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Petrophysics and Permeability in the Soultz Granite

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ABSTRACT

This study presents a multidisciplinary approach to understand and describe fracture permeability in the Soultz-sous-Forêts granite (Bas-Rhin, France). At Soultz, during the 1993 stimulation tests in the GPK1 well, it was shown that only a limited number of natural fractures contributed to flow whereas there are thousands of fractures embedded within the massive granite. In order to understand the past and actual flow hierarchy, a detailed comparison between petrophysics (log correlations), static (fracture apertures based on ARI raw curves) and dynamic data (hydraulic tests) is carried out. The hierarchy of flow is strongly dependant of the petrophysical properties of the rock and especially is directly linked to the intensity of the granite hydrothermal alteration. Log charts with Gamma Ray and bulk density logs are proposed to qualify the hydraulic behavior of fractures. The final objective remains the matching of structural and hydraulic models.

1. 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. The aim of this study is to propose a multidisciplinary approach to understand and describe fluid flow pathways observed in fractures and fracture networks based on the study of the petrophysical properties of rock and fractures. The Soultz granite was strongly altered by fluid percolation (veins and pervasive alterations). Previous results show that two scales of fracture networks are present in the Soultz granite: a highly connected network consisting of fractures with a small apertures that may represent the far field reservoir, and isolated and wide fractures which produce anisotropic permeability in the rock and allow a hydraulic connection between the injection and production wells. This hierarchy of flow is strongly dependant on the petrophysical properties of the rock and is directly linked to the intensity of the granite alteration (Sausse and Genter, in press, Sausse, 2002).

This work presents a preliminary interpretation of the complex flow profiles measured during the Soultz 1993 hydraulic tests and relates them to geophysical log values characterizing the bulk density or radioactive content of the rock matrix. The precise description of the large logging database available for the different wells is used to detect a specific permeability signature on geophysical logs.

2. GEOLOGICAL SETTINGS

The Soultz granite is a Hercynian monzogranite characterized by phenocrystals of alkali feldspars in a matrix of quartz, plagioclase, biotite and minor amphibole. 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 (fig. 1). This paper is concerned with observations in GPK1 (open hole between 2850-3600 m depth) made during major hydraulic injections conducted in 1993, before well GPK2 was drilled. The depth investigated is a 2800-3150 m depth interval which constitutes the main injection production zone between GPK1 and GPK2.

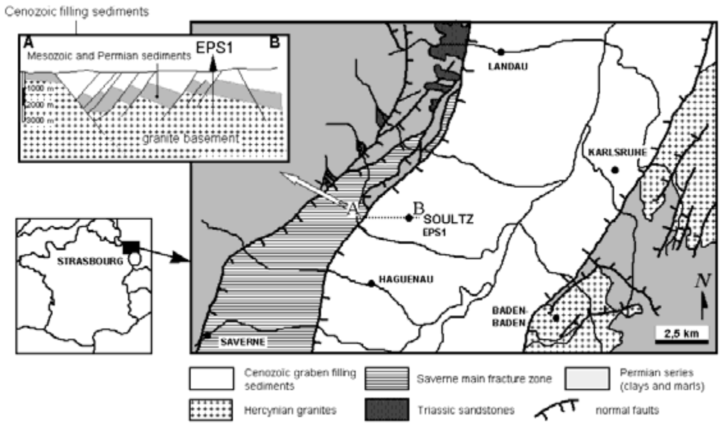

Figure 1: Schematic geological map of the Rhine graben and location of the geothermal drill site of Soultz-sous-Forêts. Vertical section AB: details of cross section (after Dezayes et al., 1995).

2.1 Logging data

2.1.1 Geophysical logging Data

The analysis of conventional geophysical well logging was used to study the relationship between fracture permeability and the petrophysic of the granite. The French geological survey (BRGM) collected geological and well logging data in order to characterize the deep geology of the Soultz fractured granite reservoirs in terms of petrography, hydrothermal alteration and natural fracture network. Data were collected by different scientific teams (BRGM, Stadtwerke Bad Urach) or measured by service companies (Schlumberger, Western Atlas, Geoservice, Datalog, ENEL, Scientific Drilling). Well logging data consist of sonic, photoelectric absorption, nuclear and caliper logs for the main data (fig. 2). Due to borehole conditions (borehole size, temperature, mud) or budget limitations, the geophysical logs are not equivalent in the Soultz wells. For instance, this paper deals with data measured in the GPK1 well in 1993, before the stimulation of the well, for a logging depth between 2800 and 3150 m, where only logging data as Thorium, Uranium, Potassium contents, standard gamma ray, caliper, bulk density, sonic and photoelectric absorption factor are available.

Several depth zones are characterized by specific log values in the 2800-3150 m depth interval.

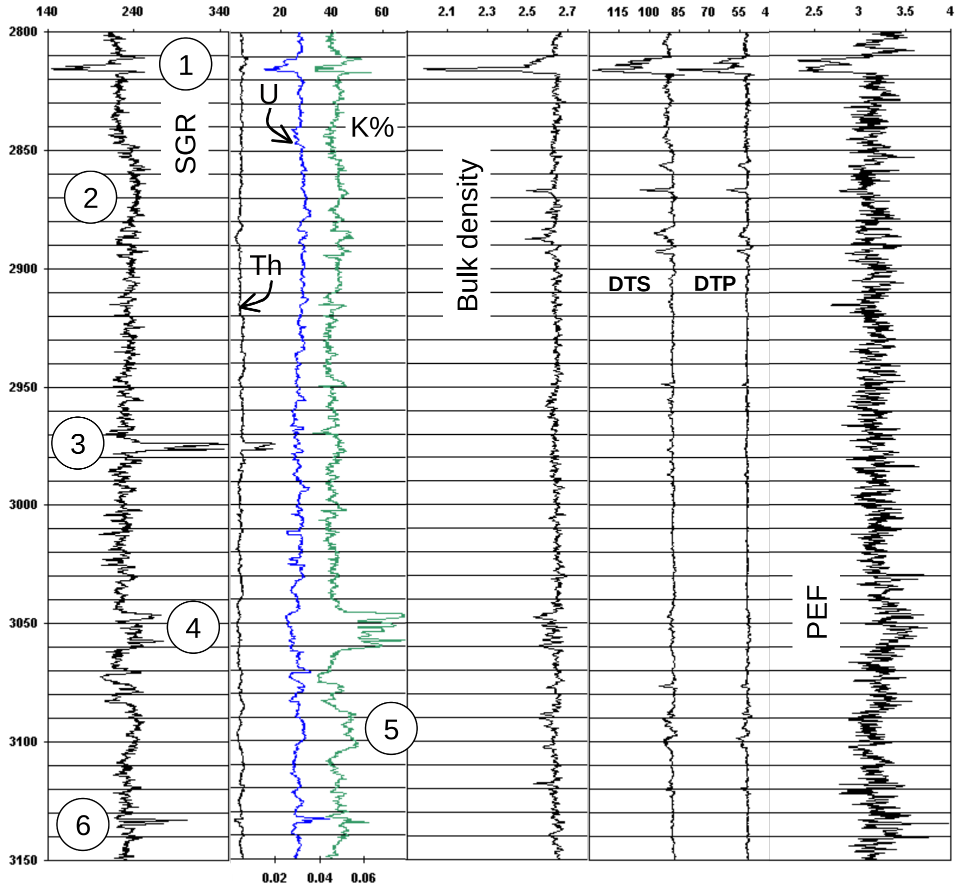

Figure 2: Main geophysical logs available and plot in the 2800-3150 m depth interval. SGR is Standard Gamma Ray (GAPI), U, Th are Uranium and Thorium contents in ppm, K% is the Potassium content in percentage, Sonic DTP and DTS corresponds respectively to the P and S wave slowness in the granite ($\mu s.ft^{-1}$) and PEF is P_e, the photo-electric absorption factor ($Barns.e^{-1}$). Numbers show the depth zones characterized by specific log values.

A first strong anomaly is detected between 2810-2820 m depth. It corresponds to a negative deviation of the standard gamma ray mainly due to the decrease of U, Th and K contents (fig. 2). The Potassium element is present in clay minerals like illite and indicates fractured altered zones. The Potassium is located also in K-Feldspar and in biotite. Uranium is present in some accessory minerals like sphene, apatite and oxides. However, However, Uranium is a mobile element and can easily be leached from, and removed from the rock matrix by solutions circulating through fracture zones. The peaks of these different curves are generally correlated with a sharp increase of the hole diameter. Moreover, this zone is characterized by a low peak of bulk density and a strong positive anomaly of the sonic log corresponding to slow acoustic speeds in the rock. The photoelectric absorption factor decreases too despite the noisy signal for this logging. These signals collectively suggest the presence of a highly altered and fractured zone between 2810 and 2820 m depth. This fracture was recognized during the logging operations as a natural permeable fracture. Prior to the stimulation, 3 main fractures were recognized as permeable at 2815, 3385 and 3492 m GPK1 depth, Genter et al., 1995).

Then, a second zone of depth shows a large but slight positive deviation of the Gamma Ray between 2845 and 2880 m. This anomaly is matched with isolated negative or positive peaks of bulk density and sonic. These peaks likely correspond to open fracture in the well. The photoelectric absorption factor remains very noisy at such depths. This zone is described as moderately altered in Sausse and Genter (in press) e. g. a pervasive alteration which surrounds fractures that affects the granite on a large scale without visible modification of rock texture. Color variations in the granite, ranging from grey to orange-green, show that low-grade transformation of biotite and plagioclase has occurred. Some of the joints sealed with calcite, chlorite, sulphides and epidote are related to this early stage of alteration.

A third zone of depth is characterized by a strong increase of Gamma Ray between 2970 and 2980 m. This peak is mainly linked to the increase of Thorium content in this zone. No real variations of the other logs can be observed. Thorium is present in zircons which can be therefore present in the granite.

The fourth zone of depth shows slight increases in Gamma Ray linked to high values of Potassium contents in the rock between 3045 and 3065 m depth. This zone is also characterized by a decrease of the bulk density and an increase in the P_e and can be defined as an altered and fractured zone.

Again, in the fifth zone of depth between 3075 and 3105 m, a slight increase of gamma ray matches with an increase of Potassium contents denoting high alteration grade in that zone. In this case, only slight variations of the bulk density and sonic are observed. The photoelectric absorption factor is a bit lower than the general trend at these levels of depth.

Finally a last zone of depth between 3130 and 3135 m presents anomalous positive values of gamma ray linked to an increase of Uranium and Potassium contents but no real deviations of the global bulk density, sonic or P_e trends are observed.

These 6 particular depth intervals are now compared to the hydraulic properties of the granite deduced from the study of flow logs measured during the hydraulic stimulation of GPK1.

2.1.2 Hydraulic tests

After the deepening of the GPK1 well in 1992 to 3600 m with the casing shoe set at 2850 m, large-scale hydraulic tests were carried out in 1993 to first characterize the natural permeability of the rock mass and then enhance the permeability of the natural fracture system through massive fluid injections (Jung et al., 1995, Baria et al., 1993 and 1999). The profile of flow in the well during the complete test sequence was obtained from analysis of spinner and temperature logs (Evans et al., 1996 and Evans, 2000). Fractures which produce flow during the stimulation were identified and precisely located in depth. Each identified fracture was assigned by Evans (2000) to one of the three categories that broadly reflected the different flow contributions (fig. 3c). They correspond to major flowing fractures that broadly correspond to important structures that supported more than 5% of the wellhead flow; moderately flowing fractures detectable from spinner logs and minor flowing fractures that produced a temperature disturbance on T-logs but are not detectable on spinner logs (fig. 3c). Evans (2000) found that following the injection stimulation some 20% of the 500 fractures identified by Genter et al. (1997) on UBI images supported detectable flow. Prior to the stimulation less than 1% were recognize as permeable (3 fractures at 2815, 3385 and 3492 m depth, Genter et al., 1995).

2.2 Permeability calculation

Permeability of the granite was estimated with a 2D horizontal unidirectional model of flow (fig. 4). This model assumes a laminar flow within a horizontal plane between an injection well and a production well. The radial flow in the near well injection zone is neglected (fig. 4). The flow is assumed to be equivalent in two opposite directions from the well and fluids move in the direction of the maximum anisotropy of the microseismic cloud detected at Soultz during the 1993 injection tests (Baria et al., 1994; Jung et al., 1995; Jung, 1994) (fig. 4).

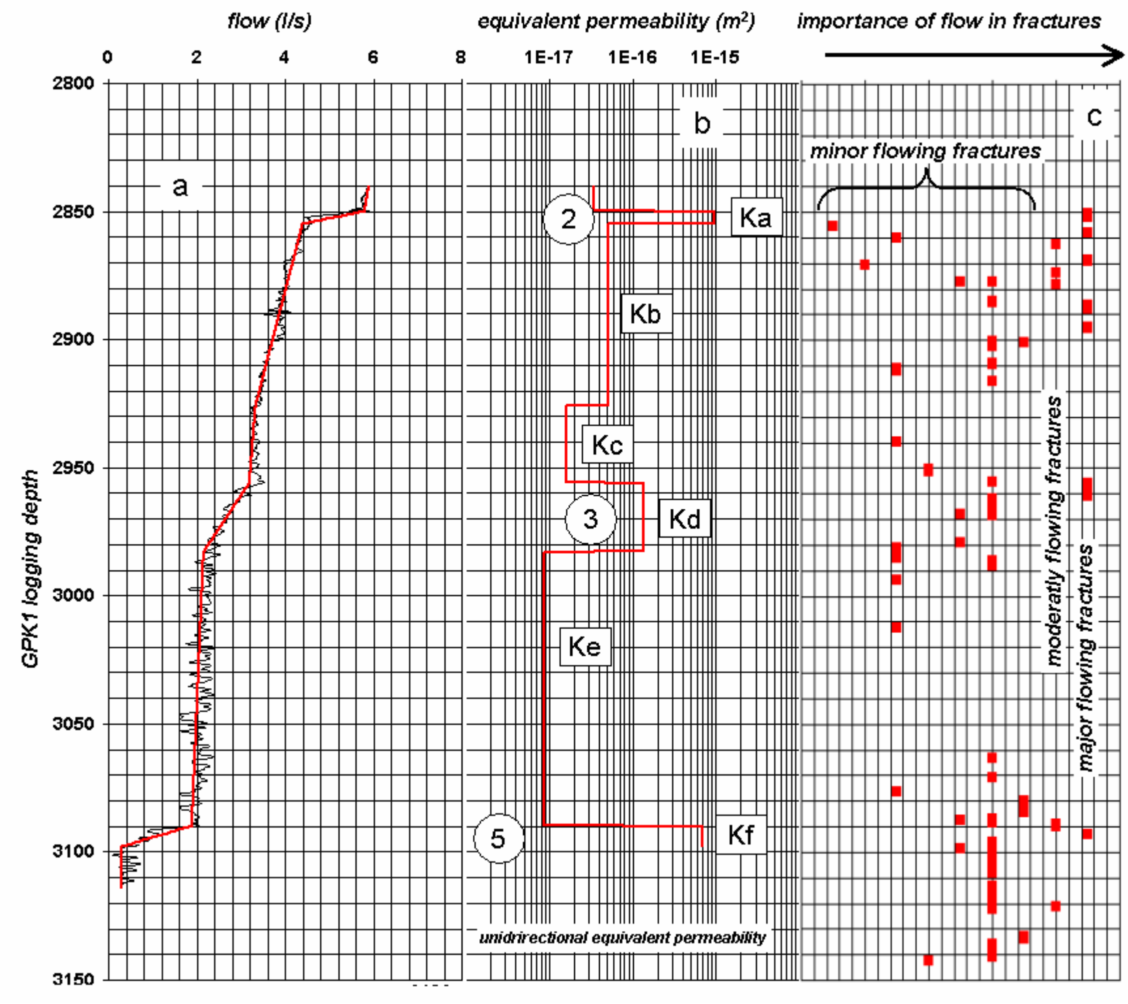

Figure 3: a) Flow profile of the GPK1 well from spinner logs run during the September 1993 injection test (black curve) and linear regressions of this curve used for the permeability calculation; b) equivalent permeabilities calculated from the 2D unidirectional model for the main zones of depth in the previous flow log; c) distribution of the main permeable fractures in the open hole section of GPK1 (Evans et al., 1996 and Evans, 2000) based on the analysis of flow profiles, spinner and temperature logs. A qualitative index is used to distinguish major flowing fractures (right side of the plot) from lesser flowing fractures (left side of the plot).

An integration of the Darcy law (equation 1) is used to quantify equivalent permeability for levels of depth chosen with a 20 cm step from 2850 m to 3150 m (end of the flow log). This step corresponds to the hydraulic sampling of flow logs in GPK1. The granite is considered as an equivalent porous medium in the model.

$$k = \frac{\mu\, L\, Q}{h\, l\, \Delta P} \qquad (1)$$

where μ is the fluid viscosity (assumed 3.10^{-4} Pa.s), L and l the length (m) and width of the model, Q the flow measured during the injection test of September 1993 (m^3/s), h the interval of depth (m) corresponding to the calculated equivalent permeability k (m^2) and ΔP, the pressure gradient between the injection wellhead and the production well. Injection pressure was 35 MPa in September 1993. The production/injection ration is assumed to be equal to the production/injection ratio observed during the 1995 circulation experiments between GPK1 and GPK2, e.g. 22 MPa at the end of the microseismic cloud extension (N150°E).

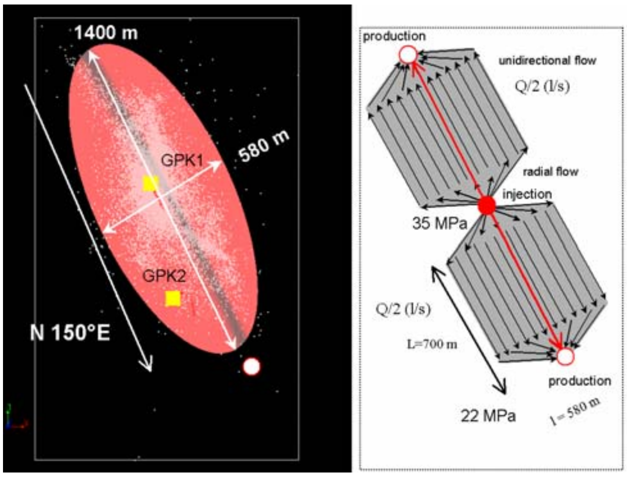

Figure 4: Horizontal dimensions of the permeability model based on the anisotropic development of the microseismic cloud observed during the 1993 injection test. A mean ellipsoid is characterized with a 1400 m length versus 580 m width. The flow is assumed to be laminar. Injection is done for a wellhead fluid pressure of 35 Mpa and propagates in an equivalent porous medium. The final pressure is 22 Mpa at the end of the microseismic cloud extension (N150°E).

The flow logs used here is the Q_13FC_S93_allZ log measured in September 1993 at Soultz. This log was simplified with a linear regression for each main slop variations of the cumulative curve (fig. 3a). This simplification doesn't take into account the precise and local flow losses corresponding to fractures but allows the definition of an equivalent permeability of the rock matrix for each zone of depth. Equivalent permeabilities for the 2800-3150 m depth interval are calculated and plotted on figure 3b.

2.3. Petrophysics versus permeability

Permeability values are compared to the petrophysics of the rock, e. g. the different log anomalies or trends detected on geophysical logs (fig. 2).

Flow logs are measured in a thinner interval of depth than the geophysical logs, zone 1 and zone 6 (fig.2) are therefore not defined in the September 1993 flow log. Despite this lack of data, 6 main zones of depth named Ka to Kf and corresponding to equivalent permeability between 8.10^{-18} and 2.10^{-16} m^2 are modeled (Table 1).

Table 1: equivalent permeabilities in m^2 calculated for the different zones of specific flow and with a 2D unidirectional model of flow.

K zones	interval of depth	Equivalent permeability
Ka	2849-2856	9.64E-16
Kb	2856-2925	5.18E-17
Kc	2925-2956	1.61E-17
Kd	2956-2985	1.34E-16
Ke	2985-3090	8.63E-18
Kf	3090-3100	6.99E-16

These zones of depth correspond broadly to those defined previously by the way of geophysical logs. The matching is quite good especially in the case of zones with high permeabilities (zone 2- Ka, zone 3-Kd and zone 5 Kf, figs. 2 and 3b). This correlation between data shows that the granite permeability is fixed by large open fractures which appear in an altered matrix and affect the petrophysical properties of the rock. These high permeability zones Ka, Kd and Kf correspond to fractured composite zones characterized by clusters of closely associated opened fractures with strong electrical apertures (Sausse and Genter, in press and fig. 3c). Moreover, the standard gamma ray values, which can be assumed as a qualitative indicator of the rock alteration degree, fit quite well with the permeability values (fig. 5). A semi-log trend between the mean values of bulk density and standard Gamma Ray is observed except for zone Ka characterized by lower gamma ray values. In the same depth interval, a second relationship between the bulk density and the permeability is observed on fig. 5 where permeability increases when bulk density decreases. This tendency shows that this decreasing in bulk density could be interpreted in terms of increasing secondary porosity. Then, as the matrix porosity increases, the resulting permeability increases too.

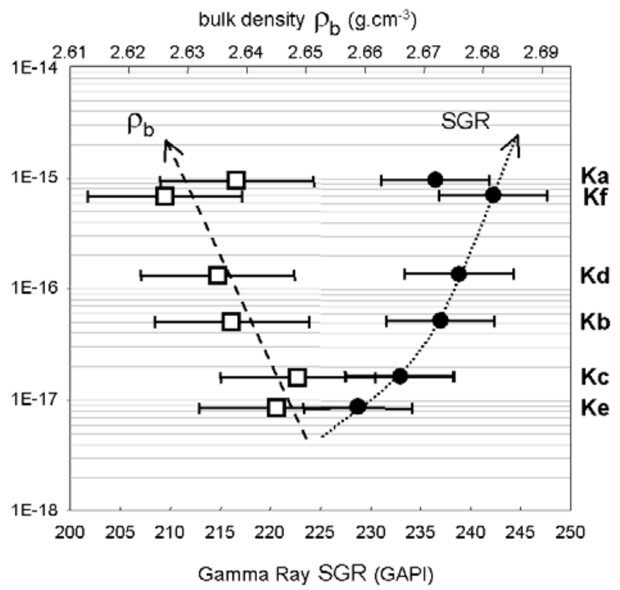

Figure 5: Cross-plots of bulk density and Standard Gamma Ray versus the logarithm of the equivalent permeability for zones Ka to Kf. Dots correspond to the mean geophysical data values weighted by their standard deviations (error bars).

However, this relationship is not clearly demonstrated on the raw geophysical logs (fig. 2) and especially when permeability values are weaker. Zones Kb, Kc, Ke constitutes more wide levels of depth where permeability remains lower than 5.10^{-17} m^2. These values characterized the granite matrix permeability. For example, Zone Ke is characterized by the lowest permeability value despite the presence of a large anomaly of gamma ray and K content on geophysical logs (zone 4 on fig. 2). This isolated anomaly could correspond to an altered zone and probably a fracture zone if compared to the other log anomalies. However, Evans (2000) doesn't see significant deviations of the flow logs at these depths (3045-3065 m depth). Cuttings study, done by BRGM teams during the drilling of GPK1, shows that on the entire 2800-3150 m depth interval, only a thin zone between 3015 and 3060 m depth is qualified as gray-dark biotite-rich granite (Genter et al., 1995). The anomalous high content of Potassium and the resulting deviation of gamma ray in zone 4 is then probably produced by the anomalous amount of biotite at these depths. Gamma Ray which shows the better relationship with permeability cannot therefore used solely to predict permeability. Other geophysical parameters have to be taken into account.

Zone Kb is characterized by several major flowing fractures which appear in a relatively fresh zone of the granite. The equivalent permeability is therefore lower than the previous zone Ka confirming again that permeability in fractures is mainly enhanced in altered zone. The Kb zone of depth can be modeled by a double porosity media with permeable fractures in an impermeable matrix. By contrast, Kd or Kf zones defined an equivalent porous medium where fractures crosscut an altered and permeable matrix.

An other zone of depth presents a problem of correlation between geophysics and permeability values. Ka is the highest level of permeability modeled. However, this zone of depth between 2849 and 2856 m depth shows very large and open fractures detected on ARI logs (Sausse and Genter, in press) or hydraulic logs (Evans, 2000, fig. 3c) but no real anomaly of geophysical logs are present on fig. 2. Only a slight positive deviation of the gamma ray is observed at these depths. High values of permeability are therefore not systematically associated with a Gamma ray increase. The Ka dot on fig. 5 is indeed out of the global trend located between the two parameters. Geophysical logs were run prior to the stimulation of GPK1. The absence of important log anomalies tends to show that no real fracture zone or alteration are characterized in the rock matrix before the hydraulic stimulation. This zone could therefore correspond to a kind of "damage zone" where numerous natural sealed fractures are initially present and re-opened by hydraulic fracturing during the injection test (Sausse and Genter, in press). The strong wellhead injection pressure and the critical stress state at Soultz seem to affect strongly the near well below the casing shoe (2850 m).

Except this first re-activated damage zone, and zones of anomalous contents of biotite in granite, gamma ray and bulk density are finally reliable indicators to predict the permeability of the granite during hydraulic tests (fig. 6).

Indeed, the cross plot of mean bulk densities versus mean standard gamma ray values presented in figure 6 shows that two classes of permeability can be defined. A first category of geophysical data corresponds to strong permeability values and are characterized by anomalous Gamma Ray values between 236-245 GAPI and by bulk densities between 2.618 and 2.637. By contrast, zones of depth where weaker permeabilities are modeled correspond to Gamma Ray intervals of 223-236 GAPI and by bulk densities between 2.630 and 2.652 g.cm^{-3}.

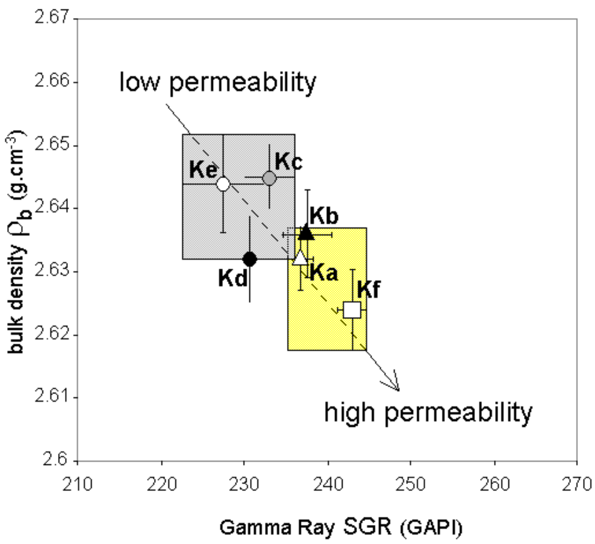

Figure 6: Cross plots of mean values of bulk density and Standard Gamma Ray for the different permeability zones of depth (Ka to Kf, see fig. 3). Mean values are weighted by the difference between the 60% and 40% percentiles to limit the value dispersion (error bars).

2.4. Discussion

The use of geophysical logs remains complicated in the case of igneous rock because values are not scattered in comparison with sedimentary rocks. Geophysical values for granite are few documented or often correspond to specific case studies. The problem of a precise log interpretation is linked to the accuracy and the representativity of log values. The bulk density of granite shows here very low variations and the third decimal is needed to distinguish anomalous values (fig.6). Here, DRHO values which qualify the quality of the bulk density measurements are equal to 0.007 for the minimum and 0.01 g.cm^{-3} for the maximum. This corresponds to the standard deviation of bulk density values used in fig. 5. Despite these error bars, a negative relationship between bulk density and permeability is observed on fig. 5. This relationship points out the effect of hydrothermal alteration on the secondary porosity and consequently on the permeability. Gamma ray are characterized by higher values in GAPI than bulk density and standard deviations measured allow to plot more distinct and characteristic values versus the permeability zones of depth. Again, errors during gamma ray logging cannot mask the quite good correlation with permeability values. Saying that alteration is directly link to the gamma ray remains however difficult, especially when Potassium content variations don't match with the increase of gamma ray (for example, zone 3 on fig. 2). Genter et al. (1998) show that zones of vein alteration, closely related to fracturing, occur throughout the different wells. They are 1 to 20 m thick, and show strong modification of the petrophysical characteristics of the granite. Water-rock interactions have resulted in the leaching of primary minerals of the granite, and the precipitation of secondary minerals within the fractures and their wall rock (quartz, clays, carbonates, sulphides). Primary biotite and plagioclase are usually transformed into clay minerals which are here assumed to produce anomalies in gamma ray logs.

These preliminary results want to bring new geophysical log interpretation in terms of permeability. Other geophysical parameters have to be included in the study as induction and electric logs and other wells must be introduced in the logging database. The future objective is now to detect a specific fracture signature on logs by using gamma ray, sonic, neutron density separation and other logging data in EPS1 where cores and chemical analysis of samples were performed. Preliminary plots of such binary diagrams show clear tendencies which distinguish again highly, moderately or weakly altered zones in the granite. Evidences of permeable fractures in strongly hydrothermally altered zones are present. The main question is how observations performed in EPS1 can be transposed in the other well. The goal is to be able to give some clues to understand the hydraulic response of the granite as a function of its petrophysical properties.

The present results try to demonstrate that a precise description of geological characteristics such as alteration of the rock or geophysical and hydraulic properties are linked to fracture permeability. Their simultaneous studies can bring some relevant insights for a better understanding of fluid flows in order to model fracture permeability.

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REFERENCES

Baria, R., J. Baumgärtner, and A. Gérard. Heat Mining in the Rhinegraben, European Geothermal Energy Project at Soultz-sous-forêts, *Socomine internal report* (1993).

Baria, R., J. Baumgärtner, A. Gérard, and R. Jung. Scientific Results Associated with Large Scale Injection Tests (A Summary of the Scientific Program carried out in 1993) European Geothermal Energy Project At Soultz-sous-Forêts, *Socomine internal report* (1994).

Baria, R., J. Baumgärtner, A. Gérard, R. Jung, and J. Garnish. European HDR Research Programme at Soultz-sous-Forêts (France) 1987-1996, *Geothermics*, **28** (4-5), (1999), 655-669,.

Dezayes, C., T. Villemin, A. Genter, H. Traineau, and J. Angelier. Analysis of Fractures in Boreholes of Hot Dry Rock Project at Soultz-sous-Forêts (Rhine Graben, France), *J. Scient. Drilling*, **5** (1), (1995), 31-41.

Evans, K.F. The Effect of the Stimulations of the Well GPK1 at Soultz on the Surrounding Rock Mass: Evidence for the Existence of a Connected Network of Permeable Fractures, *Proceedings* World Geothermal Congress 2000, Kyushu-Tohoku, Japan (2000).

Evans, K.F., T. Kohl, J. Hopkirk, and L. Rybach. Studies of the Nature of Non-linear Impedance to Flow within the Fractured Granitic Reservoir at the European Hot Dry Rock Project site at Soultz-sous-Forêts, France, Institut für Geophysik, *ETH Zurich report*-Polydynamics Engineering, Zurich (1996).

Genter, A., C. Castaing, C. Dezayes, H. Tenzer, H. Traineau, and T. Villemin. Comparative Analysis of Direct (core) and Indirect (borehole imaging tools) Collection of Fracture Data in the Hot Dry Rock Soultz Reservoir (France), *Journal of Geophysical Research*, **102** (B7), (1997), 15,419-15,431,.

Genter, A., H. Traineau, C. Dezayes, P. Elsass, B. Ledésert, A. Meunier, and T. Villemin. Fracture Analysis and Reservoir Characterization of the Granitic Basement in the HDR Soultz Project (France), *Geothermal Science and Technology*, **4** (3), (1995), 189-214.

Genter, A., C. Dezayes, S. Gentier, B. Ledésert, and J. Sausse. Conceptual Fracture Model at Soultz based on Geological Data, *Proceedings* 4th HDR Forum, Strasbourg (1998).

Jung, R. Hydraulic tests Summer/Autumn 1993. *BGR Field report* (1994).

Jung, R., J. Willis-Richard, J. Nicholls, A. Bertozzi, and B. Heinemann. Evaluation of Hydraulic Tests at Soultz-sous-Forêts, European HDR Site, *Proceedings* of World Geothermal Congress 1995, Florence, Italy (1995).

Sausse, J. Hydromechanical Properties and Alteration of Natural Fracture Surfaces in the Soultz granite (Bas-Rhin, France), *Tectonophysics*, **348**, (2002), 169-185.

Sausse, J., and A. Genter. Types of permeable fractures in granite, *Special Publication of the Geological Society of London*, in press.