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THE BOUILLANTE GEOTHERMAL FIELD (F.W.I.) REVISITED : NEW DATA ON THE FRACTURED GEOTHERMAL RESERVOIR IN LIGHT OF A FUTURE STIMULATION EXPERIMENT IN A LOW PRODUCTIVE WELL.

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ABSTRACT

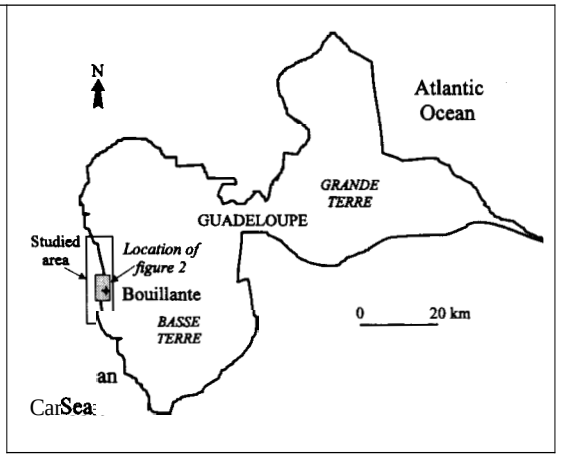
Four geothermal wells were drilled in the Bouillante geothermal fractured reservoir in the 70's. They revealed high temperature conditions at shallow depth (240°C at 350 m) but only Well BO-2 showed a significant productivity, certainly due to highly contrasted values of permeability throughout the reservoir. New data on the local fracture system, the origin of geothermal fluids and well interferences have been collected. They point out the influence of fracturing on the development of the geothermal reservoir and the observed permeability anisotropy. Recharge of surface cold water (sea water, meteoric water), fluid mixing and heating, and discharge of hot fluids appear to be controlled by extensional highly-dipping faulted zones striking N100-120°, organized into one or several, independant fractured reservoirs.
Geothermal fluids result from mixture of sea water and fresh water, as indicated by their chemical and isotopic compositions. According to new temperature profiles, the low productive Well BO-4 probably intersected fluid circulations along natural fractures and layer contacts, corresponding to lateral fluid outflows. Future experiments will be devoted to stimulate these permeable zones.

INTRODUCTION

The Bouillante geothermal field is located on the western coast of Basse-Terne Island, Guadeloupe, Lesser Antilles (Fig. 1). Its development started in 1970 when EURAFREP drilled four exploratory wells (ranging from 350 to 2500 m depth) in a narrow area characterized by abundant surface manifestations (hot springs, steaming grounds, fumaroles; Fig. 2). High temperature conditions (240°C at 350 m depth) but heterogeneity in permeability were evidenced (Cormy ***et al.,*** 1970; Demians d'Archimbaud and Surcin, 1976). Wells BO-1 and BO-3 were tight producers and abandoned. Well BO-2 (350 m depth) intersected a permeable fracture network producing 30 t/h of steam at bottom. Well BO-4 (2500 m depth) has limited productivity (15 t/h steam). The power plant now operating (4,7 MWe capacity) is connected to Well BO-2 only.
In case of a future development of the Bouillante field, there is a lack of data concerning the geometry of the fractured reservoir, the origin of fluids, location of recharge areas, and possible well interferences. Recent researches have been focused on these topics, They provide new information for a better understanding of the geothermal reservoir and the origin if its permeability anisotropy, which will be useful to design a future stimulation experiment in Well BO-4.

BACKGROUND

A re-assessment of the geothermal potential of Bouillante and adjacent areas has been carried out by BRGM in the years 1983-87, with additional geological mapping, fluid geochemistry, geophysical exploration (magneto-telluric method, natural microseismicity), radon and mercury survey in the soils (BRGM, 1984). A main result was the recognition of a recent, fissural volcanic episode called the "Bouillante Volcanic Chain" (1 to 0.2 My) which built several small monogenic volcanic centres (maars, seamounts) around Bouillante (Gadalia ***et al.***, 1988). They delivered small volumes of poorly to highly differentiated magmas. This volcanic activity is thought to be correlated to the existence of a major regional tectonic lineament oriented **NW-SE** (the Montserrat-Marie Galante Fault) recently described (Bouysse ***et al.,*** 1988; Polyak ***et al.,*** 1992).



g. 1. Location of Bouillante in the Guadeloupe Archipelago (F. W. I.).

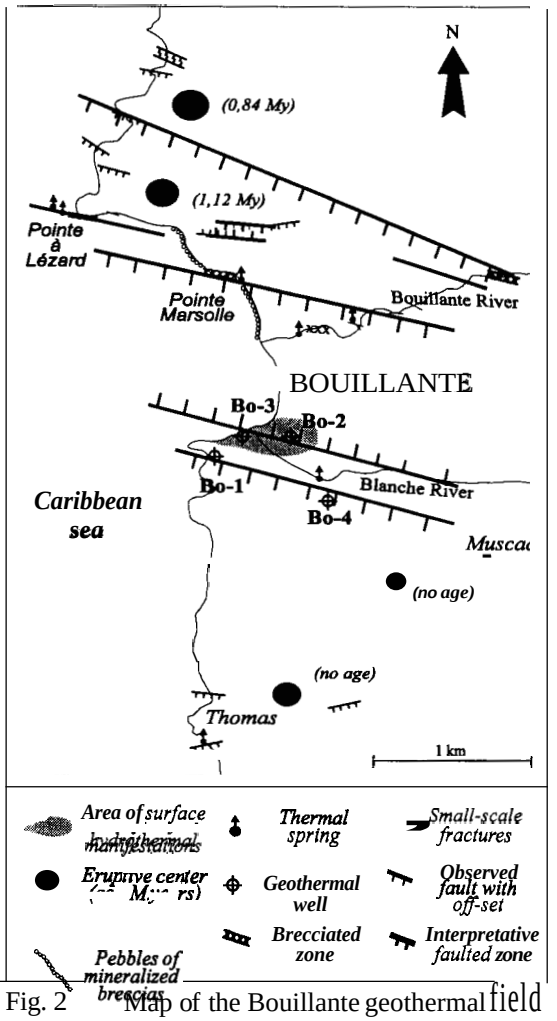
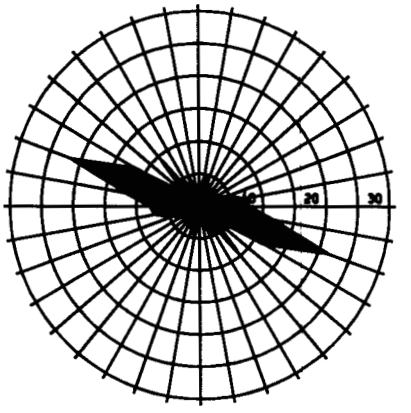
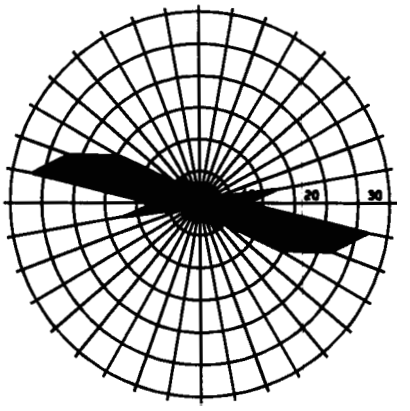


Fig. 2 Map of the Bouillante geothermal field showing significant features.





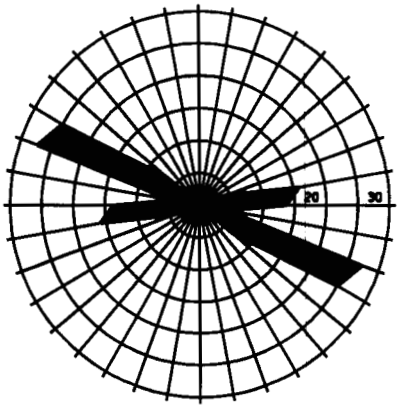


Fig. **3.** Rose diagrams of fracture strikes collected in the studied area.

The Bouillante geothermal field is located at its southern margin. Active microseismicity was recorded few kilometres Northwest of Bouillante (BRGM, 1984). It probably develops a secondary fracture permeability sustaining the development of the hydrothermal system.

The basement of the geothermal field is made of intercalations of sub-marine, volcanoclastic formations (tuffs, hyaloclastites) and aerial formations (lava flows, pyroclastites, reworked material) with low primary porosity.

STRUCTURAL GEOLOGY

The interpretation of aerial photographs and a structural analysis carried out on the ground (see location of the 12x2 km studied area on Fig. 1) enabled the recognition of three types of structures, i.e. joints, normal faults, and filled-fractures. The joints correspond to near-vertical, small-scale structures that are well distributed over the area. They group into one major and one minor sets striking N110° and N010°, respectively (Fig. 3). The normal faults are organized into one major set striking N100-120°. Their dip varies from 90 to 70" and their offset is around a few metres. They clearly indicate a NNE-SSW extensional tectonic regime.

The filled fractures are steeply dipping structures organized into one major and one minor sets striking N110-120° and N080-090°, respectively. They correspond to extensional Mode I fractures. Some of them, of 1 to 10 cm wide and filled with terrigeneous material, are scattered all over the area. The others, restricted near Bouillante, are filled with hydrothermal deposits of few mm to cm thick. The main hydrothermal neoformed phases are: silica, di-octahedral smectites (Beidellite-Nontronite), calcite, zeolites (Clinoptilolite, Heulandite, Stilbite, Mordenite), accessory kaolinite and gypsum. They are located to the southern part of Bouillante (where the wells are located) in association with abundant surface manifestations, and along the northern coastline of the Bouillante Bay (Pointe à Lézard, Pointe Marsolle; Fig. 2). In the later area, mineralized fractures are associated with brecciated lavas, which point out the possible existence of a main faulted zone trending WNW-ESE that controlled discharges of geothermal fluids. This flow path is active as demonstrated by the occurrence of sub-marine hot springs West of Pointe à Lizard, showing elevated temperature conditions (92°C) and high Helium and Radon fluxes.

Combined interpretation of our ground structural data and geological well log data from EURAFREP shows that the southern part of Bouillante is also affected by faulted zones that define a horst-like structure (Fig. 2). In conclusion, the structural features observed at Bouillante show a general direction around N100-120° with vertical to near vertical dipping, which may induce a strong anisotropy of permeability.

W MISTRY

The main aim of the study was to determine the origin of the thermal waters in the Bouillante region and to better understand the acquisition of their chemical composition in order to establish an hydrochemical model of the Bouillante geothermal field. 14 littoral and terrestrial thermal springs (Fig. 2), Wells BO-2 and BO-4, as well as local sea water and superficial waters (rivers and rain) were sampled. Water samples from submarine hydrothermal springs located near Pointe a Lézard were collected for the first time. The temperature values measured for two hydrothermal springs situated at 10 and 23 m under the sea level indicated 55 and 92°C, respectively. The emergence temperatures of the thermal springs range from 29 to 97°C. High temperature fluids (240-250°C) were sampled at the well head from Well BO-2 and directly at 650 m depth from Well BO-4.

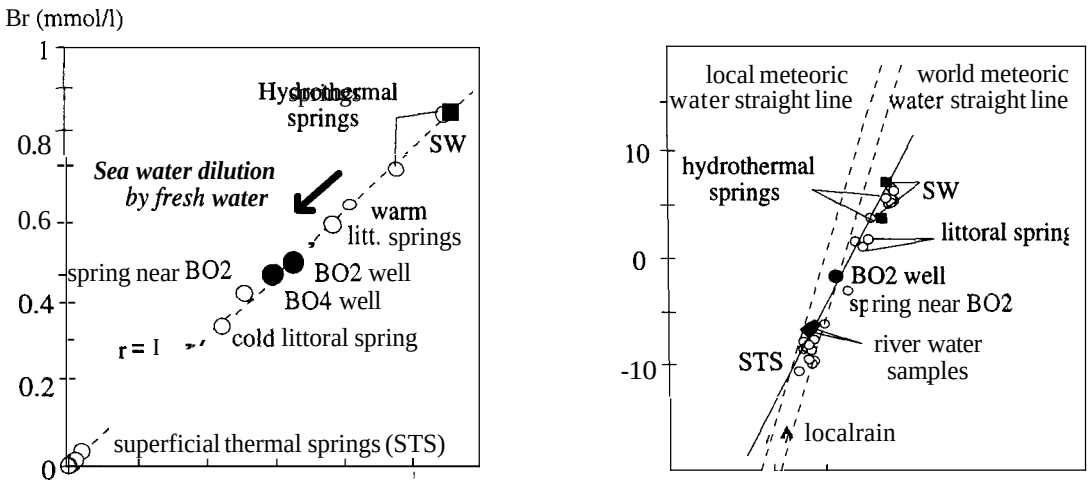
Classical methods such as atomic absorption, ion chromatography, ICP-MS, colorimetry and titration were used for the chemical analyses of samples (Na, K, Ca, Mg, Cl, SO_4, alkalinity, Si, Br, B, Sr, Ba, Mn, Li, Rb, Cs and As). Isotopic analyses (SD, $\delta^{18}O$ and $^{87}Sr/^{86}Sr$) were performed using mass spectrometry. Chemical and isotopic δD, $\delta^{18}O$ analyses from BO-2 fluid were corrected considering the steam-liquid proportions (24-76 % respectively) due to phase separation at the well head. Most results of the previous studies were confirmed and new data were obtained.

The deep fluids (Wells BO-2 and BO-4)

The geothermal fluid produced from Well BO-2 is a Na-Cl brine (Table 1) with a TDS value around 20 g/l and a calculated pH of 5.6-5.7. Conservative species such as Cl and Br (Fig. 4) indicate that this fluid represents a mixture of sea water (58 %) and fresh water (42 %). BO-4 fluid, less saline (TDS ~ 18 g/l), also results from a similar mixing but with a larger

sample	T°C	pH	Na	K	Ca	Mg	Cl	SO_4	Alk.	SiO_2	Br	B	Sr	Li	Rb (*)	Cs (*)
Bouillante river	26.9	7.83	1.07	0.15	0.40	0.27	0.62	0.03	1.76	0.84	n.d.	0.004	0.0008	n.d.	0.051	n.d.
Superf. thermal spring	39.0	7.40	1.78	0.10	0.50	0.15	0.82	0.07	2.13	1.36	0.0014	0.008	0.0009	0.001	0.161	0.0014
Sea water	28.7	8.20	460	11.40	11.10	59.00	560	29.00	2.20	0.003	0.84	0.46	0.09	0.02	1.43	0.0038
Diluted sea water			271	6.71	6.53	34.71	329	17.06	1.29	0.002	0.50	0.27	0.05	0.01	0.84	0.0022
BO2 well			213	19.38	45.22	0.04	329	0.14	0.25	7.60	0.49	1.01	0.17	0.43	26.2	1.96
BO4 well			191	14.00	45.00	0.04	300	0.30		4.72	0.46	1.02	0.18	0.38	15.4	1.72
Hydrothermal spring	92.0	6.05	351	15.00	25.30	41.72	481	17.30	2.66	2.18	0.71	0.70	0.07	0.12	5.69	0.43

Table 1. Chemical composition of some springs, BO-2 and BO-4 fluids, local sea water and river water. Concentrations are given in mmol/l or in µmol/l (*) (n.d.: not detected).



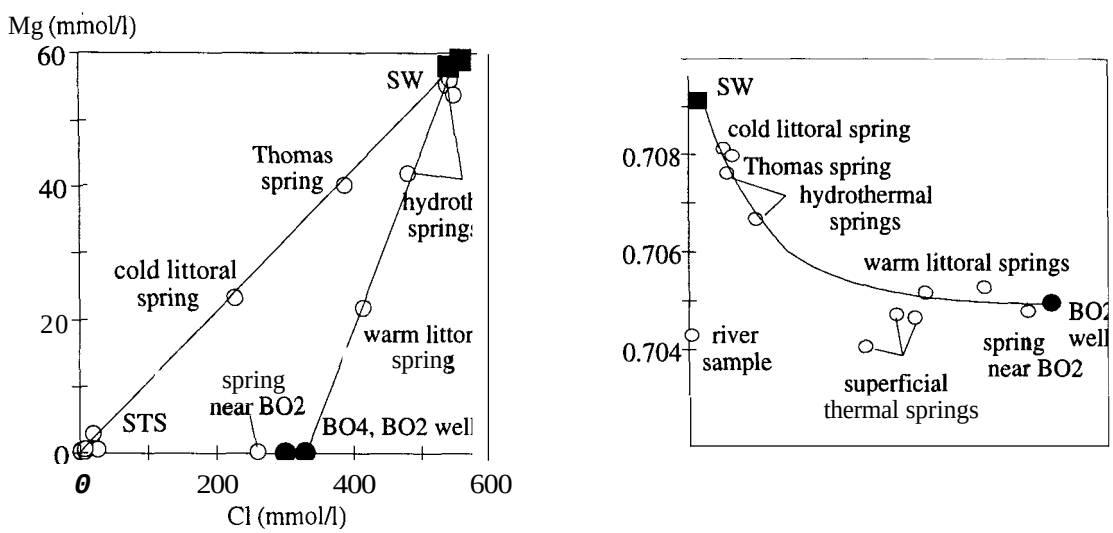


Fig. 6 - Plot of Mg concentration vs Cl concentration

proportion of fresh water (46 %). The assumption that the fresh water end-member is a steam condensate coming from a deeper reservoir may not be completely discarded in the $\delta D - \delta^{18}O$ diagram (Fig. 5). However, this end-member is more likely constituted of superficial waters fed by rain falls in the western side of the Bouillante Pitons. These mixture processes are in good agreement with the N100°-120" trending fractures on both ground surface and sea bottom. Even if more isotopic analyses must be done to validate the δD and $\delta^{18}O$ values obtained for BO-2 fluid, the δD-Cl and $\delta^{18}O$-Cl diagrams seem to confirm the proportions of sea water and fresh water calculated for this fluid using Cl and Br concentrations.

Relative to sea water diluted by 42 % of fresh water, the BO-2 fluid is depleted in Mg, **SO„** Na and is enriched in K, Ca, Si, B, Li, Cs, Rb, **Sr,** Ba, Mn, **As** (Table 1). These trends are generally observed for basalt-sea water interaction studies both in submarine hydrothermal springs (Michard ***et al.***, 1984), in thermal springs of Islande (Arnorsson ***et al.***, 1983), Djibouti (Sanjuan ***et al.***, 1990) and in the laboratory (Bischoff and Dickson, 1975). The $^{87}Sr/^{86}Sr$ ratio of the fluid sampled from Well BO-2 (0.70496), very different from that of sea water (0.709137) and similar to that of volcanic rocks such as basalt or andesite, characterizes an interaction process with these rocks close to the equilibrium state. Chemical equilibrium seems to be achieved for most major elements of this fluid because classical geothermometers such as silica (quartz), Na-K, Na-K-Ca (β = 1/3) and K-Mg (Nicholson, 1993) give temperature values ranging from 229 to 260°C which are close to that measured at the bottom in BO-2 well (242°C). Saturation calculations at this temperature performed using the EQ3NR geochemical code suggest that the geothermal fluid is in equilibrium with respect to albite, K-feldspar, quartz, zeolites (laumontite, heulandite, wairakite), smectites, anhydrite and calcite. Zeolites and smectites were observed at the emergence of all the hot springs where escapes of geothermal fluid occur. In Well BO-4, the same geothermal fluid as in Well BO-2 is probably slightly diluted (– 4%) by superficial waters.

Consequently, the geothermal fluid resulting from a mixture of sea water and fresh water reacts with volcanic rocks (probably andesite) at high temperature (242°C) for enough time to reach the equilibrium. Nevertheless, the water-rock ratio is assumed to be relatively significant because of the absence of ^{18}O enrichment (Fig. 5) due to an interaction process with silicates or calcite.

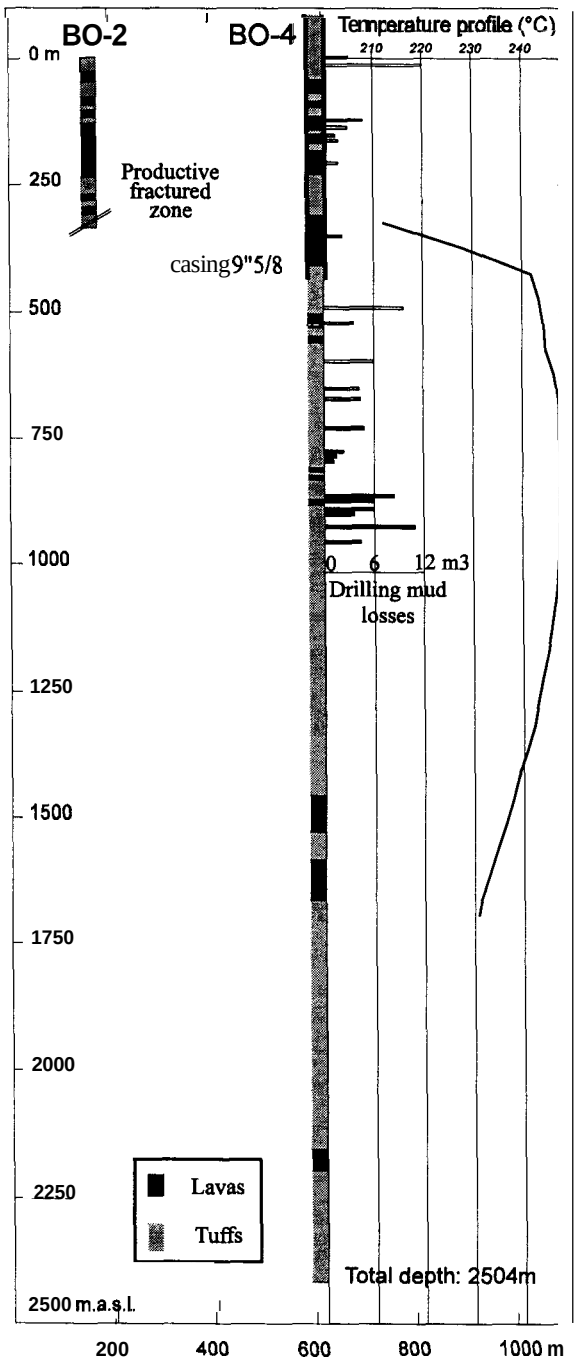
The thermal waters

Chemical and isotopic analyses lead to divide the thermal waters sampled in the Bouillante region in two groups :

- $Na\text{-}HCO_3$ waters with low salinity (< 1 g/l) and neutral pH values (7-8), which are superficial waters probably warmed by conductive heat transfert. Their chemical and isotopic compositions are similar to those of the river waters and show a meteoric origin. δD-$\delta^{18}O$ values (Fig. 5) are between the local and world meteoric water straight lines. Chemical geothermometers such as silica (chalcedony), Na-K-Ca (β = 4/3) and K-Mg (Nicholson, 1993) yield consistent temperatures ranging from 60 to 80°C but as often observed for superficial waters in granitic and volcanic zones, the Na-K geothermometer indicates unreasonable temperatures (200-300°C). Equilibrium with respect to feldspars is not achieved yet.

- Na-Cl waters with an higher salinity (from 1 to 35 g/l) and an aqueous Cl/Br molar ratio close to 660, indicative of a marine origin confirmed by the δD-$\delta^{18}O$ values (Figs. 4 and 5). This kind of waters is only found in the submarine or littoral springs. Their chemical compositions can be explained as mixtures of two or three water end-members which are sea water, superficial water of meteoric origin and the geothermal fluid sampled from Well BO-2. After mixing, few chemical reactions with surrounding rocks occur. Consequently, the existence of these mixtures is revealed in most X-CI diagrams (where X is the concentration of a major or trace element) and is well illustrated in the Mg-Cl diagram (Fig. 6). The Thomas spring is the only case where water results from a mixing of the three end-members. The presence of sea water prevent the use of the chemical geothermometers. The hyperbolic relation obtained for these waters in the $^{87}Sr/^{86}Sr$-Li/Cl diagram (Fig. 7) or the linear relations in most X/Cl-Li/Cl diagrams characterize an interaction process between sea water and volcanic rocks (Sanjuan ***et al.***, 1990). In this study, the interaction degree depends on the proportion of BO-2 fluid in the mixtures. Of course,

the BO-2 fluid shows the highest interaction degree and the superficial waters of meteoric origin of the previous group do not follow these relations (Fig. 7).



ig. 8. A N150° cross section intersecting Wells BO-2 and BO-4 showing the synthetic geological logs and the temperature profile measured in Well BO-4.

In conclusion, the thermal waters with low salinity are superficial waters sligtly warmed (up to 80°C), probably by conductive heat transfert. The mineralized waters which flow through the faulted zones in the Bouillante region are escapes from an huge geothermal reservoir where a mixture of sea water and fresh water is heated and reacts with volcanic rocks until it reaches an equilibrium state at 240-250°C. Before discharging from the submarine and littoral springs, the geothermal fluid mixes with cold sea water or fresh water or both the two end-members in subsurface. After mixing, few chemical reactions occur. This hydrochemical model is in good agreement with the fracture network striking N100-120". Nevertheless, location and boundaries of the deep geothermal reservoir are badly known.

TEMPERATURE AND HEAT SOURCE

Limited data on temperature conditions in the wells were obtained during and at the end of drilling (Demians d'Archimbaud and Surcin, 1976). They indicated a maximum temperature around 245°C in the four wells. A new temperature profile was carried out in Well BO-4 between 400-1800 m depth, using a KUSTER recorder with a 25 m sampling rate. Profile is shown on Figure **8.** A "cap-rock" horizon with an elevated thermal gradient value (30°C/100m) is evidenced between 400-500 m depth. It corresponds to a 100 m-thick lava horizon. Below, the temperature increases slightly from 242°C to 248°C, and then stays rather constant around 248°C until 1100 m depth. This 600 m-thick zone corresponds to intercalations of lava and tuff horizons showing frequent mud losses during drilling. The lower part of the temperature profile shows a reverse gradient as the temperature decreases to about 230°C at 1800 m depth. The Well BO-4 probably intersected fluid circulations along fractures and lithologic layer contacts between 600-1100 m depth. The reverse thermal gradient suggests that they correspond to some lateral outflows from a deep reservoir whose location and extent are not yet well-constrained, as quoted above.

Origin of the heat source is not clearly established. The existence of a shallow magmatic intrusion related to a young eruptive center of the "Bouillante Volcanic Chain" has been argued. However, no associated volcanic deposits have been recognized in the Bouillante area. Another hypothesis considers the role

of dykes and/or mantellic gases escaping along deep-eated faults as a possible heat source.

INTERFERENCE TESTS

In order to check the degree of connection between the productive Well BO-2 and Well BO-4 distant of 150 m only (Fig. 8), a tracer test has been carried out. Chemical tracers (isophtalic acid, potassium nitrate and sodium naphtionate) have been injected within Well BO-4 and pushed down by a 73 m3 sea water volume. A 15 day geochemical monitoring could not detected any tracer signal in the geothermal fluid produced by Well BO-2. In the same way, monitoring of BO-4 wellhead pressure (4,7 bars at equilibrium) could not detected any significant pressure variation (>1 bar) related to pressure drops in Well BO-2 during production (4-5 bars in amplitude).

These results suggest the absence of direct hydraulic connection between Wells BO-2 and BO-4. This is consistent with a fracture network striking N100-120" which may act as a permeability barrier between the two wells trending N150° (Fig.2).

CONCLUSION

The influence of fracturing on the development of the Bouillante geothermal reservoir appears to be preeminent. We assume that recharge of both sea water and surface meteoric water, fluid mixture and heating, take place somewhere along one or several faulted zones trending WNW-ESE which can be considered to represent one or several independant fractured reservoirs. Strong contrast in permeability of the four wells drilled in a narrow area can be related to the anisotropic distribution of parallel fractures striking N100-120° and steeply dipping. This is supported by the lack of interference between Wells BO-2 and BO-4. The probability of developing an accidental connection during a BO-4 stimulation experiment seems to be low. Moreover, permeability is also reduced by abundant silica and carbonate fracture sealings, as reported in the EURAFREP geological well logs.

In order to increase the productivity of permeable zones intersected by Well BO-4, cold water stimulation associated with acid stimulation may be regarded as a first step devoted to enlarge natural fractures and eliminate fillings. These methods could be applied in Well BO-4 equipped with a slotted liner to the bottom. The lack of significant productivity benefits would mean that fractures are pervasively distributed and thus, poorly connected to a main permeable fractured zones.

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