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BOUILLANTE GEOTHERMAL FIELD (GUADELOUPE, WEST INDIES): GEOCHEMICAL MONITORING DURING A THERMAL STIMULATION OPERATION

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ABSTRACT

In the geothermal Bouillante Field, only the well BO-2 is presently connected to a power plant. The now-closed well BO-4, located near BO-2 and producing around 10 t/h of steam in 1978, was considered as a potential candidate for a thermal stimulation test. During this operation (from 10th to 27th August 1998), around 8,000 m³ of cold sea water were injected into the fractured BO-4 reservoir. A chemical inhibitor was used to prevent anhydrite precipitation predicted by geochemical modelling. The two production tests, performed in BO-4 before and after the stimulation experiment (about 1,300 and 5,000 m³ of discharged brine), have shown a much higher productivity than the test carried out in 1978. An improvement in injectivity by 50% and in production stability has been observed after stimulation. Calculated well characteristic curves show that productivity has also been increased. An additional long time production test must be carried out to confirm the new data obtained from BO-4.

During the stimulation operation, a multiple tracer test (MTT) was performed using 3 organic tracers (Na-naphtionate, Na-benzoate and isophtalic acid) injected into BO-4 with sea water and monitored during 45 days from BO-2 and 3 neighbouring thermal springs. The MTT has indicated and confirmed that no direct hydraulic connection exists between BO-4 and BO-2 and the 3 springs. A geochemical monitoring from BO-4 has been carried out during the two production tests. The production improvement by thermal cracking had no significant consequences on brine, steam condensate and non-condensable gases in terms of phase proportions and chemical, isotopic composition. According to the geochemical results, the injected sea water is never found at high proportions in the discharged fluid; it is rapidly mixed with the reservoir geothermal fluid. This can be explained by a relatively large interconnected reservoir volume and a high water-rock ratio, which is in agreement with the isotopic signature of the deep brine. Monitoring has shown that the chemical and physical characteristics of the deep geothermal fluid are similar in BO-4 and BO-2.

INTRODUCTION

The geothermal Bouillante area is located on the western coast of Basse-Terre of the island of Guadeloupe, which belongs to the active volcanic island arc of the Lesser Antilles (Fig. 1a). This area is developed near the seaside and around the town of Bouillante, where numerous hydrothermal events such as hot springs, mud pools, steaming ground and fumaroles occur (Fig. 1b). At the issue of the geothermal exploration works carried out by BRGM and then by EURAFREP, this last company drilled 4 exploratory geothermal wells in the 70's. They indicated high temperature conditions (240-250°C), but only BO-2 presented an economical steam production (33 t/h at 5.3 bar-g separation pressure; around 120 t/h of brine) from a permeable zone at a depth of 320 m. BO-4 was drilled about 400 m SSE from BO-2, at a final depth of 2,500 m. The low steam output of BO-4, 10 t/h at the separation pressure of 4 bars-g, was not considered economical to justify its connection to the 4.7 MWe Bouillante Geothermal Power Plant, which came on line in 1987.

In 1997, the owner of the power plant, GEOTHERMIE BOUILLANTE considered the opportunity to stimulate BO-4 in order to increase its production and to connect it to the plant. In this aim, an experimental stimulation program by thermal cracking through cold sea water injection was carried out between on 10th and 27th August 1998. Reference and Evaluation Production Tests (RPT and EPT respectively) were performed in BO-4 before and after the stimulation to evaluate the benefits of this operation. A multiple tracer test (MTT), geochemical monitoring and micro seismic were the other components of the program carried out by CFG, ORKUSTOFNUN and BRGM partnership (Correia *et al.*, 1999). The main objective of this paper is to present and to discuss the analytical results obtained during the MTT and the geochemical monitoring associated to the RPT and EPT.

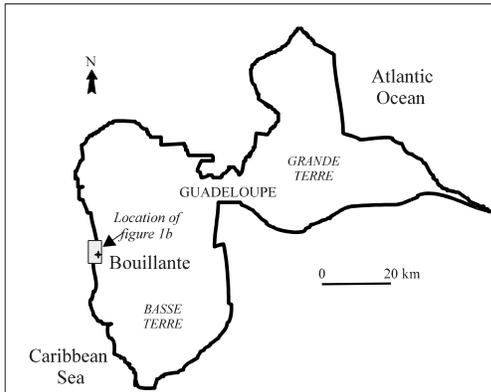


Figure 1a. Location of Bouillante in the Guadeloupe Archipelago (FWI).

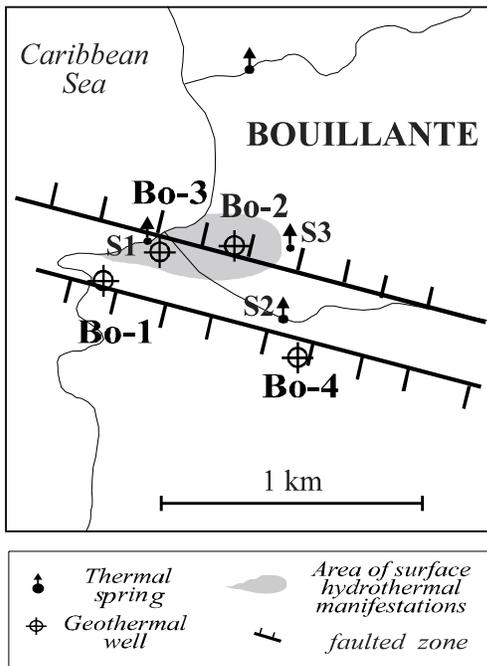


Figure 1b. Location of the geothermal wells and thermal springs used for the geochemical monitoring.

STIMULATION TEST

A problem frequently encountered in the exploration of high enthalpy geothermal reservoirs is the poor hydraulic connection between production wells and the geothermal reservoir. Stimulation methods to improve the hydraulic connection by thermal cracking through cold water injection can significantly reduce the exploitation costs.

Well BO-4 characteristics and background

BO-4 was drilled in two phases: at first, in 1974, to a depth of 1,200 m and then deepened to 2,500 m in 1977. As shown in Fig. 2, the main rocks penetrated by BO-4 below the production casing are tuffs and massive lavas. The most significant circulation losses occurred at a depth of 1,050 m; others were reported at 560-610 m, 650 m, 740-760 m and 850-880 m. A maximum temperature of 248°C was recorded between 500 and 1,100 m (Fig. 2; Herbrich, 1996). Below 1,100 m, the temperature profile shows a reverse thermal gradient: temperature decreases to around 230°C at a depth of 1,800 m.

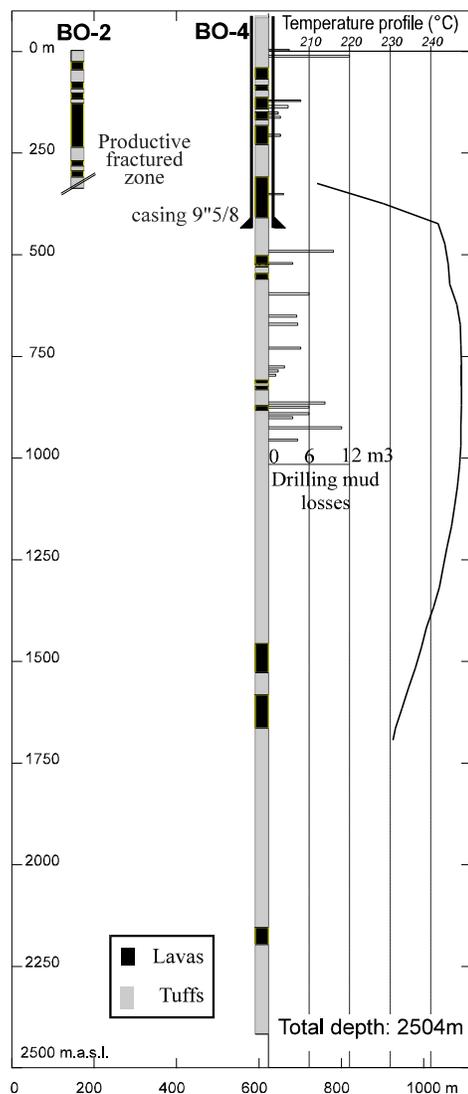


Figure 2. A N150° cross section intersecting wells BO-2 and BO-4 showing the synthetic geological logs and the temperature profile measured from well BO-4 in 1996.

Short-term discharge tests performed after the two drilling phases were characterised by intermittent eruptions of a mixture of water, steam and rock fragments. After some time, the flow stabilised at a well-head pressure (WHP) of 3.6 bar-g. A long-term production test was carried out by EURAFREP between July 1978 and June 1979, using a separator. The following stabilised parameters were obtained: a WHP of 4.2 bar-g, a separation pressure of 4 bar-g, 10.5 t/h of steam and 50 t/h of brine.

In order to check the hydraulic connection between BO-4 and BO-2, two multiple tracer tests were performed in 1996 (Herbrich, 1996; Sanjuan and Brach, 1997) and in 1998 (Sanjuan *et al.*, 1999a). Several tracers (Na-naphthionate, potassium nitrate, isophthalic acid, in the first test, and Na-benzoate, fluorescein, in the second test) were injected into BO-4 while BO-2 and 3 neighbouring thermal springs (Bord de mer: S1, Ravine blanche: S2 and Tuyau: S3) were monitored (Fig. 1b). No tracer was recovered neither in BO-2 nor in the thermal springs, suggesting the absence of a direct hydraulic connection between BO-4 and BO-2 and the thermal springs. This is consistent with a fracture system striking N100-120° which may act as permeability barriers (Traineau *et al.*, 1997).

Stimulation experiment and production tests

Water supply

As local fresh water supply could not assure sufficient flow rate for the stimulation, it was decided to use sea water which was pumped from the Power Plant pumping station, located in the BO-3 drill pad (Fig. 1b). Maximum flow rate was 25 l/s with an initial well-head injection pressure of 25 bar-g. Taking into account the risk of anhydrite scaling due to the mixing of cold sea water/geothermal fluid and predicted by geochemical modelling (Sanjuan, 1998), it was decided to inject an anhydrite scale inhibitor (IDOS 130) at a continuous concentration of 30 ppm in the sea water.

Main results of the stimulation experiment

The stimulation experiment finished with a short water loss test, followed by 4 days of pressure and temperature logging for thermal recovery follow up. The detailed presentation and interpretation of the results obtained during the stimulation experiment are reported in Correia *et al.* (1999) and Tulinus *et al.* (2000).

Initially, the injectivity was about 0.9 l/s per kg/cm² increasing to about 1.4 l/s per kg/cm² at the end of the stimulation test. Despite the high inaccuracy of the calculations, a low transmissivity was estimated for BO-4. At the stimulation end, the short water loss test gives an inferred feed around 720 m depth. The last

temperature logging shows that the well is still recovering after stimulation.

A Reference Production Test (RPT) was performed to evaluate the BO-4 initial characteristics of production before stimulation. Before discharging the well, a static temperature logging was performed down to 540 m where an obstruction was found. This obstacle was reduced or removed at the end of the stimulation. 38 days later, BO-4 was discharged again for the Evaluation Production Test (EPT) in order to assess the benefits of the stimulation.

The relevant common features observed during the RPT and EPT were:

- the flow rates measured (around 60 t/h of total discharge) are identical to those determined by EURAFREP during the long-term production tests (1974-1979) but the main difference is that WHP is about 20 bar-g while it was 4.5 bar-g;
- some pressure and temperature disturbance is recorded at a depth of about 350 m. For the moment, there is no factual explanation to this disturbance.
- physical data of both tests are identical for similar production conditions.

The different features noticed during the RPT and EPT were:

- the flow is oscillating between a “dry” and “wet” regime during the RPT whereas it is stable during the EPT; instabilities can either be a result of the flow restrictions imposed by the obstruction or indicative of a well with two feed zones of different thermodynamic conditions;
- the flashing level in the well-bore is estimated to occur close to a depth of 386 m and 323 m during the RPT and the EPT, respectively.
- significant amounts of clay and sand size solid material are accumulated in the weir-box during the RPT. X-ray diffraction has shown that it was anhydrite. The quantity of solid material from weir-box decreases significantly during the EPT. This decrease is doubtless caused by the effectiveness of the scale inhibitor injected with the sea water.

Due to problems encountered with production equipment, it was not possible to obtain well characteristic curves during the RPT and EPT. The calculated curves indicate that the maximum flow rate is about 80 t/h for the RPT and about 140 t/h for the EPT. The simulated EPT characteristic curve is confirmed up to 80 t/h by measured flow data. This improvement of the productivity is regarded as a positive stimulation result. However, it is stressed that further long term production test is required to confirm the present maximum BO-4 output and its sustainability with time.

MULTIPLE TRACER TEST (MTT)

The MTT associated to the stimulation operation started on 15th August, after the injection of a volume of sea water around 1,720 m³ in BO-4. Tracer injection was performed from BO-3 platform using the reservoir tank of the pump. After the tracer injection, about 6,300 m³ of sea water and 14 m³ of fresh water (to avoid the corrosion problems) were injected before closing the well. The geochemical monitoring was performed from BO-2 and the 3 neighbouring thermal springs S1, S2 and S3 during a 45 day period (August 15-September 30).

Selected tracers and injection conditions

Considering preliminary estimations (Sanjuan *et al.*, 1999b) and in order to increase the probability to detect these tracers, 300 kg of Na-benzoate, 200 kg of Na-naphtionate and 100 kg of isophtalic acid (+ 50 kg of NaOH) were dissolved in 10 m³ of sea water and injected into BO-4 at a flow rate of 10 l/s.

Na-naphtionate was essentially used for its immediate on site detection by spectrofluorimetry. However, the analytical interpretation can be difficult and is only qualitative. Isophtalic acid and Na-benzoate were accurately analysed by HPLC chromatography (UV detector) in the BRGM laboratories (Orléans, France) in order to quantify the different processes commonly observed in the case of a positive tracer test. Preliminary tests and analytical procedures about all these methods are reported in a technical report (Sanjuan *et al.*, 1999a). A special attention must be drawn to tracer degradability, pH range used for their analyses and contamination risks. The detection limits for Na-naphtionate, isophtalic acid and Na-benzoate analyses were 1, 50 and 10 ppb, respectively. The precision of these methods is better than $\pm 20\%$. Comparative analyses of benzoate were performed using an other HPLC chromatographic system and gave similar results.

Geochemical monitoring

Surface sampling and analyses

The detailed organisation of the geochemical monitoring is presented in a technical report (Sanjuan *et al.*, 1999b). Before the first tracer test carried out in March 1998, fluids were sampled from well BO-2 and from the 3 thermal springs in order to perform chemical and isotopic analyses of the initial fluids and to keep samples without tracers (blank samples). From BO-2, brine samples were collected at about 35°C after the high pressure separator, using a cooling system. High pressure steam condensates and non condensable gases were sometimes sampled.

Except for temperature measurements, all the on site analyses (pH, specific conductivity, Eh, alkalinity and dissolved Ca, Cl, SiO₂, NH₄, HS, Na-naphtionate

concentrations) were carried out in the laboratory of the Geothermal Power Plant. Classical analytical techniques (pH/Eh-meter, conductivity unit, titration, spectrofluorimetry, Merck colorimetry kits) were used. Except for Na-naphtionate analysis, the precision of all these methods is better than $\pm 5\%$. Dissolved silica was analysed on brine diluted 10 times with mQ water immediately after sampling in order to prevent the fast precipitation of amorphous silica due to the fluid cooling and steam separation. In order to compare the analytical data directly and to follow their evolution, specific conductivity, pH and Eh were measured at temperatures close to 25°C.

Selected fluid samples were conditioned according to the required specifications for chemical analyses (major and trace species, artificial tracers) and isotopic measurements (deuterium and 18-oxygen) in the BRGM laboratories. These were performed using standard water analytical techniques such as Titration, Potentiometry, Colorimetry, Ion electrode, Atomic Absorption Spectrophotometry, Ion Chromatography, Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), Mass Spectrometry. The precision of major and trace species is better than $\pm 5\%$ and 15% respectively. The precision of deuterium and 18-oxygen isotopes is $\pm 0.8\%$ and $\pm 0.1\%$. Ion balance values lower than 5% suggest a good quality and coherence of the aqueous major species analyses.

Results

a) Well BO-2

No substantial modification of the brine chemical and isotopic composition was observed during the stimulation operation. The monitoring of the dissolved Cl, Ca and SiO₂ concentrations (Fig. 3) or non conservative parameters such as conductivity, alkalinity and pH shows that the observed slight variations can be attributed to:

- the analytical precision ($< 5\%$),
- the small changes ($< 2\%$) in proportions of each phase (brine and steam) after fluid separation.

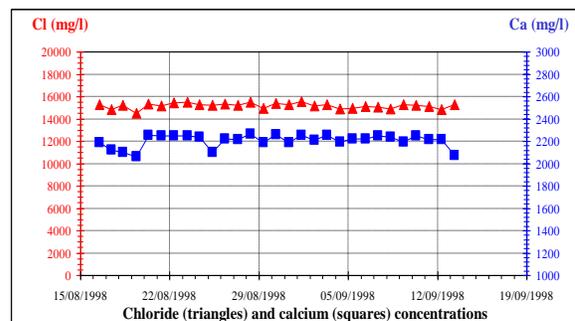


Figure 3. Evolution of Cl and Ca concentrations versus time in the BO-2 brines during the geochemical monitoring of the MTT.

These results are confirmed by the monitoring of the 3 artificial tracers. Among these last, no signal was detected. All the analytical data were below the detection limits as during the monitoring of the tracer test performed in March 1998 (Sanjuan *et al.*, 1999a). After the injection of a volume of sea water of about 8,000 m³ into BO-4 and a period of 45 days of monitoring, it can be concluded there is no direct hydraulic connection between BO-4 and BO-2.

b) Neighbouring thermal springs

The geochemical monitoring carried out from the 3 neighbouring thermal springs indicate no direct hydraulic connection with BO-4 fissures network. Na-benzoate and isophthalic acid were not detected. For Na-naphtionate, values above the limit detection (5-7 ppb for S1, 2-3 ppb for S2 and 7-9 ppb for S3) were measured even before the injection of this tracer. These values are difficult to interpret. Two assumptions can be proposed:

- an other species than Na-naphtionate is detected by spectrofluorimetry (interference problems); other analyses would have to be performed to confirm the presence of Na-naphtionate (characteristic spectra of emission and absorption) or to detect it by other methods (HPLC Chromatography with a pre-concentration technique, for example). Note that this substance was never found in the analysis of several sea water samples.
- analysed Na-naphtionate could come from the injection carried out in 1996 (Sanjuan an Brach, 1997). In this case, a very low hydraulic connection would exist between BO-4 and the thermal springs. The degradation of naphtionate would be relatively slow and it can be questioned if the tracers were injected in a deep level (high temperature) or in a more superficial aquifer (lower temperature).

According to the dissolved Cl, Mg, SO₄, Br, B and Li concentrations and δD and $\delta^{18}O$ values (Figs. 4 and 5), direct escapes of deep geothermal brine, mixed with very small variable proportions of sea water after vaporisation and cooling, outcome from the thermal spring S1, located near sea. Similar escapes without vaporisation were characterised in submarine thermal springs. During the rainy season (August-October), an additional contribution of superficial fresh water was observed in this spring. The geochemical monitoring of the thermal spring S3, situated near the Geothermal Power Plant, essentially constituted of fresh water (> 90%) with low amounts of deep geothermal brine, suggests an additional and increasing contribution of steam condensate (increasing temperature and isotopic steam signature, decreasing salinity). This contribution could have reached a stationary state (Fig. 6). According to Cl concentration and δD and $\delta^{18}O$ values, it would represent about 45% of steam condensate (Fig. 5).

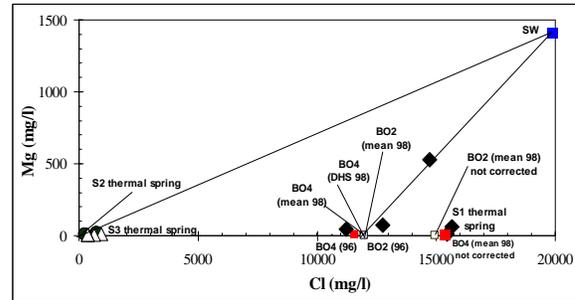


Figure 4. Mg versus Cl concentrations analysed in the fluids collected from BO-2, BO-4 and thermal springs.

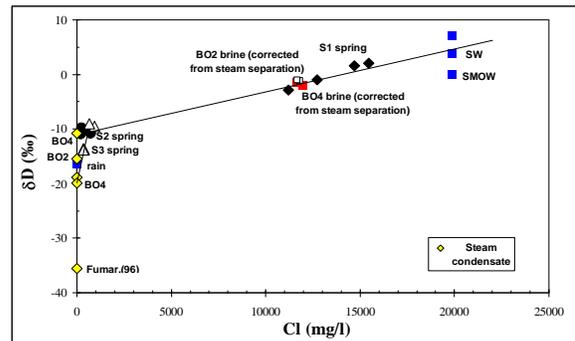


Figure 5. δD versus Cl concentrations analysed in the fluids collected from BO-2, BO-4, thermal springs, sea water and rainfall.

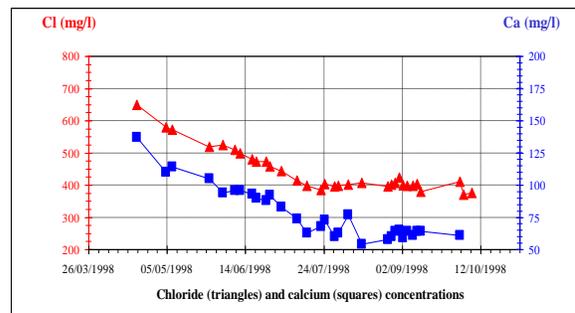


Figure 6. Evolution of Cl and Ca concentrations versus time in the S3 fluids during the geochemical monitoring of the MTT.

GEOCHEMICAL MONITORING OF THE TWO PRODUCTION TESTS (RPT AND EPT)

The geochemical aim of the RPT performed in July 1998 (15-17) was to collect reliable and accurate physical and chemical data on separated brine, steam and non condensable gas from BO-4 before stimulation. The main objective of the EPT, carried out from October 3 to 10, was to check any change in the fluid characteristics due to the stimulation. A down hole fluid sample was collected from BO-4, after the RPT. Another aim of this study, through a critical evaluation of the obtained chemical data, is a

best understanding of the composition of the deep fluid from BO-4. The reconstructed composition of the geothermal fluid can be compared to the measured local conditions of reservoir.

Surface sampling and analyses

Samples of separated brines, condensate and non condensable gases were collected using a suitable cyclonic pressure mini-separator (geochemical line). After flow rate stabilisation during both RPT and EPT, Gas/Steam Ratios (GSR) were determined from the on-line separator. Brines also were collected at weir-box. The weir-box sampling allows to study the chemistry and scaling potential of the separated hot water at atmospheric pressure. The same on site measurements and cautions for sample preparation as previously described were taken for all the collected fluids (brines + steam condensate).

During the RPT and because of the short duration of monitoring, only one sampling of fluids from weir-box and separator was performed for complete chemical and isotopic analyses in the BRGM laboratories. These samples were conditioned as those collected from BO-2. For non condensable gas analysis, airtight glass flasks were used. In the EPT, several samples were collected at weir-box and separator for complete chemical and isotopic analyses. Some non condensable gas samples were also collected. Na-naphtionate was monitored and analysed on site by spectrofluorimetry in all the types of fluids (brines and condensate). Some analyses of Na-benzoate were performed at Orléans.

Down hole sampling

Down hole sampling using a KUSTER sampler was carried out after the RPT on 1st August. Because of unexpected problems with the sampler, only one sample (< 1 litre) could be collected (below the casing shoe at a depth around 500 m). Most of on site measurements and sample preparations were immediately performed after sampling.

Geochemical results

RPT and EPT

Both production tests were limited to a single flow rate. At the EPT end, 6,500 m³ of total fluid were discharged from BO-4. This volume is lower than the total water volume injected into BO-4 (8,000 m³).

At the RPT beginning, after a production of 80 m³ of fluid, the conductivity measurements and Cl analyses indicate low values (Fig. 7). Taking into account that only sea water had been injected in the well before the RPT, these low values are unexpected and will be commented in the next chapter. After, these values are stabilised and are close to those determined for the geothermal brine, after steam separation.

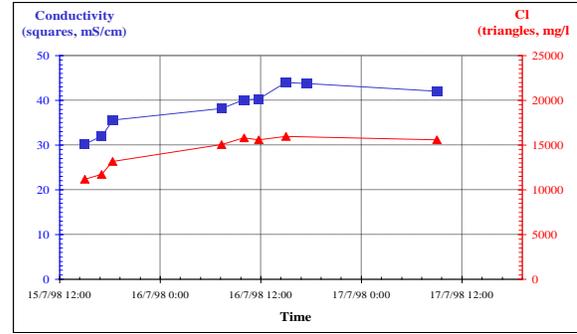


Figure 7. Evolution of conductivity and Cl content in the brines collected at weir-box during the RPT.

During the discharge of the first 40 m³ in the EPT, the general evolution of conductivity and Cl concentration curves (Fig. 8) is in good agreement with a mixing between injected fresh water (14 m³), injected sea water and geothermal fluid. After 40 m³ of discharge, the injected fresh water is completely extracted from the well. The increase of conductivity and Cl content is related to a larger contribution of fluids coming from the production zones.

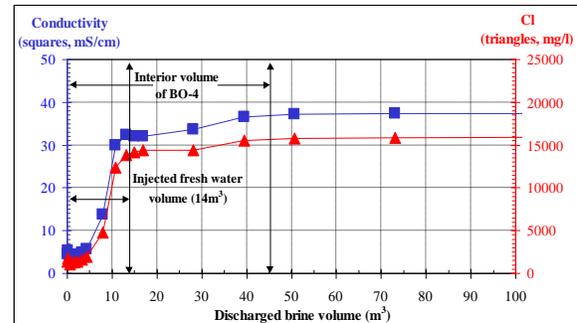


Figure 8. Evolution of conductivity and Cl concentration in the brines collected at weir-box versus discharged brine volume during the EPT.

According to the results obtained from the natural (Cl, Mg, SO₄, δD and δ¹⁸O particularly) and organic tracers, it can be observed that the injected sea water is never found at high proportions in the discharged fluid. Despite the injection of large volumes of sea water (Cl content around 20,000 mg/l) during the stimulation, the highest measured Cl concentrations are always close to those obtained for the geothermal fluid, after steam separation (Fig. 8). It can be concluded that sea water is rapidly mixed with the reservoir geothermal fluid. This can be explained by a relatively large interconnected reservoir volume and a high water-rock ratio, which is in agreement with the absence of ¹⁸O enrichment in the geothermal fluid by water-rock interactions and with the marine ³⁴S signature (19.4‰) of this fluid. From the Mg and SO₄ concentrations, the percentage of remaining sea water can be estimated to 0.2% in the discharged brine at the end of the EPT.

The improvement of production by thermal stimulation had no significant consequences on the proportions of each phase and the chemical parameters of the total discharged fluid. It can be deduced that either the improvement of production was homogeneous along the production zones (645-690 m, 730-770 m and 855-1,075 m), either the stimulated production level delivered a fluid with characteristics close to those of the total discharge of BO-4 (mixing of different feeding zones).

Critical evaluation of data obtained before and after the stimulation test

The geochemical monitoring of the RPT and EPT has allowed to better characterise the deep geothermal fluid from BO-4. The total proportions in weight of each phase of discharged fluid (brine, steam and non condensable gases) and the chemical and isotopic fluid compositions are similar to those of BO-2.

a) Chemical gas composition

From all the measurements carried out in 1998, the Gas/Steam Ratio (GSR) can be estimated to 0.45-0.5% in mass. This value is close to that determined in BO-2 (0.4% in mass; Demians d'Archimbaud and Munier-Jolain, 1975; Sanjuan *et al.*, 1999b). The chemical gas composition considered as the most representative (less contaminated by atmospheric gases) is reported in Table 1a. Gas geothermometers (Nicholson, 1993), applied on the selected BO-4 and BO-2 samples, give temperature values ranging from 157 to 251°C (Sanjuan *et al.*, 1999b). Most of these values are lower than those measured in the reservoir (240-250°C).

b) Estimation of the chemical and isotopic composition of the deep geothermal fluid

Chemical and δD , $\delta^{18}O$ analyses from BO-4 fluids were corrected using the steam-liquid proportions at separation temperature and pressure (Sanjuan *et al.*, 1999b). All the isotopic and chemical results suggest a probable common origin of the deep geothermal fluid produced from BO-2 and BO-4. This fluid is a Na-Cl brine with a TDS around 20 g/l. Recommended chemical and isotopic composition is reported in Table 1b. Aqueous Fe and HS contents are not presented because they are still badly known.

Conservative parameters such as aqueous Cl and Br concentrations or δD and $\delta^{18}O$ values indicate that this fluid represents a mixture of about 58% of sea water and 42% of fresh water (Fig. 5). Fresh water is more likely constituted of superficial waters fed by rainfalls in the western side of the Bouillante Pitons (Traineau *et al.*, 1997). These mixture processes are in good agreement with the N100-120° trending fractures on both ground surface and sea bottom (Fig. 1b). The results obtained for BO-4 are different from those determined in 1996 (Sanjuan and Brach, 1997) and at the RTP beginning (Fig. 7), which indicate a higher dilution by fresh water. A contribution of

additional water probably coming from a shallow aquifer is suspected (eventuality of a hole in the casing). This agrees with some disturbance in pressure and temperature observed at 350 m depth.

| | | | |
|---------------------|------|-----------------------------------|---------|
| CO ₂ (%) | 95.1 | He (%) | < 0.005 |
| O ₂ (%) | 0.09 | H ₂ S (%) | 2.78 |
| N ₂ (%) | 3.60 | CH ₄ (%) | 0.40 |
| Ar (%) | 0.04 | C ₂ H ₆ (%) | 0.05 |
| H ₂ (%) | 0.48 | C ₃ H ₈ (%) | 0.0005 |

Table 1a. Recommended chemical gas composition (mole %) for well BO-4.

| | | | |
|-------------------------|----------|--------------------|----------|
| pH | 5.3±0.3 | Br (mg/l) | 42.0±5.0 |
| TDS (g/l) | 20.0±1.0 | F (mg/l) | 0.9±0.1 |
| Cl (g/l) | 12.0±0.6 | B (mg/l) | 12.5±1.3 |
| Na (g/l) | 5.1±0.3 | Li (mg/l) | 6.0±1.0 |
| Ca (g/l) | 1.8±0.1 | Sr (mg/l) | 20.0±3.0 |
| K (mg/l) | 750±40 | Ba (mg/l) | 6.5±1.0 |
| HCO ₃ (mg/l) | 110±10 | Rb (mg/l) | 2.0±0.3 |
| Mg (mg/l) | 12.0±2.0 | Cs (µg/l) | 260±30 |
| SO ₄ (mg/l) | 13.0±1.0 | Cu (mg/l) | 15.0±1.0 |
| SiO ₂ (mg/l) | 500±30 | Ni (mg/l) | 2.0±0.5 |
| NH ₄ (mg/l) | 1.7±0.2 | Zn (µg/l) | 650±100 |
| Al (µg/l) | 100±10 | As (µg/l) | 450±50 |
| δD (‰) | -1.2±0.8 | $\delta^{18}O$ (‰) | -1.1±0.2 |

Table 1b. Recommended chemical and isotopic composition of the deep geothermal fluid.

The ⁸⁷Sr/⁸⁶Sr ratios of the fluids sampled from BO-2 and BO-4 (around 0.705), similar to those found for volcanic rocks such as basalt or andesite, characterise an interaction process with these rocks close to an equilibrium state. Relative to sea water diluted by 42% of fresh water, the deep geothermal fluid is depleted in Mg, SO₄, Na and is enriched in K, Ca, Si, B, Li, Sr, Ba, Mn, Cs, Rb, As and trace metal ions. These trends are generally observed for basalt-sea water interaction studies. A systematic decrease of Ca, Mg, HCO₃, Al, Si, Fe, Sr, Li and trace metal concentrations of the fluids collected at surface is observed relative to the down hole samples (Sanjuan *et al.*, 1999b): a slight precipitation of carbonate, aluminosilicate and poly-metallic sulphide minerals is suspected during the deep fluid rise from the wells.

As indicated by saturation calculations using the EQ3NR geochemical code (Wolery, 1995) and by classical geothermometers (Nicholson, 1993), the deep geothermal fluid reacts sufficient time with volcanic rocks at around 250°C to reach chemical equilibrium with a mineralogical assemblage constituted of albite, K-feldspar, quartz, calcite, disordered dolomite, anhydrite, illite, smectites and zeolites. The use of IDOS 130 during the stimulation operation has prevented anhydrite scale deposits predicted by modelling and observed during the RPT. These deposits doubtless occurred during the interference test performed in March 1998 whereas only 100 m³ of sea water had been injected.

CONCLUSION

The objective of the stimulation experiment was to increase the BO-4 production by injecting 8,000 m³ of cold water to cause thermally induced fracturing. Sea water treated with a scale inhibitor was considered as the most suitable fluid for injection. The Reference and Evaluation Production Tests (RPT and EPT), carried out before and after stimulation and limited to one flow rate at the maximum discharge pressure, have shown a much higher BO-4 productivity than the previous tests. An improvement in injectivity by 50% and in production stability has been observed after stimulation. It is likely that the pre-existing permeable levels preferentially have accepted injected cold sea water through old fractures enlarged by thermal cracking. Benefits of the cold water injection are estimated from the comparison between the calculated well characteristic curves of the RPT and EPT: the calculated maximum flow rate of BO-4 has increased from 80 t/h (RPT) to 140 t/h (EPT). A further long term production test is, however, required to confirm the present maximum output of the well and its sustainability with time.

The results from the Multiple Tracer Test (MTT) performed during the stimulation experiment indicate and confirm no direct hydraulic connections between BO-4 and BO-2 and the 3 selected neighbouring thermal springs. According to the geochemical monitoring associated to the RPT and EPT, there was no significant change in the composition of the fluids produced before and after stimulation. Moreover, the low amount of sea water always observed in the discharged brines is indicative of a relatively large interconnected reservoir volume and of a high water-rock ratio. This is in agreement with the isotopic ¹⁸O and ³⁴S signature of the geothermal fluid but is rather inconsistent with the estimated low transmissivity. Most of physical and chemical production characteristics of BO-4 seem to be similar to those of BO-2. The discharge of solid material was low during the EPT compared to the RPT. This confirms the effectiveness of the scale inhibitor to prevent anhydrite formation.

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