percentages calculated in the flow tubes (from left to right: 100-90%, 90-80%, 80-70%, 70-60%, 60-50%, 50-40% and 40-0% of the flow).

CONCLUSION

The purpose of this work is to achieve a better understanding and prediction of the hydraulic response of the granite on the basis of its petrophysical and fracture properties.

Fracture zones are well defined at Soultz and the entire database is characterized by the type of fractures: main fracture zones and moderate and minor flowing fractures called WCO (Wide Connected Open Fractures), CO (Connected Open Fractures, and DCO (Discontinuous Open Fractures). All of these fractures are characterized by their geometrical parameters (lengths, extensions, strikes and dips weighted by Fisher coefficients, main spacings, main apertures) that are the basis of a Discrete Fracture Network (DFN) modeling (Fraca®).

A Spectral Gamma ray statistical analysis (HAC) is performed and distinguishes 6 electrofacies classes of specific Potassium, Thorium and Uranium contents in the deep part of the Soultz reservoir. Gradual values of Potassium content are linked to gradual more and more intense alteration of the granite. More sparse distribution of Thorium and Uranium contents coincide probably with localized facies variation in the granite.

The DFN model is imported in the geomodeler gOcad® and the conductivity property of fractures are extrapolated in the 3D reservoir around the wells GPK3 and GPK4. GPK2 is not studied in this paper because of a lack of spectral gamma ray data in the deepest part of the reservoir.

GPK3 shows a good matching between high Potassium contents and high fracture conductivities that are developed in isolated, well connected but channelized flow pathways around the main fault plane of the reservoir (fault zone at 4775 m in GPK3). On the opposite, GPK4 develops more numerous connections but probably between less altered fractures. The main fluid flow pathways stay concentrated around the vicinity of the well that could explain the poor hydraulic behavior of GPK4.

The important result is that the 3D modeling of the reservoir must take simultaneously into account differential degrees of rock alteration and different types and intensity of fracture connections. This geological model could be used as a first geometrical basis for quantification of fracture porosity and permeability in the EGS reservoir.

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