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TRACER TESTING AT SOULTZ-SOUS-FORÊTS (FRANCE) USING NA-BENZOATE, 1,5 AND 2,7-NAPHTHALENE DISULFONATE

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ABSTRACT

A hydraulic stimulation was conducted in well GPK-2, at Soultz-sous-Forêts (France), in July 2000, one year after its deepening from a depth of 3,500 m to 5,100 m. During this operation, two organic tracers (Na-benzoate and 1,5-naphthalene disulfonate) were continuously injected at a controlled concentration of about 2 mg/l into GPK-2 with around 26,800 m^3 of fresh water. The chemical composition of this water is very different from that of the geothermal brine (NaCl fluid with a TDS close to 100 g/l). Four short-term production tests were carried out between December 2000 and April 2002. The fluid produced from GPK-2 was geochemically monitored during these tests. This paper presents the main results of that fluid monitoring. Comparison with natural tracers such as chloride indicated that the organic tracers were remarkably stable during more than 2 years at around 200°C. At each production test, the mass proportions of injected fresh water and geothermal brine could be estimated; the recovered fresh water could also be calculated (less than 7% relative to the total volume of fresh water injected into GPK-2). It was observed that the injected fresh water was internally replaced by the geothermal brine in the reservoir. The mean flow rate of the geothermal brine circulation could be estimated at 1-1.2 m^3/h. Between January and March 2003, and during another operation of hydraulic stimulation, a third tracer (2,7-naphthalene disulfonate) was injected into GPK-2 at a controlled concentration of about 3 mg/l, with about 24,000 m^3 of fresh water. The detection of 1,5-nds, almost 3 years after its injection into GPK-2, and that of 2,7-nds in the fluid discharged from GPK-3, have shown that the recently drilled GPK-3 well (depth of 5,100 m) is directly connected to GPK-2.

INTRODUCTION

The main objective of the European Hot Dry Rock Energy (HDR) Program is to develop a deep heat exchanger for power production. The site of this exchanger is Soultz-sous-Forêts, in France, within the Rhine Graben (Fig. 1), which forms part of the West European Rift. Presently, the first phase of construction of a Scientific Pilot Plant is in progress. Three deep holes (GPK-1, GPK-2 and GPK-3) have been drilled in granite rocks under a sedimentary cover thick of about 1,400 m (Fig. 2a and 2b). The drilling of a fourth hole (GPK-4) was started in August 2003 and will be finished at the beginning of 2004.

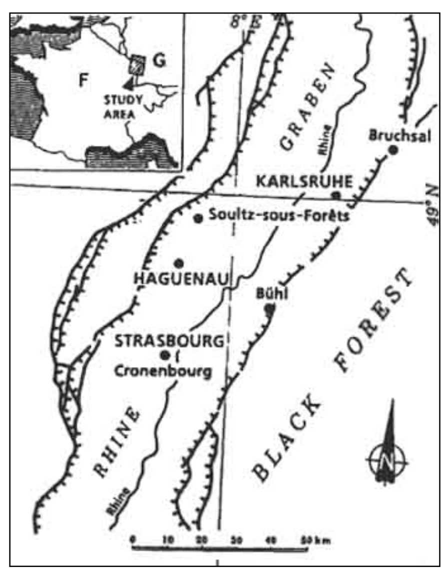


Figure 1. Location map of the Rhine Graben and Soultz-sous-Forêts.

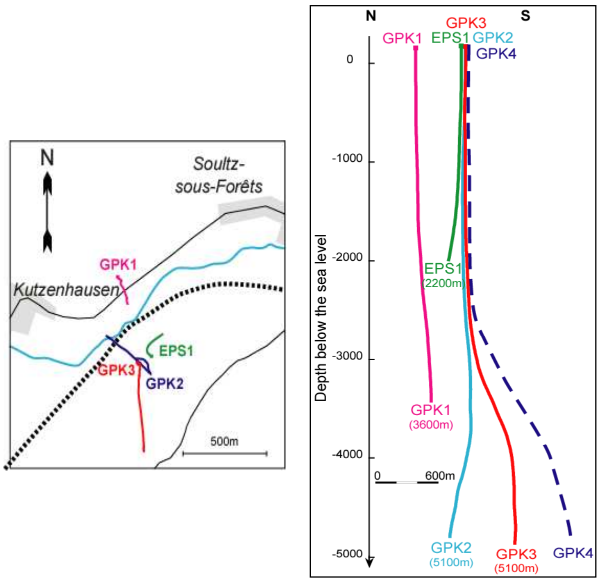


Figure 2a. Location map and profiles of the geothermal wells (From Gentier et al., 2003a; 2003b).

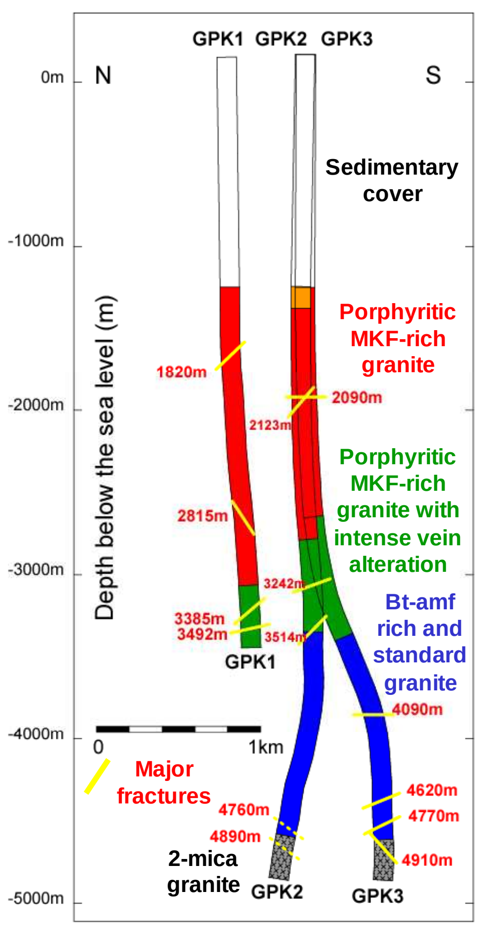


Figure 2b. Geological cross-section between the geothermal wells (From Gentier et al., 2003b).

GPK-1 has a depth of around 3,600 m. The last three holes, with depths of about 5,100 m, will make up the thermal exchanger. GPK-3 will be the injection well and GPK-2 and GPK-4 will be the production wells. Temperature at depth is close to 200°C and a geothermal NaCl fluid (TDS ≈ 100 g/l) was intersected by each hole. In order to ameliorate the quality of the connections between wells (Fig. 2b), hydraulic stimulation tests were carried out in GPK-1 in 1997, in GPK-2 in 2000 and 2003, and in GPK-3 in 2003. Tracer tests accompanied each stimulation operation. This study presents the main results obtained during the tracer testing associated with the stimulation operations carried out in GPK-2 in 2000 and 2003.

TRACER TEST CARRIED OUT ON GPK-2 IN JULY 2000

Previous works

A four-month circulation test between GPK-1 and GPK-2 was carried out in 1997. A circulation loop had been created between these two wells. The hot fluid produced from GPK-2 (3,500 m of depth at that time) was cooled in a surface heat exchanger before being re-injected into GPK-1, at around the same depth. The bottom hole temperature was close to 150°C. Tracing of the circulating fluid during this experiment was performed using Na-benzoate (292 kg) among other tracers. It demonstrated a direct hydraulic connection between both wells. At the beginning of the experiment, the tracers injected into GPK-1 were detected 3 to 6 days after their injection in the fluid produced from GPK-2 (Vaute, 1998). Tracer maxima were observed between 6 and 10 days after this injection. It was also shown that only 25 to 30% of the total amount of injected Na-benzoate was recovered at the end of the four month circulation test.

Tracer injection

A hydraulic stimulation of GPK-2 was conducted one year after it was deepened from 3,600 m to 5,100 m. A tracer experiment accompanied the hydraulic stimulation. During this experiment, a large volume of water (26,800 m^3 of fresh water and 1,000 m^3 of heavy brine) was injected into GPK-2. At the same time, Na-benzoate and 1,5-naphthalene disulfonate (1,5-nds), two organic tracers chosen for their properties (thermally stable, low adsorption, high solubility, low detection limit, no toxicity) and their low cost, were continuously introduced in the fluid injected into GPK-2 at a controlled concentration with a pump whose flow rate was set to that of the injected fluid. Na-benzoate had been already used by BRGM at Soultz (Vaute, 1998) and in another geothermal site (Bouillante, in Guadeloupe, French West Indies; Sanjuan *et al.*, 1999; 2000). The 1,5-nds had also been used in several tracer tests carried out in geothermal areas (Rose *et al.*, 1999; 2000; 2001). The mean concentration during the injection of these tracers was estimated at 2.25 mg/l for Na-benzoate and 1.75 mg/l for 1,5-nds.

Geochemical monitoring of the fluid produced from GPK-2

After this tracer injection, four short-term production tests were performed on GPK-2 between December 2000 and April 2002. During each test, the fluid discharged from GPK-2 was geochemically monitored by BRGM (December 11-21 2000; January 30-February 23 2001; June 21-28 2001; April 23-24 2002). The volume of fluid discharged during each test was 1,170, 2,720, 450 and 253 m^3 respectively, which represents a total discharged volume (TDV) of 4,593 m^3.

Parameters such as temperature, conductivity, pH, redox potential (Eh), alkalinity and dissolved chloride, calcium and silica concentrations were measured on site. For these measurements, the analytical relative uncertainties are 2 to 5%.

Fluid samples were collected and conditioned to perform additional analyzes of calcium, sodium, sulphate, bromine, lithium and organic tracers in the BRGM laboratories. The 1,5-nds also was analyzed by EGI, at the University of Utah. A more detailed analysis was performed on the last fluid sample collected from GPK-2 during the fourth production test, in the BRGM laboratories.

Classical methods (titration, ion chromatography, atomic absorption spectrometry, ICP-MS, etc.) were used for the analyzes of the major, trace and infra-trace species. The organic tracers (Na-benzoate and 1,5-nds) were analyzed by High Pressure Liquid Chromatography (HPLC).

The analytical relative uncertainties are 5 to 10% for major species and 15 to 20% for trace, infra-trace species and organic tracers. The absolute precision on the deuterium, 18-oxygen and tritium analyzes are 0.8‰, 0.1‰ and 1 TU, respectively.

Analytical results

All the analytical results obtained during the geochemical monitoring of the four production tests are presented in Gentier *et al.* (2003a). Partial results are reported in Tables 1 and 2 and in Figures 3 and 4. Most of the results obtained for the organic tracers by BRGM are in good agreement with those found by EGI (Tab. 1 and Fig. 4).

In Table 2, the results of detailed analyzes of fluids collected from GPK-2 before the fresh water injection are also reported to compare them with the results obtained in the last fluid sample collected during the fourth production test (GPK2-P71).

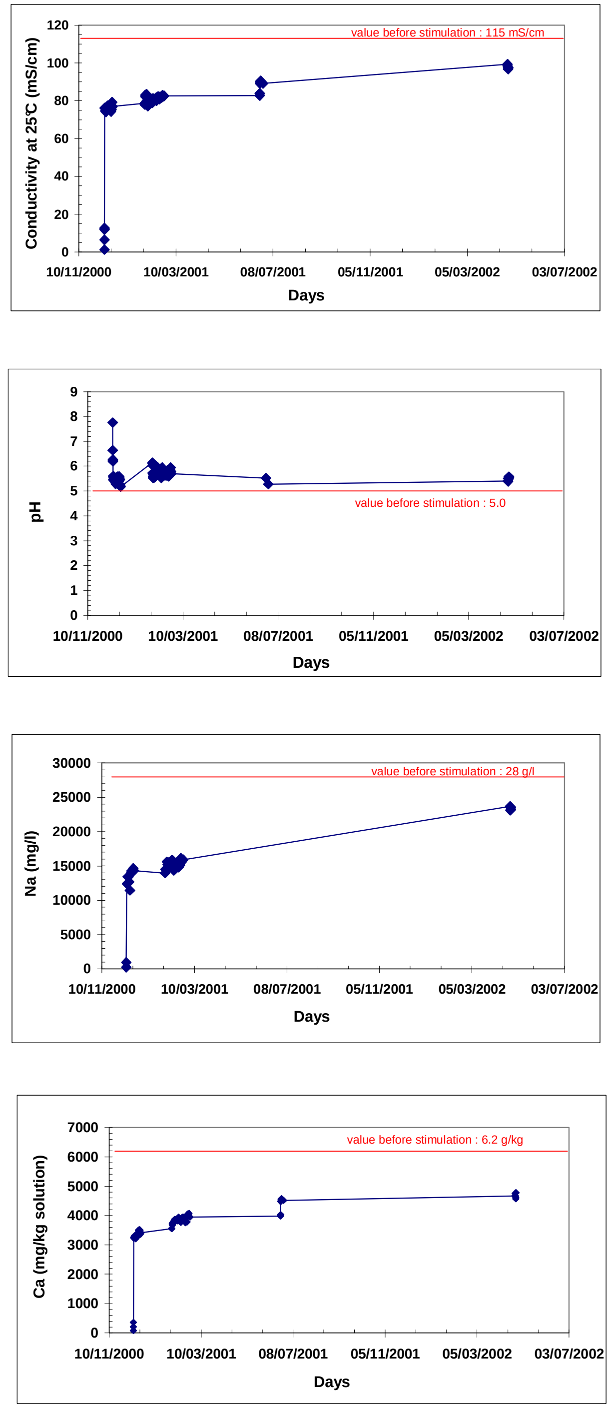


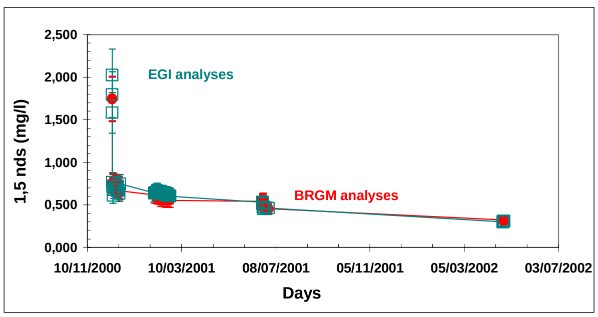
Figure 3. Geochemical monitoring of the GPK-2 fluid during the four production tests carried out between December 2000 and April 2002 (conductivity and pH measurements on site, concentrations of dissolved Na, Ca).

Table 1. Geochemical monitoring of the fluid produced from GPK-2 during the four production tests: partial results.

Fluid sample	P1	P5	P8	P45	P14
Date	12/00	12/00	12/00	12/00	02/01
T (°C)	17.9	22.2	23.3	15.0	21.9
Density	1.000	1.0045	1.0344	1.0384	1.040
Conductivity (25°C)	1.2	12.8	75.8	77.0	77.1
pH	7.76	6.19	5.61	5.17	5.75
Cl (mg/kg solution)	282	4098	28455	30118	33408
Ca (mg/kg solution)	80	362	3281	3418	3870
SiO_2 (mg/l)	42	*n.a.*	292	268	*n.a.*
Alk. (meq/l)	2.52	5.21	4.93	4.06	*n.a.*
Na (mg/l)	252	*n.a.*	12400	14350	15200
SO_4 (mg/l)	7.5	*n.a.*	175	161	170
Li (mg/l)	0.47	*n.a.*	95	108	116
Br (mg/l)	1.05	*n.a.*	125	135	149
Na-benz. (mg/l)	2.25	1.95	1.10	0.79	0.74
1,5-nds (mg/l) (BRGM)	1.75	1.74	0.75	0.66	0.62
1,5-nds (mg/l) (EGI)	1.79	1.58	0.61	0.75	0.64

n.a.: not analyzed

Fluid sample	P54	P64	P66	P71
Date	02/01	06/01	04/02	04/02
T (°C)	22.2	29.0	23.7	39.4
Density	1.04	1.04	1.05	1.05
Conductivity (25°C)	82.6	89.2	99.3	97.4
pH	5.70	5.28	5.41	5.58
Cl (mg/kg solution)	35186	37576	43301	44040
Ca (mg/kg solution)	3950	4519	4670	4780
SiO_2 (mg/l)	*n.a.*	283	244	262
Alk. (meq/l)	*n.a.*	4.64	5.68	4.98
Na (mg/l)	15900	*n.a.*	23700	23500
SO_4 (mg/l)	163	*n.a.*	147	150
Li (mg/l)	118	*n.a.*	138	141
Br (mg/l)	156	*n.a.*	212	227
Na-benz. (mg/l)	0.70	0.60	0.39	0.44
1,5-nds (mg/l) (BRGM)	0.55	0.46	0.32	0.32
1,5-nds (mg/l) (EGI)	0.60	0.46	0.30	0.31



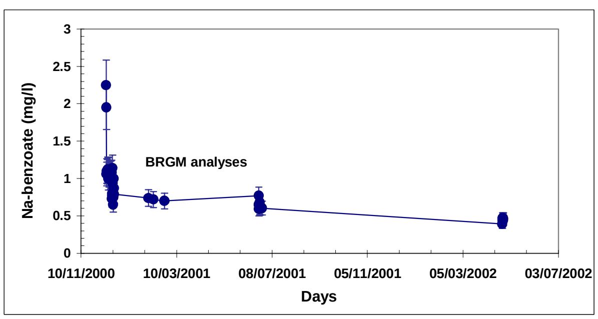


Figure 4. Concentrations of organic tracer analyzed in the fluid samples collected from GPK-2 during the four production tests carried out between December 2000 and April 2002, after the stimulation operation.

Table 2. Chemical and isotopic results obtained on three fluid samples collected from GPK-2 before the stimulation operation performed in July 2000 and on one sample collected after this operation, at the end of the fourth test production (GPK2-P71).

Fluid sample Depth Date	Unit	KP3-97-600 well head 16/11/97	GPK2-D1 650 m 02/12/99	GPK2-S4 well head 03/12/99	GPK2-P71 well head 24/04/02
T	°C	33	20	20	39
Cond (25°C)	mS/cm	115.6	113.0	118.9	97.4
pH		5.04	5.45	5.46	5.58
Eh	mV	140	-63	8	-23
$\delta^{18}O$	‰	*n.a.*	-3.3	-2.9	-3.1
δD	‰	*n.a.*	-34.5	-35.1	-36.0
$^{87}Sr/^{86}Sr$		*n.a.*	0.71126	*n.a.*	*n.a.*
$\delta^{18}O$ (SO_4)	‰	*n.a.*	5.5	5.2	*n.a.*
$\delta^{34}S$ (SO_4)	‰	*n.a.*	13.1	12.6	*n.a.*
^3H	TU	*n.a.*	*n.a.*	*n.a.*	3
Na	g/l	25.3	27.4	26.4	23.5
K	g/l	3.38	2.86	2.87	2.77
Ca	g/l	6.67	6.60	6.78	5.02
Mg	mg/l	119	98	78	124
Cl	g/l	57.0	59.0	58.5	46.2
SO_4	mg/l	221	159	170	150
Alk.	meq/l	3.6	6.3	7.7	5.0
DOC	mg/l	*n.a.*	*n.a.*	58	*n.a.*
Na-benzoate	µg/l	*n.a.*	*n.a.*	97	440
SiO_2	mg/l	151	*n.a.*	364	262
NO_3	mg/l	*n.a.*	< 5	< 5	< 5
NO_2	mg/l	*n.a.*	0.02	< 0.01	0.01
NH_4	mg/l	*n.a.*	21.9	20.0	17.2
PO_4	mg/l	*n.a.*	< 0.1	< 0.1	1.2
Br	mg/l	231	223	250	227
B	mg/l	33.7	36.0	32.9	26.6
F	mg/l	n.a.	4.7	3.9	5.4
Sr	mg/l	385	400	421	320
Li	mg/l	175	125	126	141
Mn	mg/l	16.3	15.4	13.0	17.3
Ba	mg/l	2.9	8.2	8.6	4.7
As	mg/l	11.0	6.50	8.45	4.20
Rb	mg/l	22.6	23.1	21.3	18.1
Cs	mg/l	15.0	14.4	13.1	20.7
Al	mg/l	< 0.03	0.031	< 0.03	< 1.0
Fe	mg/l	*n.a.*	96	146	75
Ge	µg/l	*n.a.*	*n.a.*	*n.a.*	53
Be	µg/l	*n.a.*	< 20	< 5	50
Ni	µg/l	77	205	100	< 100
Cu	µg/l	16	260	60	< 40
Co	µg/l	9	60	48	< 40
Cr	µg/l	43	18	< 10	< 100
Cd	µg/l	10	28	15	< 40
Zn	µg/l	2280	3400	6000	1740
Ti	µg/l	193	181	*n.a.*	*n.a.*
Pb	µg/l	258	307	270	< 100
Ag	µg/l	< 5	< 20	< 5	< 100

n.a.: not analyzed

Estimation of the mass proportions of injected fresh water and geothermal brine in the fluid discharged from GPK-2

From the mass balance equation applied to a mixture, the proportions of injected fresh water and geothermal brine in the fluid produced from GPK-2 can be estimated using the concentrations of chloride (conservative element) as well as the benzoate and 1,5-nds contents (Tab. 3 and Fig. 5).

Table 3. Estimation of the mass percentage of fresh water (FW) in the fluid discharged from GPK-2 using the concentrations of Cl, Ca, Na, Br, Li and organic tracers during the four production tests carried out between December 2000 and April 2002, after the stimulation operation. Estimation of the percentage of fresh water recovered from GPK-2 (PRFW) relative to the total fresh water injected into this well.

Sample Date	Initial Conc.	P1 12/00	P5 12/00	P8 12/00	P45 12/00	P14 02/01	P54 02/01	P64 06/01	P66 04/02	P71 04/02
% FW (Cl)	54.5 g/kg	100	92	48	45	39	35	31	21	19
% FW (Na-benz)	2.25 mg/l	100	87	49	35	33	31	27	17	20
% FW (1,5-nds BRGM)	1.75 mg/l	100	99	43	38	35	32	26	18	18
% FW (1,5-nds EGI)	1.75 mg/l	100	90	35	43	37	35	27	17	18
% FW (Ca)	6.2 g/kg	99	94	47	45	38	36	27	25	23
% FW (Na)	28.0 g/l	99		56	49	46	43		15	16
% FW (Br)	250 mg/l	100		50	46	40	38		15	9
% FW (Li)	175 mg/l	100		46	38	34	33		21	19
% FW estimated		100	90	46	43	37	35	27	20	19
TDV (m^3)					1170		3890	4340		4593
TDVFW (m^3)					503		1455	1577		1625
% PRFW					1.9		5.4	5.9		6.1

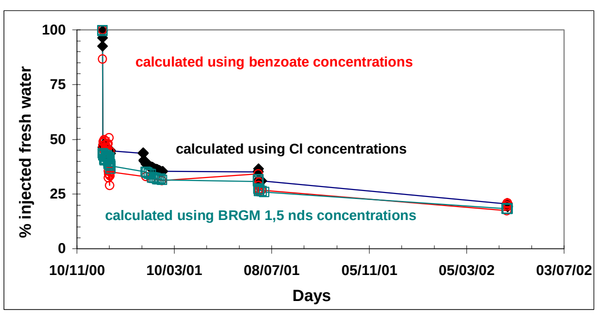


Figure 5. Estimation of the mass percentage of fresh water (FW) in the fluid discharged from GPK-2 using the concentrations of Cl and organic tracers during the four production tests carried out between December 2000 and April 2002, after the stimulation operation.

We can conclude that the results found with each tracer are in relatively good agreement in the range of uncertainty determined for each analysis. These results suggest that the Na-benzoate and 1,5-nds have a conservative behavior at least during a period of almost 2 years under the conditions within GPK-2. Other species such as Ca, Na, Br and Li give similar estimations of mixing (Tab. 3) whereas SO_4 and SiO_2 are not conservative. From the results of Table 2, it can be noticed that elements such as B, Sr and Rb also yield similar proportions of fresh water. The concentration of tritium (Tab. 2) confirms the presence of injected fresh water in the fluid produced from GPK-2.

At the end of the fourth and last production test carried out in GPK-2, after the stimulation operation performed in July 2000, the proportion of fresh water injected during this operation has decreased from about 46% (at the beginning of the first production test) to 19% (almost two years later) in the fluid produced from GPK-2 whereas only 4,593 m^3 of fluid have been discharged.

Estimation of the proportions of injected fresh water recovered from GPK-2

The proportion of injected fresh water recovered from GPK-2 can also be calculated. Knowing the total volume of fluid discharged from GPK-2 and the proportion of fresh water in this fluid, it is possible to estimate the total amount of fresh water extracted during the production test and then to calculate the percentage of fresh water recovered from GPK-2 (PRFW) relative to the total volume of fresh water injected into this well:

$$PRFW\ (\%) = 100 \times TDVFW / TIVFW$$

where TDVFW is the total volume of fresh water discharged from GPK-2 and TIVFW (26,800 m^3) is the total volume of fresh water injected into GPK-2. Calculations have been performed at the end of each production test and are reported in Table 3. It appears that at the end of the fourth production test, less than 7% of injected fresh water has been recovered. The major part of injected fresh water was recovered during the first and second production tests (5-6%). A low volume of fluid was discharged during the third and fourth production tests, and only 0.7% of injected fresh water was recovered during these tests.

Estimation of the mean internal flow rate for the deep fluid

The mean internal flow rate has been estimated from two different methods.

The first method uses the chloride concentrations analyzed during the production tests compared to that of the geothermal brine (54.5 g/kg of solution). From the diagram representing the chloride concentrations versus time (Fig. 6), we can evaluate the number of days (1,029 days) necessary to cancel the total volume of fresh water injected during the stimulation experiment (26,800 m^3). Using these data, an approximate internal flow rate for the geothermal brine can be then estimated to: 26,800 / 1,029 x 24 = 1.09 m^3/h. For more accuracy, we can eliminate the volume of fresh water discharged during the 4 production tests (26,800 x 0.07 = 1,876 m^3) from the total volume of injected fresh water and the production days (43 days) from the total days. In this case, we obtain an internal flow rate of 1.05 m^3/h (24,924 / 986 x 24).

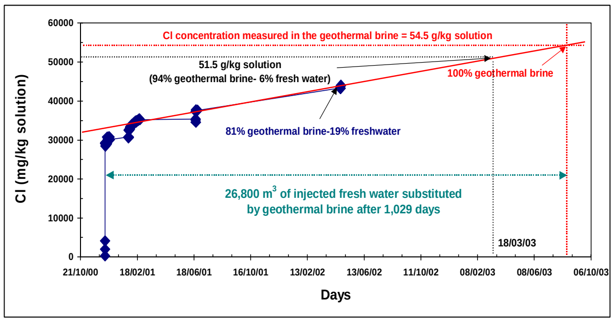


Figure 6. Chloride concentrations versus time during the four production tests carried out on GPK-2 between December 2000 and April 2002, after the stimulation operation.

The second method uses the mass balance equations. If we consider the data obtained at the beginning of the first test (46% of fresh water and 54% of formation brine in the discharged fluid) and assume that all the injected fresh water (about 26,800 m^3) has been homogeneously mixed with the brine formation, we can roughly estimate the total volume of mixture (about 56,600 m^3) and the volume of the geothermal brine (29,800 m^3). If the total volume of mixture is assumed to be constant as a function of time, there remains approximately 11,300 m^3 of injected fresh water in the reservoir at the end of the fourth production test. The injected fresh water that has naturally left the volume of mixture is then: 26,800 (injected fresh water) - 11,300 (remaining fresh water) - 0.07 x 26,800 (fresh water recovered during the four production tests) ≈ 13,624 m^3. The corresponding time period is 499 days (December 2000 - April 2002). Consequently, we can estimate the mean flow rate of fresh water outflow and formation brine inflow at: 13,624 / (499 x 24) ≈ 1.14 m^3/h.

The values estimated using the two methods are very close. We can then estimate the mean internal flow rate for the deep fluid to be close to 1-1.2 m^3/h.

TRACER TEST CARRIED OUT BETWEEN JANUARY AND MARCH 2003

Tracer injection into GPK-2

Three injection tests were carried out in GPK-2 between January and March 2003 during this hydraulic stimulation operation. The volume of fluid injected during the first test (January 23-30) was 9,214 m^3 using a flow rate of 15 l/s. During the second and third tests (February 12-16; March 11-16), this volume was 5,814 and 8,950 m^3, respectively, using flow rates of 15 and 30 l/s. The complete fluid volume injected into GPK-2 was 23,978 m^3.

During each injection test, the 2,7-naphthalene disulfonate (2,7-nds) tracer was continuously injected at a constant concentration into GPK-2. For this injection, 100 kg of pure 2,7-nds were dissolved in 950 l of fresh water by BRGM into a tank of 1 m^3 in order to prepare a tracer solution of about 105 g/l. This solution was mixed to the fluid injected into GPK-2 well with a pump whose flow rate was set to that of the injected fluid in order to have a constant concentration of about 3 mg/l. For mass balance calculations, it was decided to use a mean value of 3.06 mg/l. This value was calculated considering that, during the three injection tests, only about 0.7 m^3 of solution of 2,7-nds at 105 g/l were injected with 23,978 m^3 of fresh water into GPK-2.

Geochemical monitoring of the fluid produced from GPK-3

After this tracer injection, a volume of fluid of about 1,890 m^3 was discharged from GPK-3 in March 2003, using a flow rate of 4 l/s.

Geochemical monitoring of this fluid was carried out by BRGM between March 12 and 18. Some parameters (conductivity, pH, alkalinity, concentrations of dissolved chloride, calcium and silica) were measured on site. Some fluid samples were collected in order to perform additional analyzes of species such as Na, K, Mg, SO_4, Br, Li and organic tracers (Na-benzoate, 1,5 and 2,7-nds) in the BRGM laboratories. The 1,5 and 2,7-nds were also analyzed by EGI using HPLC with fluorescence detection (Waters Corporation, Milford, MA). These analytical results are given in Gentier *et al.* (2003b). Partial results are reported in Table 4.

The chloride concentration analyzed in the fluid discharged from GPK-3 at the end of the production test carried out in March 2003 (Tab. 4) is close to that estimated for the same period (March 18) from Figure 6 using the chloride concentrations measured in the GPK-2 fluid. From these concentrations, it can be determined that about 94-95% of geothermal brine and 5-6% of fresh water injected into GPK-2 are present in the fluid discharged from GPK-3. The concentrations of dissolved sodium, potassium, calcium, magnesium, lithium and bromide analyzed in this fluid on March 18 (Tab. 4) are very close to those estimated ($P8_{estim.}$) using the initial concentrations of geothermal brine and fresh water measured in GPK-2 (Tab. 2 and 3) and the percentages of these fluids determined from the Cl concentrations. These results give evidence of a direct hydraulic connection between the two wells whose existence had already been suggested by the presence of 1,5-nds and Na-benzoate in the mud samples collected during the drilling of GPK-3. They confirm the internal convection evidenced from the monitoring of the previous production tests carried out in GPK-2 and the value estimated for the natural flow rate of the deep fluid (1-1,2 m^3/h).

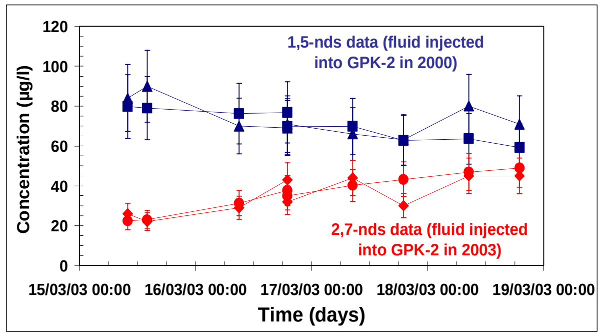
Table 4. Geochemical monitoring of the fluid produced from GPK-3 in March 2003: partial results. Estimation of the mass percentage of fresh water (FW) in this fluid using the concentrations of Cl and 1,5- and 2,7-nds.

Sample	Unit	P1	P2	P4	P5	P8	$P8_{estim.}$	P9
Date		14/03	15/03	16/03	16/03	18/03	18/03	18/03
T	°C	60	70	51	65	40	n.a.	37
pH		7.34	6.32	6.33	6.26	5.51	n.a.	5.49
Cond. 25°C	mS/cm	0.80	128.0	120.0	113.0	106.0	n.a.	115.0
Density		1.000	1.065	1.064	n.a.	1.062	n.a.	1.064
Alk.	meq/l	1.41	4.38	4.31	4.03	6.85	n.a.	6.66
SiO_2	mg/l	29	175	188	167	216	n.a.	231
Na	mg/l	n.a.	28200	28600	26600	27200	26500	n.a.
K	mg/l	n.a.	2620	2610	2650	2700	2740	n.a.
Ca	mg/kg	n.a.	5366	5671	5703	5851	5850	6003
Mg	mg/l	n.a.	95	105	103	100	104	n.a.
Li	mg/l	n.a.	145	147	150	154	165	n.a.
Cl	mg/kg	185	50575	53744	51944	51456	51500	51270
SO_4	mg/l	n.a.	167	172	167	163	160	n.a.
Br	mg/l	n.a.	185	202	199	202	236	n.a.
Na-benz.	µg/l	1	12	382	309	251	126	596
1,5-nds (BRGM)	µg/l	< 5	84	70	69	80	98	71
1,5-nds (EGI)	µg/l	0.22	80	76	77	64	98	59
2,7-nds (BRGM)	µg/l	< 5	26	29	43	45	n.a.	45
2,7-nds (EGI)	µg/l	0.08	22	31	38	47	n.a.	49
FW_{Cl} (total)	%	n.a.	7.2	1.4	4.7	5.6	5.6	5.9
$FW_{1,5-nds}$ (2000)	%	0.01	5.0	4.5	4.5	3.9	n.a.	3.6
$FW_{2,7-nds}$ (2003)	%	0.002	0.9	1.0	1.4	1.6	n.a.	1.7

Among the 5-6% of fresh water, the concentrations of 1,5-nds and 2,7-nds measured by BRGM and EGI indicate that the fluid discharged from GPK-3 consisted of about 4-5% of fresh water injected into GPK-2 in 2000 and about 1-2% of fresh water injected into GPK-2 in 2003 (Tab. 4).

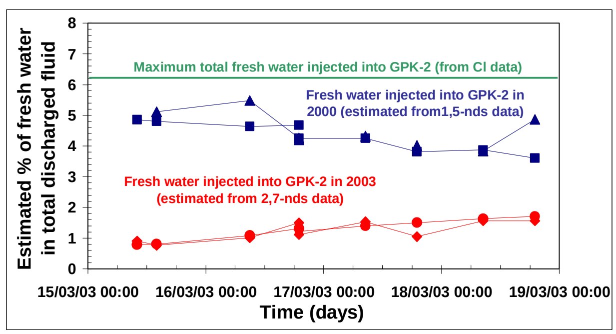
Taking into account the analytical uncertainties, the 1,5-nds and 2,7-nds data are in very good agreement with the Cl concentrations. These results show that the 1,5-nds tracer has a conservative behavior at least during a period of almost 3 years at temperature close to 200°C.

The figures 7 and 8 illustrate how the fresh water injected in 2000 into GPK-2 (represented by 1,5-nds) is progressively replaced by the fresh water injected in 2003 into this same well (represented by 2,7-nds) between March 14 and 18, 2003.



Blue triangles and red diamonds: BRGM data
Blue squares and red circles: EGI data

Figure 7. Geochemical monitoring of the fluid discharged from GPK-3 in March 2003: Analytical results of the organic tracers (1,5-nds and 2,7-nds).



Blue triangles and red diamonds: BRGM data
Blue squares and red circles: EGI data

Figure 8. Estimation of the proportions of fresh water injected into GPK-2 in 2000 and 2003, relative to the total mass of fluid discharged from GPK-3 (March 2003), using the concentrations of Cl and organic tracers (1,5-nds and 2,7-nds).

During this period, the contribution of fresh water injected in 2000 decreases approximately from 5.0 to 4.0% whereas that of fresh water injected in 2003 increases from 0.9 to 1.6% (Tab. 4). Overall, fresh water slightly decreases. At the beginning of this production test, the fresh water consisted of about 87% of fresh water injected in 2000 and 13% of fresh water injected in 2003. At the end of this test, the respective proportions are around 70 and 30%. The amount of fresh water injected between January and March 2003 into GPK-2, which has been recovered in GPK-3, after a production of 1,890 m^3 of fluid, can be estimated at 32 m^3, which represents 0.13% of the total volume of fresh water injected into GPK-2 (23,978 m^3). A tracer test using $NaNO_3$ and carried out in July 2003 showed that only 7.25 days were necessary for this tracer to be advected from GPK-3 to GPK-2 (production flow rate of 12-20 l/s). A maximum concentration was detected between 8 and 11 days after the $NaNO_3$ injection. The mean fluid circulation rate between GPK-3 and GPK-2 (3.73 m/h) was similar to that calculated in 1997 between GPK-1 and GPK-2.

CONCLUSION

This study showed that the Na-benzoate and 1,5-nds organic tracers have a conservative behavior at least during a period of almost 3 years under bottom-hole GPK-2 conditions (temperature close to 200°C).

At the end of the fourth and last production test carried out on GPK-2, after the stimulation operation performed in July 2000, the mass proportion of fresh water injected during this operation has decreased from about 46% to 19% (almost two later years) in the fluid produced from GPK-2 whereas less than 7% of this water has been recovered. All these results coupled with the temperature of the deep geothermal brine estimated using the chemical geothermometers (about 240°C) suggest the existence of an internal convection in the reservoir with a relatively significant circulation rate. A value close to 1-1.2 m^3/h has been determined for this circulation rate.

The results obtained in March 2003 during the tracer test carried out between GPK-2 and GPK-3 using the 1,5 and 2,7-nds tracers give evidence of a direct hydraulic connection between the two wells. They confirm the internal convection evidenced from the monitoring of the previous production tests carried out in GPK-2 and the value estimated for the natural flow rate of the deep fluid.

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