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GEOCHEMICAL FLUID CHARACTERISTICS AND MAIN ACHIEVEMENTS ABOUT TRACER TESTS AT SOULTZ-SOUS-FORÊTS (FRANCE)

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ABSTRACT

Three wells drilled at a depth of about 5,000 m in the granite (T ≈ 200°C) will constitute the heat exchanger for electricity generation in the site of Soultz-sous-Forêts. After several hydraulic stimulation operations carried out in these wells in order to improve the well injectivity and the quality of inter-well connections, a five month fluid circulation test was conducted in 2005 between the injection well GPK-3 and the production wells GPK-2 and GPK-4, in the framework of the construction of the Scientific Pilot Plant of the European HDR Program, initiated in 2001. A tracer test using fluorescein and a geochemical fluid monitoring accompanied this operation. This paper presents the major results obtained during these works and summarizes the main characteristics of the native geothermal fluids (reservoir brine and gases) which can be drawn up in 2006, in terms of geochemistry (chemical and isotopic composition, fluid origin, reservoir temperature, water-rock-gas interaction processes) and circulation (natural fluid convection flux, existence of more permeable areas and different circulation paths in the heat exchanger, fluid velocities).

INTRODUCTION

The main objective of the European Hot Dry Rock Energy (HDR) Program is to develop a deep heat exchanger to generate electricity, in the site of Soultz-sous-Forêts, France. This site, located within the Tertiary Rhine Graben (Fig. 1), which forms part of the West European Rift, was selected for its large surface heat flow anomaly exceeding 140 mW/m² (Pribnow and Clauser, 2000) and for its tectonic structure, characterized by prominent north-south faults, reaching into the crystalline basement (Rousset *et al.*, 1992).

The construction of a Scientific Pilot Plant was initiated in 2001 (Gérard, 2005). Between 1987 and 1996, three wells (GPK-1, EPS1 and GPK-2) had been drilled at depths lower than 3,900 m (Fig. 2a). In 1997, a forced four month fluid circulation test suggested that it was possible to circulate between GPK-1 and GPK-2 at a mean injection flow rate of 25 l/s and at a temperature close to 140°C (Aquilina *et al.*, 2004). However, mainly for economical reasons, it was decided to drill deeper wells. The well GPK-2 was deepened from 3,900 to about 5,000 m in 1999, and the wells GPK-3 and GPK-4 were drilled at similar depths in 2002 and 2004. These wells, which will make up the heat exchanger, reached into a granitic basement (Figs. 2a and 2b; Hooijkaas

et al., 2006), with a temperature close to 200°C and the presence of a geothermal NaCl brine (TDS ≈ 100 g/l). GPK-3 will be the injection well and GPK-2 and GPK-4 will be the production wells. For each of the three wells, an open hole section is located between about 4,500 and 5,000 m.
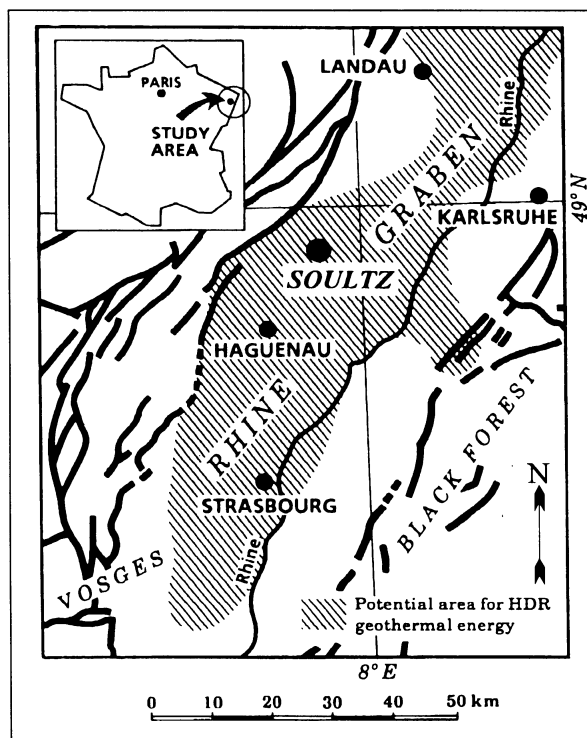
Figure 1 - Location map of the Rhine Graben and Soultz-sous-Forêts.

In order to improve the well injectivity and the quality of the existing connections between wells (major fractures shown in Fig. 2b), which can be sometimes sealed by hydrothermal alteration products, different hydraulic stimulation tests were carried out into these wells between 2000 and 2005, accompanied of tracer tests, production tests, geophysical and geochemical monitoring (Sanjuan *et al.*, 2004; 2006).

Figure 2a - Location map and profiles of the geothermal wells (from Dezayes et al., 2005).

Figure 2b - Geological cross-section between the geothermal wells (from Gentier et al., 2003b).
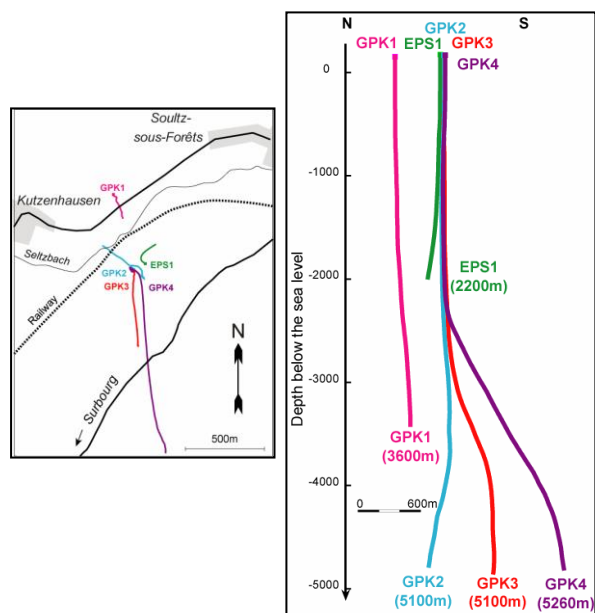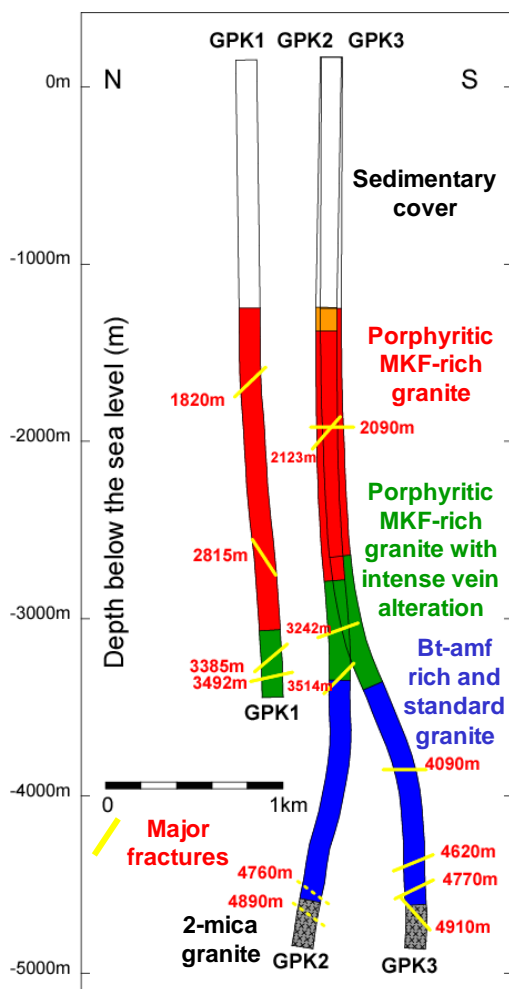
After these stimulation operations, and as in 1997 but at higher depth and temperature, a fluid circulation test was conducted between the injection well GPK-3 and the production wells GPK-2 and GPK-4, from July to December 2005, with a mean injection flow rate of 15 l/s.

This study, performed in the framework of the accompanying scientific work of the European HDR Program, presents the major results obtained during the tracer test and the geochemical fluid monitoring, which accompanied the five month fluid circulation test carried out in 2005. It summarizes the main characteristics of the native geothermal brine and associated gases, which can be drawn up in 2006 from these works and previous works, in terms of geochemistry (chemical and isotopic composition, fluid origin, reservoir temperature, water-rock-gas interaction processes) and circulation (natural fluid convection flux, existence of more permeable areas and different circulation paths in the heat exchanger, fluid velocities).

GEOCHEMICAL FLUID CHARACTERISTICS

Chemical and isotopic composition of the geothermal brine

Representative chemical and isotopic compositions of the native geothermal brine discharged from the well GPK-1 at different depths (Table 1) are reported by Pauwels *et al.* (1993) and Aquilina *et al.* (1997). This native brine was produced from GPK-1 at depths of about 1,800-1,900 m and 3,500 m, respectively.

Even if the chemical and isotopic compositions are similar, some discrepancies are observed between the fluids produced at different depths. So, the fluid sample collected at a depth of about 3,500 m and at a temperature close to 165°C indicates concentrations of dissolved Cl and Ca slightly higher (61 and 7,3 g/l, respectively) than those analyzed in the fluid produced at 1,800-1,900 m (58.5 and 6.7-6.9 g/l). Its concentrations of dissolved K, Mg, Br and B are slightly lower (Table 1). Its alkalinity is markedly lower; dissolved silica and some trace elements such as Al and As are higher. These last results agree well with a higher degree of water-rock interaction observed from Sr isotopic measurements.

Three fluid samples were also collected by BRGM at well head from GPK-1 in 1999, after several hydraulic stimulation tests and injections of fresh water into GPK-1 and GPK-2 conducted between 1993 and 1996, and a fluid circulation test carried out in 1997 between these wells. So, a total volume of 85,000 m^3 of fresh water had been injected in 1995 and 1996 (Vaute, 1998). According to the analytical results (Table 1), low amounts of residual injected fresh water (< 5%) are probably still mixed with the native geothermal brine, but these results are close to those obtained by Aquilina *et al.* (1997). Only the concentrations of dissolved K and SO$_4$ are higher; the concentrations of some trace elements (Al, Zn, Cr) and alkalinity are markedly lower.

Contrary to the well GPK-1, it has not been possible to collect and analyze a representative sample of the deep geothermal brine discharged from the wells GPK-2, GPK-3 and GPK-4. During or just after the drilling of these wells, the fluid samples were contaminated by drilling fluids. During the production tests carried out after hydraulic stimulation operations where large volumes of fresh water were injected, the fluid samples were constituted of a mixing of geothermal brine and injected fresh water.

However, the geochemical fluid monitoring carried out during the 1997 circulation test suggested that, at the end of this test, the proportions of injected fresh water present in the

fluid discharged from GPK-2 were low (close to 5%). For this fluid (KP3 samples in table 1), chemical compositions similar to that of the fluid produced by GPK-1 were found.

In a same way, the last samples of the geochemical monitoring of the fluid discharged from GPK-2, carried out in 1999 after the deepening of this well from 3,900 to about 5,000 m (GPK2-99 samples in table 1; Sanjuan *et al.*, 2001), also showed chemical and isotopic compositions close to those of the fluids discharged from GPK-1 and GPK-2, at a depth range of 3,500-3,900 m. These results suggested that the amounts of residual injected fresh water present in the fluid discharged from GPK-2 at a depth of about 5,000 m were very low (< 5%) and that the fractured and permeable areas located at 3,500-3,900 m and 4,500-5,000 m had relatively direct hydraulic connections.

In the next production tests (December 2000- April 2002 and June-July 2003), after hydraulic stimulation operations carried out in this well and in GPK-3, and during the fluid circulation test (July-December 2005), the analyzed chemical compositions (Table 1) indicated that the fluid discharged from GPK-2 was always constituted of a mixing of native reservoir brine and injected fresh water, with minimum proportions of injected fresh water lower than 15% at the end of the 2005 circulation test (Sanjuan *et al.*, 2006). These results were also confirmed by the use of naphthalene disulfonate (nds) compounds, organic tracers which were continuously injected during most of the stimulation operations (Sanjuan *et al.*, 2004; 2006).

Only three short term production tests were carried out in GPK-3 in March 2003, August and September 2004, after hydraulic stimulation operations. As for GPK-2, the fluid discharged from this well was consisted of a mixing of native geothermal brine and injected fresh water. The minimum proportion of injected fresh water (about 6%) was observed at the end of the production test carried out in March 2003 (Table 1). As this fresh water had been injected into GPK-2 (and not into GPK-3) in July 2000 and January-February 2003, and a similar fluid mixing would have been observed in the fluid discharged from GPK-2, it was showed that the well GPK-3 was directly connected to GPK-2 (Gentier *et al.*, 2003b; Sanjuan *et al.*, 2004; 2006).

The well GPK-4 only discharged a fluid during the five month fluid circulation test conducted in 2005, after several hydraulic stimulation operations carried out in this well between September 2004 and March 2005, where a volume of 2,6-nds-traced fresh water of about 32,000 m³ had been injected (Sanjuan *et al.*, 2006). During the fluid circulation test, the chemical and tracer analyses showed that the previously injected fresh water was very quickly replaced by native reservoir brine in the fluid discharged from GPK-4. At the beginning of this test, the proportion of native geothermal brine was already close to 60-65%. It was about 80% at the end of this test (Table 1; Sanjuan *et al.*, 2006).

Except the analytical data relative to the fluid discharged from GPK-1 at a depth of 1,800-1,900 m, all the other results (Table 1) were used in order to more accurately define the chemical and isotopic composition of the native reservoir brine, which was intersected by the wells GPK-2, GPK-3 and GPK-4 at depths of 4,500 and 5,000 m. A value of 59 ± 2 g/l was selected as the representative Cl concentration in the native reservoir brine. Although the regression coefficients indicated poor correlations for some species ($R^2 < 0.6$), the linear relations obtained in the figures 3 to 12 were used or taken into account in order to determine the representative concentrations of the dissolved major species Na, K, Ca, Mg, SO_4 and some trace species such as Br, B, NH_4, Li and Sr in the native reservoir brine (Table 1). Relative uncertainty is estimated at 5-10% for major species and 10-15% for trace species.
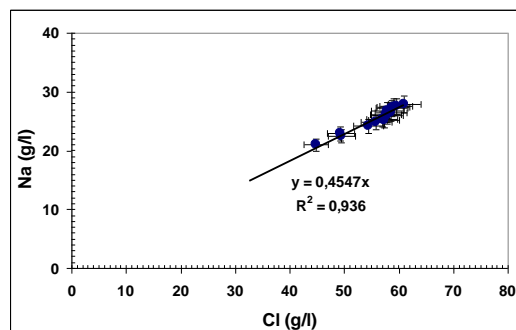

Figure 3 - Na versus Cl concentrations in fluid samples collected from the wells GPK-1, GPK-2, GPK-3 and GPK-4 (well depth < 3,500 m).

Figure 4 - K versus Cl concentrations in fluid samples collected from the wells GPK-1, GPK-2, GPK-3 and GPK-4 (well depth < 3,500 m).

Figure 5 - Ca versus Cl concentrations in fluid samples collected from the wells GPK-1, GPK-2, GPK-3 and GPK-4 (well depth < 3,500 m).

Figure 6 - Mg versus Cl concentrations in fluid samples collected from the wells GPK-1, GPK-2, GPK-3 and GPK-4 (well depth < 3,500 m).

Figure 7 - SO₄ versus Cl concentrations in fluid samples collected from the wells GPK-1, GPK-2, GPK-3 and GPK-4 (well depth < 3,500 m).
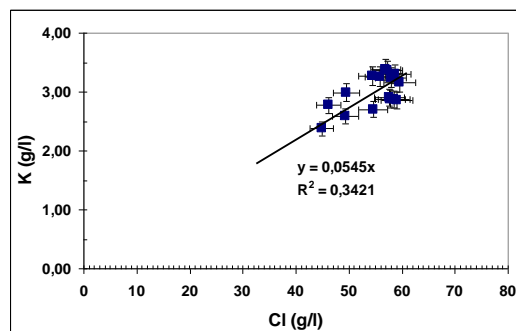

Figure 8 - Br versus Cl concentrations in fluid samples collected from the wells GPK-1, GPK-2, GPK-3 and GPK-4 (well depth < 3,500 m).

Figure 9 - B versus Cl concentrations in fluid samples collected from the wells GPK-1, GPK-2, GPK-3 and GPK-4 (well depth < 3,500 m).

Figure 10 - NH₄ versus Cl concentrations in fluid samples collected from the wells GPK-1, GPK-2, GPK-3 and GPK-4 (well depth < 3,500 m).
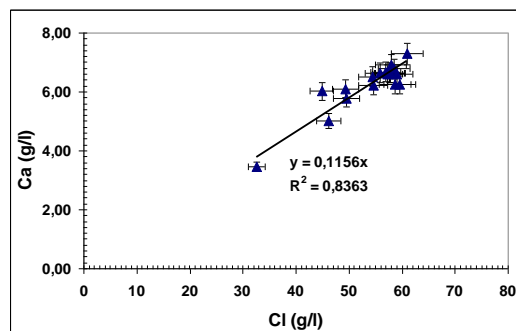

Figure 11 - Sr versus Cl concentrations in fluid samples collected from the wells GPK-1, GPK-2, GPK-3 and GPK-4 (well depth < 3,500 m).

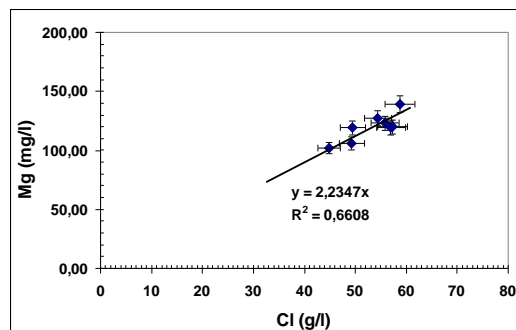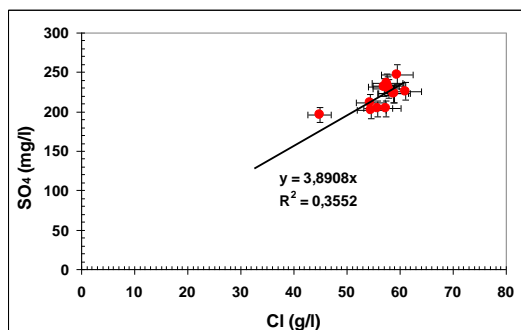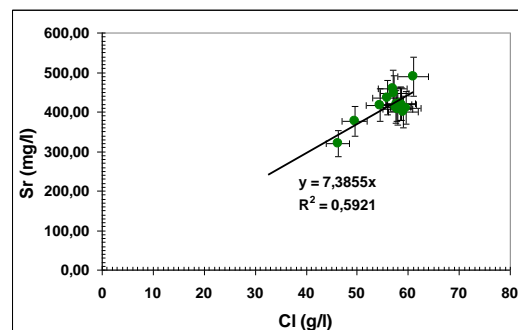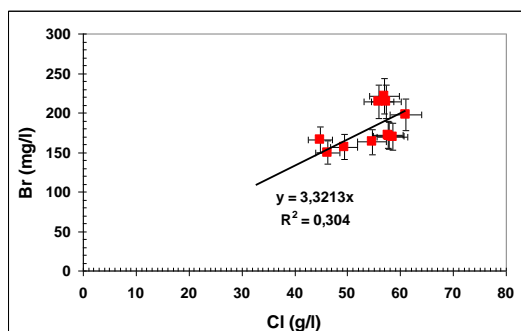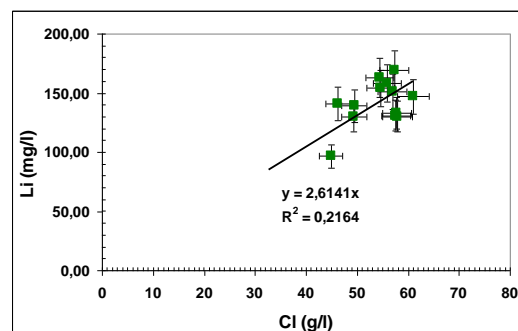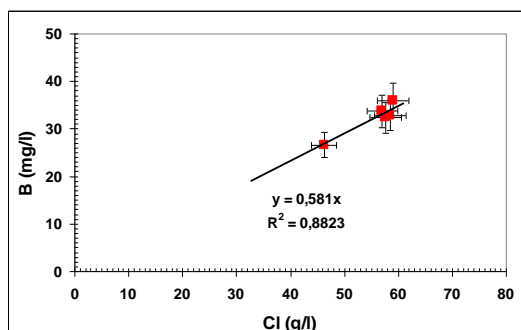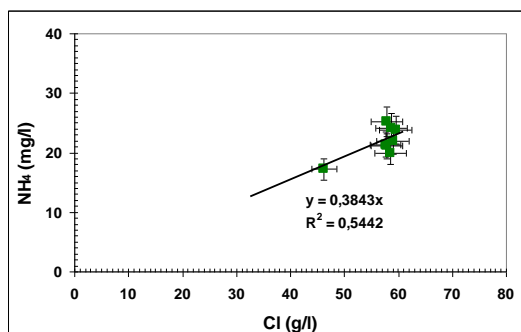*Figure 12 - Li versus Cl concentrations in fluid samples collected from the wells GPK-1, GPK-2, GPK-3 and GPK-4 (well depth < 3,500 m).*

For the other trace species (F, Ba, Ti, As, Rb, Cs, Fe, Ni, Cu, Co, Cr, Cd, Zn, Ag and Pb), which indicate relatively unstable concentrations, representative values are proposed in Table 1. They are often close to those analyzed in the fluid sample GPK2-99-D1, collected from GPK-2 at a depth of 650 m in December 1999. For these last species, it is obvious that additional analyses in samples of uncontaminated reservoir brine would be very useful.

The values of pH, partial CO_2 pressure and dissolved HCO_3, Al and SiO_2 concentrations, were determined using the reconstructed chemical composition of the geothermal brine (Table 1) and the EQ3NR geochemical modeling code (Wolery, 1995). This code used the thermodynamic data0.com.R2 database and the B-dot equation, an extended Debye-Hückel equation, to take into account the salinity effect. The pressure effect, which is negligible in this study case, was not considered.

The reservoir temperature was set to 230-240°C (see later). The pH and CO_2 fugacity were calculated assuming that pH was controlled by the brine/calcite equilibrium reaction and the CO_2 fugacity by the concentration of dissolved HCO_3. This concentration was estimated at about 85 mg/l from the analytical alkalinity and DOC (Dissolved Organic Carbon) values (Table 1). A SiO_2 concentration of 427 mg/l was selected in order to be close to the concentration value controlled by the brine/quartz equilibrium reaction, which is also similar to the maximum values analyzed in the fluid discharged from GPK-2 in 1999. The concentration of dissolved Al was calculated assuming that it was controlled by the equilibrium brine/K-feldspar.

The results obtained using the EQ3NR code are reported in Table 1. CO_2 pressure and pH values close to 6 bar and 5.0 were respectively found. By using the K-Ca geobarometer of

Giggenbach (1988), an approximate value of CO_2 fugacity of 1.7-2 bar in the reservoir is evaluated. Taking into account the fugacity coefficient for CO_2 at 500 bar and 240°C (0.84; Duan *et al.*, 1992), the CO_2 partial pressure can be estimated to around 2-2.4 bar. The estimated pH value is ranging from that measured directly in the line at 60°C in 1997 (4.79; Vaute, 1998) to those determined on site at 20-30°C (5.1-5.5; Table 1). If alkalinity is considered as only constituted of bicarbonate ions, unrealistic CO_2 fugacity and pH values are calculated by geochemical modelling. The DOC values analyzed in the fluid samples collected from GPK-1 and GPK-2 in 1999 suggest that alkalinity is also constituted of dissolved organic compounds (acetate ions, residual compounds of drilling mud ?). Additional analyses are necessary to better identify and quantify the alkalinity components. The concentration of dissolved Al was calculated to be 52 µg/l at 230°C and 93 µg/l at 240°C. These values are relatively close to those analyzed in the fluid discharged from GPK-2 in 1999 (30 and 54 µg/l). A value of 50 µg/l was selected (Table 1).

The isotopic values analyzed in the fluids collected in 1999, very close to those determined in 1993 and in 2002, were considered to be representative of the native reservoir brine (Table 1).

Chemical composition of the gases

Only three gas samples were collected at well head from GPK-2 and GPK-4 by BRGM during the five month fluid circulation test carried out in 2005. These gases were analyzed by gas chromatography. Uncertainty analytical is about 5%. Results are reported in Table 2 where other analytical data previously obtained from the wells GPK-1 and GPK-2 are also presented (Pauwels *et al.*, 1993; Aquilina *et al.*, 1997; Naumann *et al.*, 1999, 2000; Sanjuan *et al.*, 2001).

Most of these analytical results are relatively heterogeneous. These discrepancies are probably due to the different techniques used for sampling, to the different sampling locations and to the different flow rate values. When the sampling conditions are similar, the analytical results are closer. So, except for H_2 content, the chemical compositions of the gases collected from GPK-2 and GPK-4 in 2005 are similar to those obtained in 1999 from a continuous gas monitoring carried out in GPK-2, from the gas separator (degasser) and casing (Naumann *et al.*, 2000; Table 2). For the moment, although additional gas analyses will have to be performed and tested, these gas analyses will be considered as the most representative for gases collected from gas separator, after the well heads. CO_2 is the predominant gas. The partial pressure of this gas in the reservoir was estimated to be close to 6 bar in the previous chapter. No trace of H_2S was found in the gas analyses.

Naumann *et al.* (2000) presented a chemical composition of gases from measurements done on fluid GPK-2 samples completely degassed in the laboratory under vacuum and with ultrasonic treatment (Table 2). CO_2 is always preponderant but at higher contents (about 90%). N_2, CH_4 and He proportions are much lower than those determined in GPK-2 from the separator and the casing in 1999 or after well head in 2005. The GLR value is higher (38%) than in the previous measurements.

In other analyses (especially for the gas samples collected at 650-700 m depths from GPK-2 or for some surface samples), significant amounts of H_2 and He are observed (Table 2). These gases perhaps have been preferentially collected in the down-hole sampler because of their higher mobility (lighter molecules) and their low solubility in water. Interactions between brine and bore-hole material can be also responsible for the high H_2 values observed in the surface samples (Pauwels *et al.*, 1993).

Fluid origin

The determinations of δD isotopes of the water associated to the concentrations of Cl and Br (Table 1) suggest the following scheme to explain the brine origin, which was assumed by Pauwels *et al.* (1993):

- formation of a primary brine by advanced evaporation of sea water up to halite precipitation, at least; so, the observed Cl/Br ratios, lower than that of sea water (≈ 300), can be explained but the degree of the evaporation cannot be determined;
- migration of this primary brine and mixing with more dilute fluids;
- dissolution of halite to increase the Cl/Br ratios and to be close to the analysed values.

The $\delta^{18}O$ values cannot be used to determine the fluid origin in this study because, as we will see it in the next chapter, they are not conservative and can be used to estimate the reservoir fluid temperature.

For the geothermal brine sampled from GPK-1 at depths of 1,800-1,900 m (Table 1), the δD values and the lower concentration of dissolved Cl suggest contributions of dilute waters slightly higher than in the fluids discharged from GPK-1 or GPK-2, at depths of 3,500 m or 4,500-5,000 m. These results are in good agreement with the assumption that marine evaporite minerals such as anhydrite or barite are dissolved during the raise and the cooling of the geothermal brine from the deep hot reservoir (Pauwels *et al.,* 1993; Aquilina *et al.*,1997). This assumption is based upon the following observations:

- the concentrations of dissolved SO_4, Br and Ba tend to increase with decreasing well depth and temperature (Table 1);
- the $\delta^{34}S$ values of the dissolved sulfate move away from 20 (marine value) and becomes closer to 0 (magmatic sulfide) with increasing depth and temperature (Table 1);
- a similar trend is found for the $\delta^{18}O$ values of the dissolved SO_4 (Table 1).

Reservoir fluid temperature and processes of water-rock-gas interactions

From the chemical composition reconstructed for the native reservoir brine (Table 1), temperature values of 220-240°C are estimated in the deep reservoir using classical chemical geothermometers (Table 3). These estimations are similar to those previously performed on all the fluids collected from GPK-1 and GPK-2 (Pauwels *et al.*, 1993; Aquilina *et al.*, 1997; Sanjuan *et al.*, 2001; Table 3).

These concordant temperature values suggest the existence of chemical equilibrium reactions between the native reservoir brine and a mineralogical assemblage at 220-240°C. In order to determine the constituents of this mineralogical assemblage, solubility calculations were performed using the EQ3NR geochemical code (Wolery, 1995) and the chemical composition reconstructed for the native reservoir brine (Table 1). The calculations of the saturation indices for minerals indicated that the native reservoir brine was close to an equilibrium at 230-240°C with respect to quartz, albite, K-feldspar, calcite, dolomite, $CaSO_4 \cdot 0.5H_2O$ (β), fluorite, muscovite (illite) and smectites (smectite, montmorillonites). Most of these minerals had been already observed by Ledésert *et al.* (1999) in a hydrothermal alteration sequence in the Soultz granite. As the sulfides were never detected in solution nor in the gases, they were not considered in the calculations.

The good results obtained using Na/Li and Mg/Li geothermometers (Kharaka *et al.*, 1982; Kharaka and Mariner, 1989), especially created from sedimentary basin waters, and the δLi values (Table 1), suggest that the mineralogical assemblage in equilibrium with the native reservoir brine is partially constituted of sedimentary minerals. The bad temperatures estimated using Na/Li (Fouillac and Michard, 1981), Sr/K, Na/Cs and Na/Rb (Michard, 1990) geothermometers, all determined in volcanic and granitic areas, and the probable presence of dissolved organic compounds in the GPK-1 and GPK-2 brines (Ledésert *et al.*, 1996; this study), raises the problem of the nature of the rocks surrounding the deep reservoir (granite or sedimentary reservoir?).

The reservoir fluid temperature estimated using the $\delta^{18}O$-$\delta^{18}O$ (SO_4) geothermometer (Mizutani and Rafter, 1969) is close to 210°C. This geothermometer yields more concordant values than in the study carried out by Pauwels *et al.* (1993) and consequently, seems to confirm that the isotopic values are modified by the dissolution of marine sulphate minerals, during the raise and the cooling of the geothermal brine from the deep reservoir.

Generally, a cooling of hot fluid during its raise causes silicate mineral precipitation (amorphous silica at surface, chalcedony or quartz in deeper areas). The risk of silica precipitation is increased when the fluid raise is slow. This probably explains why the concentrations of dissolved SiO_2 are lower in most of the fluids, especially those collected from GPK-1 at depths of 1,800-1,900 m (Table 1).

Calcite can also be precipitated at surface during the raise of the geothermal brine and CO_2 degassing. However, in the case of the Soultz site, the alkalinity measurements tend to increase in solution with decreasing well depth and temperature (Table 1). Two assumptions can explain this evolution: dissolution of carbonate minerals (calcite, for instance) and/or dissolution of organic compounds present in the granite, during the raise and the cooling of the deep geothermal brine (Ledésert *et al.*, 1996). The results obtained using geochemical modeling rather suggests dissolution of organic compounds.

Gas geothermometers such as $CO_2/H_2/CH_4$ (Marini, 1987), CO_2/Ar and CO_2/CH_4 (Giggenbach, 1991) applied to the gas analyses of the samples collected from GPK-2 and GPK-4 in 2005 or from GPK-1 in 1993 by BRGM yield temperature values ranging from 195 to 240°C (Table 4). Similar values of temperature are found for the gases analysed in GPK-2 by Naumann *et al.* (2000) from the separator and the casing and for the gas sample completely degassed in laboratory (Table 4). However, for this last gas sample, the CO_2/CH_4 geothermometer gives a higher temperature value (269°C). These values are in agreement with those found using the chemical cation geothermometers. This suggests that CO_2, CH_4, H_2 and Ar are near equilibrium with the deep geothermal brine at a temperature of 220-240°C.

The gas geothermometer H_2/Ar (Giggenbach and Goguel, 1989) gives temperature values of 248-315°C (Table 4), which are higher than those found with the other geothermometers. The relative abundance of helium could indicate a crustal origin of some of these gases (see triangular diagram in Giggenbach, 1991). The gas geothermometer $CO_2/H_2S/H_2/CH_4$ (D'Amore and Panichi, 1980) cannot be applied because the amounts of H_2S are very low (< 0,005%). Moreover, this gas geothermometer is not applicable to all the fields.

As the measured temperatures are close to 200°C at the bottom of the three wells and the local thermal gradient becomes normal in the granite located under the sedimentary cover (Bächler, 2003), the values estimated

using most of the geothermometers (220-240°C) suggest that the native reservoir brine comes from a deeper vertical area (< 6 km) or from a relatively distant lateral hotter area.

FLUID CIRCULATION CHARACTERISTICS

Detection of more permeable and fractured areas during the drilling of the wells GPK-2, GPK-3 and GPK-4

As GPK-2, GPK-3 and GPK-4 are deviated wells (Fig. 2a) and no correction was done, the depths described in this chapter correspond to the drilling lengths (and not to true vertical depths).

In order to detect or to confirm the presence of high permeability zones, or water inflows during the drilling of the wells GPK-2, GPK-3 and GPK-4, two kinds of geochemical monitoring were carried out :

- continuous helium (He) gas analysis on site using a mass spectrometer ALCATEL ASM 100, directly connected to the well; analytical uncertainty is 0.02 ppm.
- periodic survey of pH, conductivity and concentrations of dissolved species such as Cl, Na, K, Ca, SO_4, SiO_2, Br and Li in the drilling mud injected (In) and discharged (Out) from the well. Relative analytical uncertainty ranges from 5 to 10%.

GPK-2

During the deepening of GPK-2 from 3,890 to 5,084 m, in 1999, the high natural He values (up to 37 ppm) observed at some depths (4,068, 4,541, 4,671, 4,733, 4,781, 4,940, 5,018, 5,034 and 5,063 m; Fig. 13) suggest the existence of highly altered and fractured deep zones. Remember that the atmospheric He concentration is 5.24 ppm.

During the geochemical monitoring of the drilling mud associated to this deepening, the pH values measured in the mud samples discharged from GPK-2 are decreasing in most of the anomalous He areas (Fig. 14). These results seem confirm the existence of highly altered and fractured deep zones and suggest the presence of some inflows of geothermal brine (characterized by a low pH value).

GPK-3

During the drilling of GPK-3 in 2002, He monitoring was not possible between 2,875 and 3,695 m and between 4,100 and 5,100 m because of technical problems (spectrometer breakdown). Significant helium anomalies (up to 50 ppm) were observed at depths of 2,520-2,540 m, 2,575-2,660 m and 2,830-2,885 m (Fig. 15). These anomalies are often well correlated with methane anomalies. They suggest the presence of altered or fractured areas at these depths. Between 3,700 and 4,100 m, no helium anomalies were detected.

A restricted geochemical monitoring of the drilling mud between 4,500 and 5,100 m (collection of a daily fluid sample In and Out) was also carried out. The pH decrease between In and Out fluid sample indicated that several fluid inflows had been intersected at depths of about 4,682 m, 4,789-4,963 m and 5,075-5,087 m (Fig. 16). Only the slight increase of dissolved SiO_2 and the low decrease of aqueous Mg observed in many Out fluid samples confirmed these fluid inflows. The presence of traces of 1,5-nds (tracer injected into GPK-2) in the drilling mud samples collected from GPK-3 suggested that the fluid inflows evidenced by pH measurements were hydraulically connected to the well GPK-2. It was estimated that about 2 to 5% of GPK-2 fluid was mixed to the drilling mud.
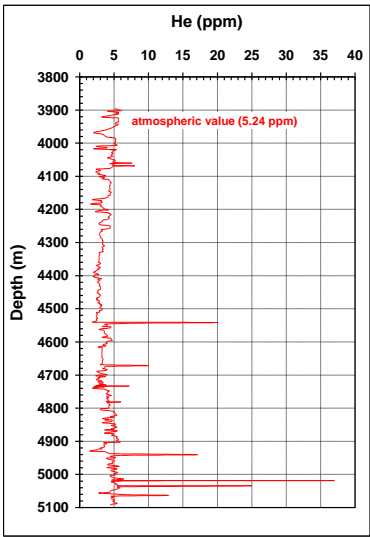
Figure 13 - He profile obtained during the deepening of the well GPK-2 in 1999.
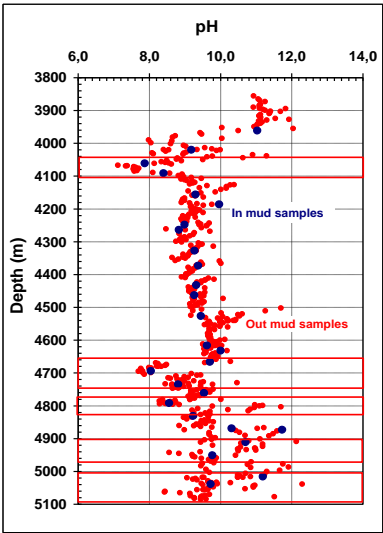

Figure 14 - pH monitoring carried out during the deepening of the well GPK-2 in 1999.
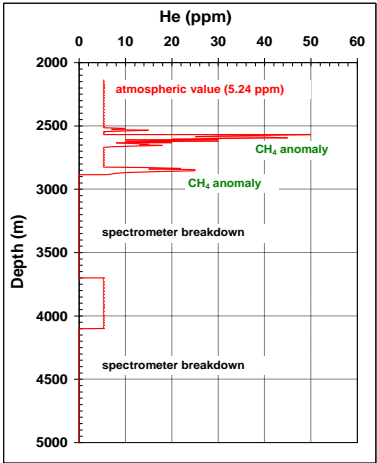

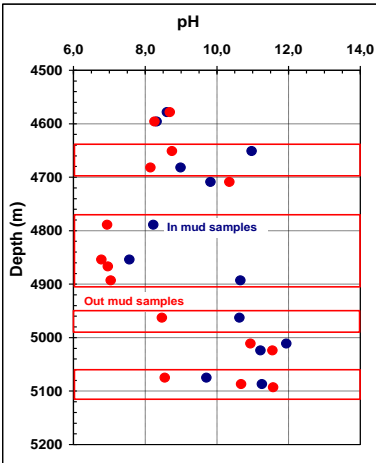Figure 15 - He profile obtained during the drilling of the well GPK-3 in 2002.

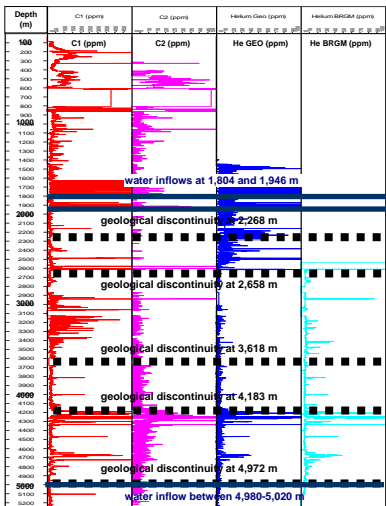Figure 16 - pH monitoring carried out during the drilling of the well GPK-3 in 2002.

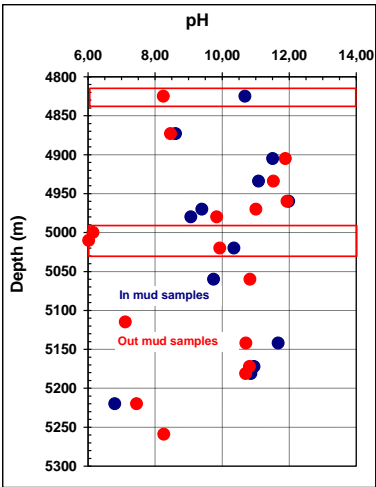Figure 17 - He profile obtained during the drilling of the well GPK-4 in 2004.

Figure 18 - pH monitoring carried out during the drilling of the well GPK-4 in 2004.

GPK-4

During the drilling of GPK-4 (September 2003-April 2004), continuous gas profiles (C1, C2 and He) were performed by GEOSERVICES (Fig. 17). A He profile was also done by BRGM from a depth of 2,600 m (Fig. 17). Results indicated that several deep gas inflows were intersected by the well GPK-4, especially in the areas located between depths of 1,450-1,550 m, 1,570-1,800 m, 1,880-1,960 m, 2,150-2,300 m, 2,380-2,400 m, 2,490-2,500 m, 2,612-2,618 m, 2,940-2,943 m, 3,815-3,821 m, 4,192-4,337 m, 4,468-4,472 m and 4,667-4,733 m. In some of these areas (the most superficial and between 4,192-4,337 m), the He anomalies are higher than 100 ppm and can be, sometimes, close to 200 ppm.

Except for the areas situated at depths of 1,804 m, 1,946 m and between 4,980 and 5,020 m, the restricted geochemical monitoring of the drilling fluids carried out by BRGM during the drilling of GPK-4 shows no significant inflow of geothermal brine (Fig. 18). The chemistry of two fluid samples collected between 4,980 and 5,020 m (low pH values close to 6, salinity and chemical compositions similar to those previously analyzed for the geothermal brines of GPK-1, GPK-2 and GPK-3) suggests an inflow of geothermal reservoir brine.

The main areas of gas anomalies and the water inflow observed between 4,980 and 5,020 m coincide with most of the geological discontinuities in terms of lithofacies and fracturation, which are more permeable areas (Fig. 17; Dezayes *et al.*, 2005). Most of the areas of He anomalies are common to the three wells. The areas of fluid inflows are rather common to GPK-2 and GPK-3.

Estimation of the natural convection fluid flux

A natural flux value of 1-1.2 m^3/h was estimated for the native reservoir brine during a tracer test and a geochemical fluid monitoring associated to four short term production tests carried out in GPK-2 between December 2000 and April 2004, after a hydraulic stimulation operation conducted in this well in July 2000 (injection of 27,800 m^3 of fresh water; Sanjuan *et al.*, 2004; 2006). Despite the low amount of fluid discharged from GPK-2 (about 4,600 m^3) and the low recovery of fresh water injected in July 2000 (less than 7%), the latter was progressively replaced by the geothermal brine (about 80% at the end of the production tests).

Taking into account the conclusions of Pribnow and Schellschmidt (2000) on the regional redistribution of heat by convection due to fluid flow in the upper crust, the interpretation of the thermal gradient of GPK-2 by Kohl *et al.* (2002), and the temperature at depth according to chemical geothermometers (about 240°C), the value of 1-1.2 m^3/h may be also applied to the natural flux of fluid convection. This value is identical to that calculated by Bächler (2003) for the graben-parallel fluid flux in the Soultz site, using numerical 3D modelling and the velocity distribution above the centre of a convection cell multiplied by the fault width and half the height of the cell. Bächler (2003) also gives an estimate of the graben-perpendicular fluid flux and demonstrates that it is negligible compared to the graben-parallel flux.

Although the total volume of the fluids injected into the wells is higher than that of the discharged fluids, most of the tracer tests conducted between 2000 and 2005 showed that low amounts of injected fresh water were recovered through discharged fluids and the contribution of native reservoir brine was always high, even after significant fresh water injection. It was estimated that the fresh water injected into the wells since 2000 had mixed with a volume higher than 750,000 m^3 of native reservoir brine (Sanjuan *et al.*, 2006).

Presence of different circulation paths in the heat exchanger and estimation of the corresponding tracer recovery rates and linear mean fluid velocities

The tracer test using 150 kg of fluorescein (82,5% pure) and the geochemical fluid monitoring, which accompanied the fluid circulation test between the injection well GPK-3 and the production wells GPK-2 and GPK-4 from July to December 2005, have brought very useful information about the fluid circulation in the heat exchanger at a depth of 4,500-5,000 m. The detailed study is reported in Sanjuan *et al.* (2006). In this paper, we only will present the main results and conclusions.

During this fluid circulation test, the average injection flow rate into GPK-3 was estimated to be close to 15 l/s, with 11.9 l/s produced from GPK-2 and 3.1 l/s produced from GPK-4. Based on these values, about 209,000 m^3 of fluid was injected into GPK-3, and 165,500 m^3 and 40,500 m^3, respectively, were discharged from GPK-2 and GPK-4. Production temperatures increased during the circulation test from 140 to 160°C for GPK-2 and from 100 to 125°C for GPK-4.

The analytical fluorescein results obtained from the tracer test and their interpretation (Figs. 19, 20 and 21) using the TEMPO code (Pinault, 2001), based on a model of dispersive transfer (Pinault *et al.*, 2005), confirmed a relatively direct hydraulic connection between GPK-3 and GPK-2 (short-scale loop; n°1 in figure 22) but have also shown evidence for another larger and slower hydraulic connection between these two wells (large-scale loop; n°2 in figure 22). The calculated parameters relative to the two fluid circulation loops are reported in Table 5.

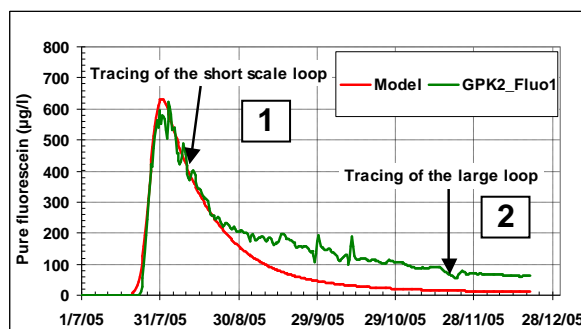*Figure 19 - Fitting of the fluorescein recovery in the fluid discharged from GPK-2 by a dispersive transfer model (extracted from Sanjuan et al., 2006).*
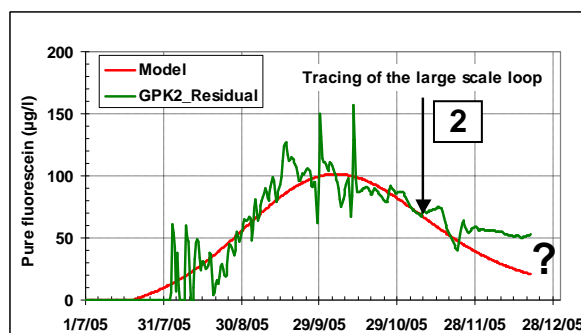

Figure 20 - Fitting of the fluorescein recovery residual (see Fig. 19) in the fluid discharged from GPK-2 using the dispersive transfer model (extracted from Sanjuan et al., 2006).
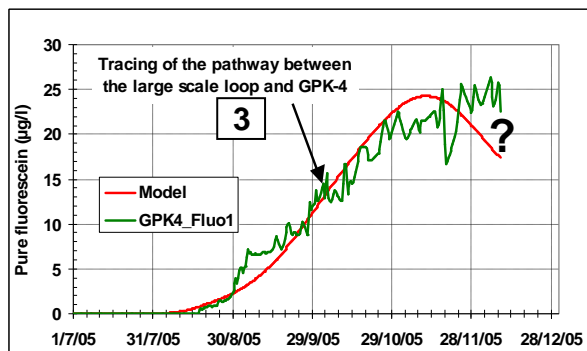
Figure 21 - Fitting of the measured fluorescein recovery in the fluid discharged from GPK-4 using the dispersive transfer model applied to the residual curve of fluorescein recovery for GPK-2 (extracted from Sanjuan et al., 2006).
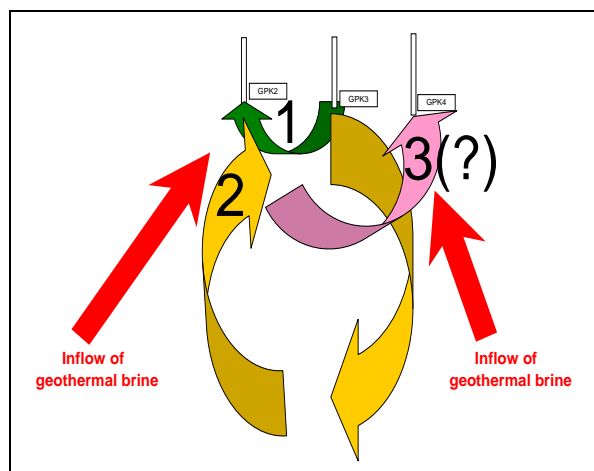

Figure 22 - Conceptual model of fluid circulation in the Soultz geothermal exchanger: 1. Short scale loop between GPK-3 and GPK-2; 2. Large scale loop between GPK-3 and GPK-2; 3. Connection between the large scale loop and GPK-4 (extracted from Sanjuan et al., 2006).

The relatively direct hydraulic connection between GPK-3 and GPK-2 had already been evidenced by tracer tests conducted in 2003, using nitrates and 1,6-nds. Fluorescein was first detected in the fluid produced from GPK-2 about 4 days after its injection into GPK-3, that is to say about 3.25 days earlier than the nitrates (first detected 7.25 days after their injection into GPK-3). However, the maximum concentration was observed at similar times. The earlier arrival time for fluorescein can be most likely explained by the higher detection limit of the nitrates.

The total fluorescein recovery through GPK-2 was estimated as 23.5%; the total swept volume (10,400 m^3) corresponds to about 5% of the fluid injected into GPK-3 (209,000 m^3) and the effective average fluid velocities range from 0.3 to 1.1 m/h, depending on the traveled paths. These results, which are relevant for great depth (about 5,000 m), are similar, or even slightly higher, to those obtained between GPK-1 and GPK-2, at depths of 3,500-3900 m, during the circulation test conducted in 1997 with an injection flow rate of 21 to 25 l/s (0.25-0.45 m/h; Vaute, 1998; Aquilina *et al.*, 2004).

The hydraulic connections between GPK-3 and GPK-4 seem to be very poor because fluorescein was detected very late in the fluid discharged from GPK-4 (about 28 days after its injection into GPK-3) and at very low concentrations. Although the fluorescein-recovery curve for GPK-4 could not be fully interpreted since the fluorescein concentration did not attain a maximum (Fig. 19), it was suggested that GPK-4 was probably connected to the large scale loop between GPK-3 and GPK-2 rather than directly to GPK-3 (loop n°3 in figure 22). The characteristics of this fluid circulation loop are also reported in Table 5.

The differences observed between experimental and modeled data at the end of the fluorescein-recovery curves (Figs. 20 and 21) suggested the existence of a further quasi-infinite loop, which could connect both GPK-2 and GPK-4 to GPK-3. The presence of this loop could explain the low fluorescein recovery rate estimated at the end of the circulation test (25.3%). These results were interpreted as indicating the presence of different networks of fractures close to the exchanger, more or less open, and progressively intersected by the injected fluids.

The fluorescein data do not seem to have been much affected by processes of adsorption or chemical degradation because, when compared with those obtained using 1,6-nds between GPK-3 and GPK-2 (41.4/175 kg = 23.7% of 1,6-nds recovery), and between GPK-3 and GPK-4 (3.6/175 kg = 2.1% of 1,6-nds recovery) during the same circulation test, they give similar results (Table 5).

CONCLUSION

Several production tests have been conducted between 1999 and 2005, after the GPK-2 drilling and the hydraulic stimulation tests carried out in the wells GPK-2, GPK-3 and GPK-4, or during the fluid circulation test in 2005, between the injection well GPK-3 and the production wells GPK-2 and GPK-4. The geochemical fluid monitoring performed during these production tests has allowed to better know the chemical and isotopic compositions of the native reservoir brine and deep associated gases.

Reconstructed chemical and isotopic data for this brine and associated gases are proposed in this study. Even if additional analyses of several trace elements in samples of uncontaminated native reservoir brine would be necessary, these data will be very useful to prevent and solve the scaling and corrosion problems during the running of the heat exchanger. Additional investigations will have to be performed in order to better identify and quantify the dissolved compounds, which constitute the alkalinity. The knowledge of the accurate contributions of bicarbonate ions, the presence of dissolved organic compounds, etc., is necessary in order to validate the estimation of CO_2 pressure.

Considering the chemical composition of the native reservoir brine and the results obtained using the classical chemical geothermometers, the problem of the nature of the rocks surrounding the deep reservoir (granite or sedimentary rocks?) remains difficult to resolve. As the measured temperatures are close to 200°C at the bottom of the wells GPK-2, GPK-3 and GPK-4 and the local thermal gradient becomes normal in the granites located under the sedimentary cover, the values estimated using most of the geothermometers (220-240°C) suggest that the native reservoir brine comes from a deeper vertical area (< 6 km) or from a relatively distant lateral hotter area. In the reservoir, this brine is in equilibrium with a mineralogical assemblage at 220-240°C.

The very important fluid-flow data obtained from tracer tests conducted between 2000 and 2005 (especially in 2005) should be confirmed by further tracer testing and other techniques (hydraulic tests, numerical modeling, geophysical monitoring, etc.). Nevertheless, the present data highlight the omnipresence of the native reservoir brine in the geothermal exchanger (with a natural convection flux estimated at 1-1.2 m^3/h), the relatively low rate of recovery of injected fresh water from the discharged fluids, the existence of at least three pathways between GPK-2 and GPK-3 with different effective fluid velocities and the poor connections between GPK-3 and GPK-4, which reflects the asymmetry of the Soultz heat exchanger at depths of 4,500-5,000 m.

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Fluid sample	Sampling date	Depth m	T °C	Density 20°C	Conductivity mS/cm	pH	O$_2$ %	Eh mV	$\delta^{18}O$ ‰	δD ‰	^3H TU	$^{87}Sr/^{86}Sr$	δ^7Li ‰	$\delta^{18}O(SO_4)$ ‰	$\delta^{34}S(SO_4)$ ‰
GPK-1															
GPK1-KS228	1986-1991	Well head				5.82			-3.1	-41.0		0.711590		8.5	17.1
GPK1-KD006	1986-1991	1845	137			5.02			-2.6	-39.8				7.8	17.4
KP-3500	1993	3470	165			5.03			-2.9	-36.7		0.711320		5.9	14.0
GPK1-99-P1	02/03/99	Well head	47.8		111 (20°C)	5.52 (20°C)									
GPK1-99-P2	08/04/99	Well head			131 (25°C)	5.35 (31°C)	1.0								
GPK1-99-P3	06/05/99	Well head			131 (25°C)	5.48 (17°C)	3.9						-0.4		
GPK-2															
KP3-97-16	25/07/97	Well head	30.5	1.053	95 (20°C)	5.73 (30°C)	3.9	34							
KP3-97-122	25/08/97	Well head	31.0	1.059		5.06 (31°C)	0.7	120							
KP3-97-296	25/09/97	Well head	47.3	1.065		5.13 (47°C)	0	114							
KP3-97-435	25/10/97	Well head	27.3	1.064	116 (20°C)	5.04 (27°C)	0	140							
KP3-97-600	16/11/97	Well head	32.8	1.064	116 (20°C)	5.04 (33°C)	0	140					0.6		
GPK2-99-S2	26/11/99	Well head	34.0	1.064	114 (20°C)	5.43 (20°C)		30	-3.6	-34.7			-0.1		
GPK2-99-S3	29/11/99	Well head	40.0	1.063	114 (20°C)	5.41 (20°C)		20	-3.1	-35.3				4.9	12.8
GPK2-99-S4	03/12/99	Well head	35.0	1.065	119 (20°C)	5.46 (20°C)		8	-2.9	-35.1				5.2	12.6
GPK2-99-D1	02/12/99	650 m		1.063	113 (20°C)	5.45 (20°C)		-63	-3.3	-34.5		0.711264		5.5	13.1
GPK2-99-D2	02/12/99	650 m		1.063	114 (20°C)	5.51 (20°C)		17							
GPK2-99-D3	02/12/99	700 m		1.063	114 (20°C)	5.72 (20°C)		-35							
GPK2-02-P71	24/04/02	Well head	39.4	1.050	97 (25°C)	5.58 (20°C)		-23	-3.1	-36.0	3				
GPK2-03-P42	09/07/03	Well head		1.040	78 (25°C)	5.67 (20°C)									
GPK2-05-P149	22/11/05	Well head	159	1.060	110 (25°C)	5.39 (20°C)	16	-1							
GPK-3															
GPK3-03-P8	18/03/03	Well head	40.0	1.062	106 (25°C)	5.51 (20°C)									
GPK-4															
GPK4-05-P212	22/11/05	Well head	121	1.057	106 (25°C)	5.15 (20°C)	16	14							
Reconstructed chemical and isotopic composition of the native reservoir brine		200		1.065	120 (20°C)	5.0	0	< -100	-3.1	-35.1	0	0.71126	-0.4	5.2	13.0

Fluid sample	Sampling date	Na g/l	K g/l	Ca g/l	Mg mg/l	Cl g/l	SO$_4$ mg/l	[1]Alk. meq/l	[2]Alk. meq/l	DOC mg/l	SiO$_2$ mg/l	NO$_3$ mg/l	NO$_2$ mg/l	NH$_4$ mg/l	PO$_4$ mg/l	TDS g/l	Cl/Br mass
GPK-1																	
GPK1-KS228	1986-1991	28.2	3.32	6.73	150	58.5	215	10.6	n.a.	n.a.	97	n.a.	n.a.	n.a.	n.a.	99	196
GPK1-KD006	1986-1991	28.0	3.28	6.96	152	58.1	220	3.1	n.a.	n.a.	94	n.a.	n.a.	n.a.	n.a.	97	187
KP-3500	1993	27.9	2.81	7.30	112	61.0	198	7.5	n.a.	n.a.	210	n.a.	n.a.	n.a.	n.a.	101	270
GPK1-99-P1	02/03/99	27.2	3.30	6.26	139	58.7	255	4.4	2.8	18	98	< 0.5	< 0.01	24.2	< 0.1	97	263
GPK1-99-P2	08/04/99	25.9	3.25	6.92	109	57.9	246	5.6	3.9	n.a.	89	< 0.5	0.02	25.2	0.5	96	253
GPK1-99-P3	06/05/99	27.5	3.16	6.24	111	59.5	231	5.3	3.2	n.a.	81	< 0.5	< 0.01	23.8	< 0.2	98	241
GPK-2																	
KP3-97-16	25/07/97	22.5	2.99	5.77	119	49.5	217	3.6	2.6	n.a.	63	n.a.	n.a.	n.a.	n.a.	82	313
KP3-97-122	25/08/97	24.2	3.27	6.52	127	54.5	225	3.9	2.4	n.a.	131	n.a.	n.a.	n.a.	n.a.	90	257
KP3-97-296	25/09/97	24.8	3.26	6.65	123	55.9	214	4.9	2.3	n.a.	152	n.a.	n.a.	n.a.	n.a.	92	274
KP3-97-435	25/10/97	25.2	3.36	6.59	120	57.3	214	4.4	2.2	n.a.	151	n.a.	n.a.	n.a.	n.a.	94	281
KP3-97-600	16/11/97	25.3	3.38	6.67	119	57.0	221	3.6	2.1	n.a.	151	n.a.	n.a.	n.a.	n.a.	94	247
GPK2-99-S2	26/11/99	26.8	2.88	6.65	75	57.8	171	6.6	n.a.	n.a.	409	< 5	< 0.01	21.1	2.0	95	248
GPK2-99-S3	29/11/99	26.2	2.91	6.65	77	57.6	172	6.3	n.a.	56	392	< 5	< 0.01	21.4	0.5	94	244
GPK2-99-S4	03/12/99	26.4	2.87	6.78	78	58.5	170	7.7	n.a.	58	364	< 5	< 0.01	20.0	< 0.1	95	234
GPK2-99-D1	02/12/99	27.4	2.86	6.60	98	59.0	159	n.a.	6.3	6.3	175	< 5	0.02	21.9	< 0.1	98	265
GPK2-99-D2	02/12/99	n.a.	n.a.	n.a.	n.a.	58.5	158	n.a.	6.3	6.3	130	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
GPK2-99-D3	02/12/99	27.5	2.93	6.80	99	n.a.	n.a.	n.a.	6.3	6.3	225	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
GPK2-02-P71	24/04/02	23.5	2.77	5.02	124	46.2	150	5.0	n.a.	n.a.	262	< 5	0.01	17.2	1.2	78	204
GPK2-03-P42	09/07/03	n.a.	n.a.	3.46	n.a.	32.6	n.a.	2.1	n.a.	n.a.	212	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
GPK2-05-P149	22/11/05	22.9	2.59	6.10	106	49.3	157	2.3	n.a.	n.a.	255	n.a.	n.a.	n.a.	n.a.	82	225
GPK-3																	
GPK3-03-P8	18/03/03	27.2	2.70	6.21	100	54.6	163	6.9	n.a.	n.a.	216	n.a.	n.a.	n.a.	n.a.	92	270
GPK-4																	
GPK4-05-P212	22/11/05	21.0	2.38	6.03	102	44.9	166	3.7	n.a.	n.a.	231	n.a.	n.a.	n.a.	n.a.	75	229
Reconstructed chemical composition of the native reservoir brine		27.5	3.25	6.90	125	59.0	190	5.0 (85 mg/l HCO$_3$)		43	427	< 0.5	< 0.01	23.5	< 0.1	97	268

n.a.: not analyzed

Fluid sample	Sampling date	Br mg/l	B mg/l	F mg/l	Sr mg/l	Li mg/l	Mn mg/l	Ba mg/l	Fe mg/l	Al mg/l	As mg/l	Rb mg/l	Cs mg/l	Ge µg/l	Be µg/l	Ni µg/l	Cu µg/l	Co µg/l	Cr µg/l	Cd µg/l	Zn µg/l	Ag µg/l	Ti µg/l	Pb µg/l
GPK-1																								
GPK1-KS228	1986-1991	299	34.0	3.9	480	123	18.1	12.3	232	0.044	0.6	25.1	15.7	n.a.	n.a.	90	30	20	70	17	4000	4	320	n.a.
GPK1-KD006	1986-1991	310	33.6	n.a.	126	n.a.	12.5	7.5	n.a.	n.a.	28.8	12.0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	5500	3	220	n.a.
KP-3500	1993	226	29.0	n.a.	490	147	15.4	12.0	n.a.	0.150	5.7	21.1	12.2	n.a.	n.a.	110	30	30	60	14	5500	3	220	n.a.
GPK1-99-P1	02/03/99	223	24.6	3.9	420	122	16.8	14.0	50	< 0.03	5.5	n.a.	n.a.	n.a.	26	67	18	13	5	14	2360	< 10	n.a.	782
GPK1-99-P2	08/04/99	229	24.7	3.8	407	130	15.2	8.8	56	< 0.03	4.5	n.a.	n.a.	n.a.	33	74	27	15	9	8	2060	< 5	n.a.	181
GPK1-99-P3	06/05/99	247	22.6	3.9	410	115	14.7	13.7	35	0.054	5.9	n.a.	n.a.	n.a.	12	320	33	37	< 15	< 10	1030	< 10	n.a.	210
GPK-2																								
KP3-97-16	25/07/97	158	n.a.	n.a.	377	139	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
KP3-97-122	25/08/97	212	n.a.	n.a.	417	163	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	320
KP3-97-296	25/09/97	204	n.a.	n.a.	436	158	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	320
KP3-97-435	25/10/97	204	n.a.	n.a.	447	169	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	270
KP3-97-600	16/11/97	231	33.7	n.a.	460	151	14.8	2.9	n.a.	< 0.03	11.0	22.7	14.0	n.a.	n.a.	176	17	36	43	10	3180	< 5	193	289
GPK2-99-S2	26/11/99	233	27.5	4.6	419	133	12.0	8.2	97	< 0.03	8.3	21.2	13.7	n.a.	< 5	71	76	52	< 10	4	3200	< 5	n.a.	320
GPK2-99-S3	29/11/99	236	32.4	4.5	412	131	13.0	9.3	108	0.030	8.4	22.2	14.5	n.a.	< 5	80	68	59	< 10	4	3300	< 5	n.a.	320
GPK2-99-S4	03/12/99	250	32.9	3.9	421	126	13.0	8.6	146	< 0.03	8.5	21.3	13.1	n.a.	< 5	100	60	48	< 10	15	6000	< 5	n.a.	270
GPK2-99-D1	02/12/99	223	36.0	4.7	400	125	15.4	8.2	96	0.031	6.5	23.1	14.4	n.a.	< 20	205	260	60	18	28	3400	< 20	181	307
GPK2-99-D2	02/12/99	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
GPK2-99-D3	02/12/99	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
GPK2-02-P71	24/04/02	227	26.6	5.4	320	141	17.3	4.7	75	< 1	4.2	18.1	20.7	53	50	< 100	< 40	< 40	< 100	< 40	1740	< 100	n.a.	< 100
GPK2-03-P42	09/07/03	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
GPK2-05-P149	22/11/05	219	n.a.	n.a.	n.a.	130	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
GPK-3																								
GPK3-03-P8	18/03/03	202	n.a.	n.a.	n.a.	154	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
GPK-4																								
GPK4-05-P212	22/11/05	196	n.a.	n.a.	n.a.	97	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Reconstructed chemical composition of the native reservoir brine		220	35	4.5	450	140	15	10	100	0.05	6	22	14	53	30	100	45	50	40	10	3000	< 5	200	300

n.a.: not analyzed

Table 1 - *Analytical data of fluids discharged from the wells GPK-1 (Pauwels et al., 1993; Aquilina et al., 1997; Sanjuan et al., 2001), GPK-2, GPK-3 and GPK-4 (Vaute, 1998; Sanjuan et al., 2001; Gentier et al., 2003a, b; Sanjuan et al., 2004; this study) used in order to reconstruct the chemical and isotopic composition of the native Soultz reservoir brine.*

Well	Date	Depth m	Laboratory	GLR % vol.	CO2 % vol.	O2 % vol.	N2 % vol.	Ar % vol.	He % vol.	H2 % vol.	He+H2 % vol.	CH4 % vol.	C2H6 % vol.	C3H8 % vol.	H2S % vol.	N2/Ar vol.	He/Ar vol.
GPK-1																	
GPK1 KS228	1986-1991	Well head	BRGM	20.0	46.3	0	27.3	n.a.	1.0	20.1	n.a.	4.8	n.a.	n.a.	n.a.	n.a.	n.a.
GPK1 KD006	1986-1991	1845	BRGM	n.a.	67.1	0	27.4	n.a.	0.61		n.a.	4.2	n.a.	n.a.	n.a.	n.a.	n.a.
GPK1 KD007	1986-1991	1930	BRGM	n.a.	54.3	0	37.0	n.a.	n.a.	0.25	n.a.	6.1	n.a.	n.a.	n.a.	n.a.	n.a.
GPK1 KP3500	1993	3470	BRGM	16.7	79.0	0	11.0	0.074	0.45	7.2	n.a.	3.4	0.03	0.0011		149	6.1
GPK-2																	
GPK2-99-S1	04/11/99	Well head	BRGM	13.2	14.2	0.48	29.9	0.23	1.0	46.3	n.a.	6.8	0.12	0.018	< 0,005	130	4.4
GPK2-99-D1	02/12/99	650	IFP	2.6	15.8	0	48.6	0	2.2	26.5	28.7	7.0	0	0	n.a.	n.a.	n.a.
GPK2-99-D3	02/12/99	700	IFP	17.8	37.2	0	37.2	0	n.a.	n.a.	19.2	6.5	0	0	n.a.	n.a.	n.a.
GPK2-99-CM1	Continuous monitoring 1999	Surface (from gas separator and casing)	GFZ	17-29	59-64	0	24-30	0.1-0.2	0.5-0.8	5-7	n.a.	4-6	n.a.	n.a.	n.a.	120-300	2-8
GPK2-99-CM2	Nov. 25th to 29th, 1999	Surface (from gas separator)	GFZ	29.0	62.0	0	27.0	0.15	0.65	6.0	n.a.	5.0	n.a.	n.a.	n.a.	180	4.3
GPK2-99-DG	24/11/99	Inlet of the gas separator and complete degassing in lab	GFZ	38.0	89.7	0	7.2	0.17	0.13	1.7	n.a.	1.2	n.a.	n.a.	n.a.	42	0.8
GPK2-05-G1	19/10/05	Well head	BRGM	n.a.	56.6	0.05	34.3	0.17	1.98	1.9	n.a.	6.3	0.06	0.003	< 0,005	202	11.6
GPK2-05-G2	19/10/05	Well head	BRGM	n.a.	56.4	0.04	35.5	0.14	1.93	1.9	n.a.	6.2	0.06	0.003	< 0,005	254	13.8
GPK-4																	
GPK4-05-G1	19/10/05	Well head	BRGM	n.a.	61.2	0.05	30.8	0.18	1.66	2.8	n.a.	5.8	0.06	0.003	< 0,005	171	9.2

n.a.: not analyzed; GLR: Gaz-Liquid Ratio

The atmospheric volume ratios N_2/Ar et He/Ar are 84 et 5.7.10-4, respectively; a volume ratio He/Ar around 0.1 generally represents a magmatic origin

Table 2 - Chemical composition of deep gases discharged from the wells GPK-1(Pauwels et al., 1993; Aquilina et al., 1997), GPK-2 and GPK-4 (Sanjuan et al., 2001; Naumann et al., 2000;this study)

Brine sample	GPK1-99-P1 (02/03/99)	GPK2-99-S3 (29/11/99)	GPK2-99-S4 (03/12/99)	GPK2-99-D1 (02/12/99)	Reconstructed native reservoir brine
Geothermometers	T°C	T°C	T°C	T°C	T°C
T_{Quartz} (Fournier and Rowe, 1966)	136	231	225	239	239
T_{Na-K} (Michard, 1979)	218	209	206	229	218
T_{Na-K} (Fournier, 1979)	233	225	224	242	233
$T_{Na-K-Ca}$ (b = 1/3; Fournier and Truesdell, 1973)	237	230	228	243	235
$T_{Mg correction}$ (Fournier and Potter, 1979)	225	224	223	236	226
T_{K-Mg} (Giggenbach, 1988)	211	219	218	224	213
T_{Na-Li} (Cl > 0.3 M; Fouillac and Michard, 1979)	431	451	442	434	458
T_{Na-Li} (Cl < 0.3 M; Fouillac and Michard, 1979)	180	190	186	181	193
T_{Na-Li} (Kharakha *et al.*, 1982)	232	240	237	233	242
T_{Mg-Li} (Kharakha and Mariner, 1989)	221	239	237	230	230
T_{Sr-K} (Michard, 1990)	301	288	285	316	295
T_{Rb-Na} (Michard, 1990)	-	140	139	140	139
T_{Cs-Na} (Michard, 1990)	-	128	126	127	127
T_{Fe-K} (Michard, 1990)	279	229	214	255	242
T_{Mn-K} (Michard, 1990)	186	186	185	195	189
$T_{18O(H2O-SO4)}$ (Mizutani and Rafter, 1969)	-	215	213	199	209
Measured temperature at the bottom hole	165	200	200	200	200

Table 3 - Chemical and isotopic geothermometers applied to samples of native Soultz reservoir brine .

Gas sample	GPK1 KP3500 (1993)	GPK2-99-CM2 (Nov. 1999)	GPK2-99-DG (24/11/99)	GPK2-05-G1 (19/10/05)	GPK4-05-G1 (19/10/05)
Gas geothermometers	T°C	T°C	T°C	T°C	T°C
$T_{CO2/H2/CH4}$ (Marini, 1987)	240	226	230	193	203
$T_{CH4/CO2}$ (Giggenbach, 1991)	239	224	269	217	220
$T_{H2/Ar}$ (Giggenbach and Goguel, 1989)	314	287	245	248	259
$T_{CO2/Ar}$ (Giggenbach, 1991)	236	215	220	210	210
Measured temperature at the bottom hole	165	200	200	200	200

Table 4 - Geothermometers applied to samples of deep gases associated to the native reservoir brine.

Parameter	GPK-3/GPK-2 loop n°1	GPK-3/GPK-2 loop n°2	GPK-3/GPK-4 loop n°3
Time of the first fluorescein arrival (days)	4		28
Maximum linear fluid velocity (m/h)	8.1		1.0
Maximum fluorescein concentration (µg/l)	630 - 770		> 30
Time of the maximum fluorescein arrival (days)	9 - 16		> 150
Velocity corresponding to the maximum fluorescein arrival (m/h)	1.9 - 3.2		< 0.2
Fluorescein recovery rate (%)	15.6	7.9	1.8
Mean transfer time (days)	24.3	80	25
Mean linear fluid velocity (m/h)	1.1	0.3	1.1
Swept volume : fracture pore volume occupied by fluorescein (m^3)	3900	6500	120

Table 5 - Main parameters estimated during the 5 month fluid circulation test carried out in 2005 between the injection well GPK-3 and the production wells GPK-2 and GPK-4 .