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Monitoring of the Bouillante Geothermal Exploitation (Guadeloupe, French West Indies) and the Impact on Its Immediate Environment

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ABSTRACT

The Bouillante high enthalpy geothermal field, 250-260°C, is located in the Guadeloupe volcanic Island (French West Indies). Since 2005, the new geothermal power plant has had an installed capacity of 15 MWe gross which represents about 8% of the annual electricity needs in the Island. It is supplied by 3 wells which can produce up to 120 tons/h of steam. No residual water is re-injected. Among the research efforts carried out by the BRGM group and partially funded by ADEME (French Environment and Energy Management Agency), different monitoring methods of the geothermal exploitation have been started, tested and developed in order to optimize and secure electricity production and to control its impact on the immediate environment of the power plant. This is especially important because the power plant is located inside the Bouillante town. These methods are: geochemical monitoring of the fluids collected from the geothermal wells and neighboring thermal springs in order to control the evolution of the fluid geochemistry and the Gas/Steam Ratio, surface soil thermometry monitoring, geophysical monitoring such as broadband seismology, microgravity and SAR interferometry to detect mass transfers or changes in the geothermal reservoir during its exploitation as well as vertical surface ground deformations. This paper presents the main results and conclusions obtained from these different monitoring techniques. On the whole, despite the pressure decrease observed in the geothermal reservoir due to an annual production estimated at about 4.5 millions of tons of fluid, no significant variation of the monitored parameters has been detected from these methods during four quasi-continuous years of geothermal exploitation. Most of these monitoring techniques will be continued and probably developed in the next few years, especially if the produced fluids are re-injected, in order to anticipate and/or quickly take into account problems such as issues related to chemical change of the reservoir fluid or induced microseismicity.

1. INTRODUCTION

The Bouillante high enthalpy geothermal field, 250-260°C, located in the Guadeloupe volcanic Island (French West Indies, Fig. 1), is the only French field of this type. It is currently being exploited by Géothermie Bouillante, a subsidiary of BRGM and EDF. Since 2005, three deep wells (Figs. 2 and 3) that can produce up to 600 tons/h of geothermal fluid including up to 120 tons/h of steam, supply the new geothermal power plant which has an installed capacity of 15 MWe gross, representing about 8% of the annual electricity needs of the island. No produced fluid is re-injected.

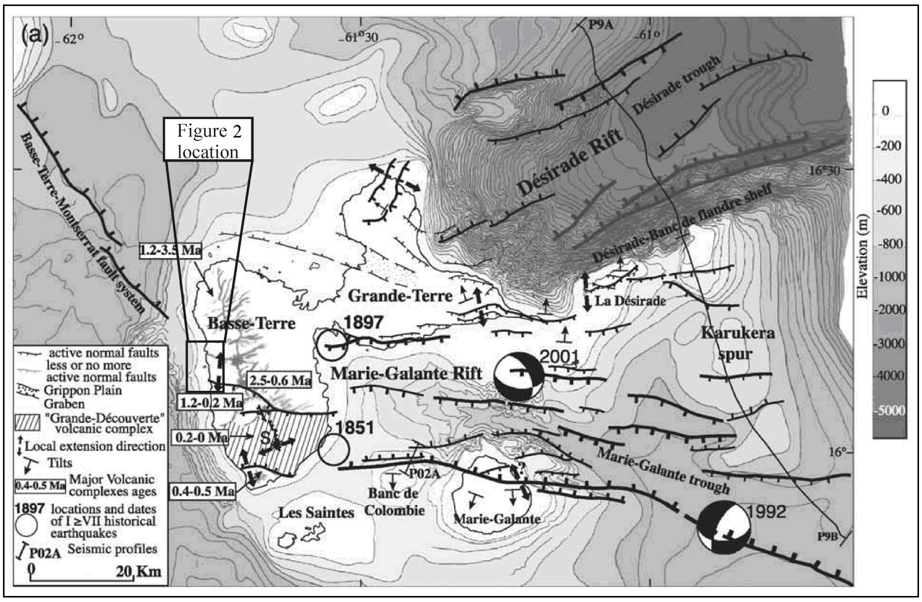

Figure 1: Bathymetric and tectonic map of the Guadeloupe Archipelago (FWI), after Feuillet *et al.* (2002) and Lachassagne *et al.* (2009). Location of the Bouillante area in this archipelago (Figure 2 location)

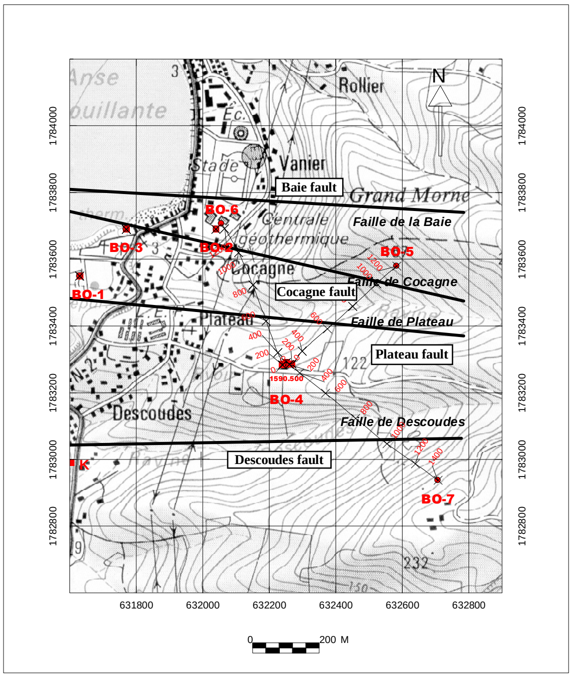

Figure 2: Location of the Bouillante geothermal wells. Projection at surface of the wells BO-5, BO-6 and BO-7 (from CFG Services)

In the framework of the research carried out by the BRGM group and partially funded by ADEME, it was decided to initiate, test and develop different geochemical and geophysical monitoring methods of the geothermal exploitation in an island context such as that of Guadeloupe. These methods facilitate optimization of the exploitation and the life span of the Bouillante field, securing electricity production, and controlling its impact on the immediate environment of the power plant. Over-exploitation must be avoided because it would reduce the geothermal resource and could be a source of nuisances and risks for population, given the location of the power plant in the Bouillante town.

This paper presents the main results and conclusions obtained from the development of these different monitoring techniques at Bouillante over four quasi-continuous years of geothermal exploitation. These results and conclusions have been and will be used in the conceptual geological models which have been established (Lachassagne *et al.*, 2009; Bouchot *et al.*, 2009) and must be developed. They will be also used for hydrodynamic and geochemical modeling.

2. FLUID GEOCHEMICAL MONITORING

Since the beginning of operation of the new power plant at the beginning of 2005, which has increased the production of geothermal fluid by a factor of about 4 relative to previous exploitation conditions (maximum of 600 tons/h of fluid against 150 tons/h, before), the geochemical monitoring of the fluids discharged from the wells BO-4, BO-5 and BO-6 (Fig. 3) and from the neighboring thermal springs of the power plant has been intensified.

2.1 Fluids Discharged from the Production Wells

Geochemical monitoring of the fluids discharged from the production wells has been carried out since 1998 and has been intensified since 2005 in order to control the evolution of the fluid geochemistry and the Gas/Steam Ratio (GSR).

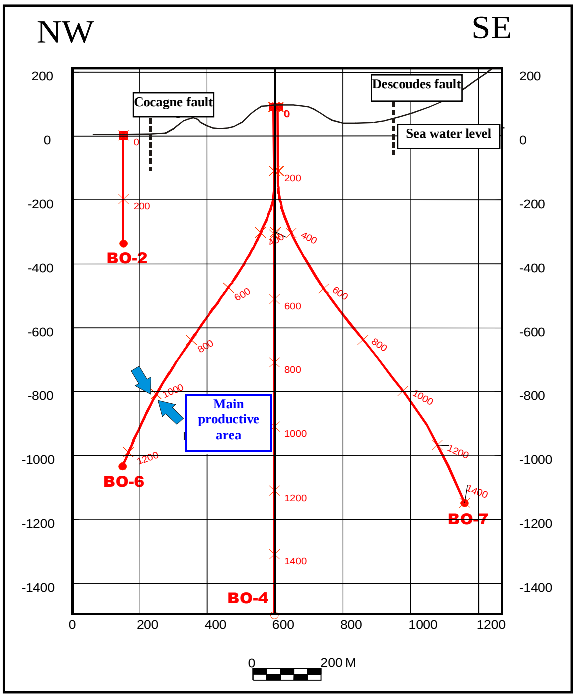

Figure 3: Vertical NW-SE cross-section showing the vertical wells BO-2 and BO-4 and the deviated wells BO-6 and BO-7. BO-5 is in a perpendicular plan (from CFG Services)

Three to five campaigns of fluid sampling and on site measurements are carried out every year by BRGM in collaboration with CFG Services. Several fluid sampling points are used, but as those associated with the well-heads have been relatively badly installed, the fluid monitoring is mainly done after the High-Pressure (HP) separator. Separated water, steam and incondensable gases, representative of the fluids discharged from all the wells, are then collected. The parameters measured on site are conductivity, pH and Redox potential (Eh) on the water and steam condensate and GSR. The chemical and isotopic analyses of the waters, steam condensates and incondensable gases are performed in the BRGM laboratories. All these analyses and respective uncertainties are described in Sanjuan *et al.* (2002; 2004; 2008).

The analytical results indicate that since the beginning of operation of the new power plant at the beginning of 2005, the chemical and isotopic compositions of the fluids discharged from the wells BO-4, BO-5 et BO-6 have been homogeneous and remained relatively stable (Figs. 4 , 5, 6; Sanjuan *et al.*, 2007, 2008). They are similar to the results of the analyses on the fluid discharged from BO-2 when it was the only well in production between 1996 and 2002.

The mass GSR measured at the outflow of the separator, which is a parameter that tends to indicate that the reservoir is being over-exploited (increasing GSR value with increasing amounts of incondensable gases relative to the geothermal water) remains stable at around 0.4% (Fig. 6), and is comparable to the measurements when BO-2 was the only well in production.

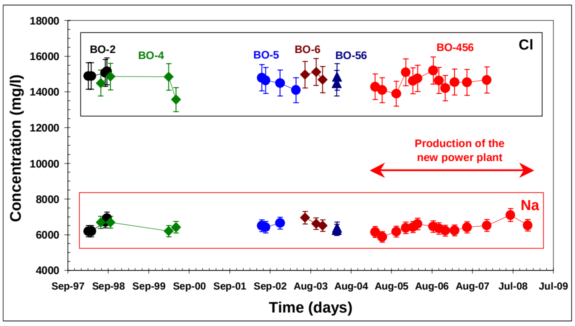

Figure 4: Chloride and Sodium analyzed in the waters collected after phase separation at 160°C

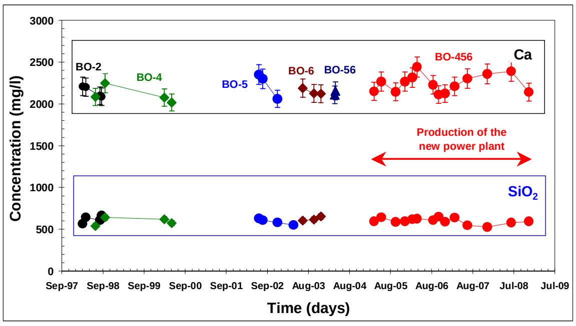

Figure 5: Calcium and Silica analyzed in the waters collected after phase separation at 160°C

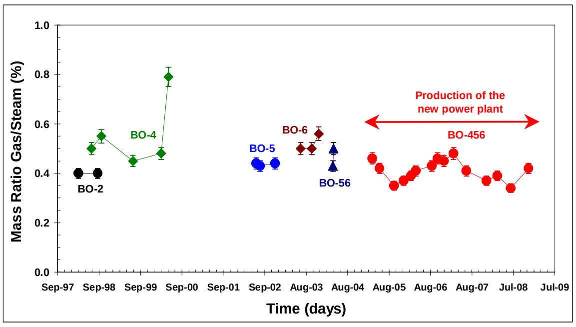

Figure 6: Gas/Steam Ratio determined after phase separation at 160°C

The characteristics of the reservoir fluid do not seem to be affected by the significant increase in production started in 2005, even though 4.5 millions of tons of fluid are estimated to be annually produced and the reservoir pressure has fallen from 13 to about 9 bars. These characteristics have been described in detail in numerous reports (Sanjuan and Brach, 1997; Sanjuan, 2001; Correia *et al.*, 1999; Sanjuan *et al.*, 1999; 2002; 2004; 2007; 2008) and papers (Traineau *et al.*, 1997; Sanjuan *et al.*, 2000; Correia *et al.*, 2000; Sanjuan *et al.*, 2001; Mas *et al.*, 2005; Lachassagne *et al.*, 2009). The main analytical results obtained on the reservoir geothermal water, the steam condensates and the incondensable gases are summarized in Tables 1, 2 and 3. The Neodyme (Nd) concentration in the geothermal water was determined to be close to 0.005 µg/l, a value similar to that of sea water (0.003-0.005 µg/l). Because of this low Nd concentration, a sample with a minimum volume of 30 l is necessary for the determination of the isotopic ratio $^{143}Nd/^{144}Nd$, which will be done later.

The scale deposits collected from BO-2 in May 2000 and from BO-5 in 2003 and 2006 during work on well (caliper or cleaning operations) mainly consist of successive alternating thin layers of amorphous silica mixed with manganese and iron oxides, poly-metallic sulfides such as chalcopyrite, galena and sphalerite, and traces of calcite (Sanjuan *et al.*, 2002; Serra *et al.*, 2004; Sanjuan *et al.*, 2008). The type of deposits suggests that the scale formed during production stoppage or changes in exploitation conditions.

Table 1. Reconstructed chemical and isotopic composition of the reservoir fluid at 260°C from analyses done on separated water and steam condensate samples collected after phase separation at 160°C.

Species	Value	Species	Value
pH	5.3 ± 0.3	**Sr (mg/l)**	16.0 ± 2.0
TDS (g/l)	20.0 ± 1.0	**Ba (mg/l)**	6.5 ± 1.0
Cl (g/l)	12.0 ± 0.6	**Mn (mg/l)**	4.8 ± 1.0
Na (g/l)	5.1 ± 0.3	**Li (mg/l)**	4.5 ± 0.5
Ca (g/l)	1.8 ± 0.1	**Rb (mg/l)**	2.2 ± 0.3
K (mg/l)	750 ± 40	**Cs (µg/l)**	260 ± 30
HCO_3 (mg/l)	50 ± 20	**Al (µg/l)**	60 ± 10
Mg (mg/l)	1.6 ± 0.2	**Fe (mg/l)**	3.2 ± 1.0
SO_4 (mg/l)	16 ± 1	**Cu (mg/l)**	15.0 ± 1.0
SiO_2 (mg/l)	500 ± 30	**Ni (mg/l)**	2.0 ± 0.5
H_2S (mg/l)	34 ± 3	**Zn (µg/l)**	650 ± 100
Br (mg/l)	42 ± 5	**As (µg/l)**	350 ± 50
B (mg/l)	12.5 ± 1.3	**As(III) (µg/l)**	280 ± 40
F (mg/l)	0.9 ± 0.1	**As(V) (µg/l)**	70 ± 15
NH_4 (mg/l)	1.7 ± 0.2	**Cr (µg/l)**	15 ± 2
NO_3 (mg/l)	< 0.5	**Co (µg/l)**	13 ± 1
NO_2 (mg/l)	< 0.01	**Pb (µg/l)**	4.0 ± 1.0
PO_4 (mg/l)	< 0.1	**Be (µg/l)**	< 0.1
δD (‰)	-1.2 ± 0.8	**$\delta^{18}O$ (‰)**	-1.1 ± 0.2
$\delta^{34}S$ (SO_4) (‰)	19.1 ± 0.4	**$\delta^{18}O$ (SO_4) (‰)**	5.6 ± 0.2
$\delta^{13}C$ (‰)	-3.9 ± 0.2	**$\delta^{11}B$ (‰)**	16.3 ± 0.2
$\delta^{7}Li$ (‰)	4.4 ± 0.3	**$^{87}Sr/^{86}Sr$**	0.70496 ± 0.0001

Table 2. Chemical and isotopic compositions of steam condensate samples collected after phase separation at 160°C.

Species	Values	Species	Values
pH	4.3-4.6	**$Eh_{non\ corr.}$ (mV)**	-235 / -135
TDS (mg/l)	50-90	**Na (mg/l)**	0.2-1.4
H_2S (mg/l)	30-45	**K (mg/l)**	< 0.5
Alk. (mg/l HCO_3)	12-24	**Ca (mg/l)**	< 0.1-0.7
Cl (mg/l)	0.7-3.3	**Mg (mg/l)**	< 0.1
SO_4 (mg/l)	0.8-8.7	**NH_4 (mg/l)**	4.5
SiO_2 (mg/l)	< 0.5	**B (mg/l)**	0.2
δD (‰)	-8.0 ± 3.0	**$\delta^{18}O$ (‰)**	-3.2 ± 0.3

Table 3. Reconstructed chemical composition (mol %) of the incondensable gases discharged from the production wells. GSR is given in mass %.

Gas	%	Gas	%
CO_2	93	**He**	0.0035
O_2	0	**H_2S**	2.8
N_2	3.5	**CH_4**	0.4
Ar	0.04	**C_2H_6**	0.006
H_2	0.3	**C_3H_8**	0.0008
GSR	0.4	**$\delta^{13}C$**	-2.6‰

All the Bouillante tracer tests were conducted by BRGM and CFG Services. The tracer tests carried out in 1998, during the BO-4 thermal stimulation used about 8000 m^3 of cold sea water and suggested the absence of direct connections between the wells BO-2 and BO-4. They also allowed estimation of the minimum volume of the geothermal reservoir at about 30 millions m^3 (Sanjuan *et al.*, 1999; 2000; 2001; Correia *et al.*, 1999; 2000).

The tracer test between the wells BO-4 and BO-5/BO-6 was started in July 2003 and used 100 kg of 1,6-naphthalene disulfonate (1,6-nds). It showed the existence of hydraulic connections between these wells. However, because the tracer was only detected in the fluids discharged from BO-5 and BO-6 12 to 16 months after its injection into BO-4, it was concluded that these connections were complex, although BO-5 and BO-6 were in alternating production (Sanjuan *et al.*, 2004). The minimum volume of the geothermal reservoir previously estimated was confirmed.

The tracer test using 200 kg of 2,6-nds and 100 kg of fluorescein was initiated in October 2007 and was between the wells BO-2 and BO-4/BO-5/BO-6. It indicated direct hydraulic connections between BO-2 and BO-6 and BO-2 and BO-4 (Sanjuan *et al.*, 2008). The tracers were first (14 and 21 days after tracer injection into BO-2) detected at low concentrations in the fluid discharged from BO-6 and later (30 and 36 days after tracer injection into BO-2) at higher concentrations in the fluid discharged from BO-4 (Sanjuan *et al.*, 2008). The maximum concentration of 2,6-nds was detected from BO-6 and BO-4 55 and 65 days, respectively, after tracer injection. Only about 0.3% of 2,6-nds was recovered from BO-6 compared to 3.4% from BO-4. These recovery rates remain low. These results suggest that the tracers circulated in the upper level of the geothermal reservoir and that the direction of fluid flow was rather from the North to South. The apparent mean fluid velocity was estimated to be 0.3-0.4 m/h (0.6-0.7 m/h for the apparent maximum fluid velocity).

2.2 Fluids from the Discharge Canal and Thermal Manifestations Located Near The Power Plant

2.2.1. Water Collected from the Discharge Canal of the Power Plant and from the Neighboring Marine Area

Given the chemical composition of the water collected from the discharge canal of the power plant (Sanjuan *et al.*, 2005; 2007; 2008), Arsenic (As) is probably the specie which must be the most monitored in these waters and in the neighboring marine area. The analytical results reported in Table 4 do not show particular problems from 2005 to 2008 relative to the data analyzed in the previous years. The As concentrations in the neighboring marine area remain low (< 13 µg/l).

2.2.2. Fluids Collected from the Thermal Manifestations Located Near the Power Plant

The numerous thermal manifestations (fumaroles, springs, hot grounds…) recognized in the Bouillante area are the expression of a hydrothermal sub-surface system. The new exploitation conditions of the geothermal resource may influence the evolution of the geochemical characteristics of certain surface thermal manifestations located near the power plant (Fig. 7).

In the framework of research works done by BRGM, partially funded by ADEME, an inventory and reconnaissance of all the present and past thermal manifestations located in the Bouillante area was carried out in 1996, 1998 and 1999 (Sanjuan and Brach, 1997; Sanjuan, 2001; Sanjuan *et al.*, 1999; 2002).

Table 4. Analyses of dissolved Arsenic in the water collected from the discharge canal of the Bouillante power plant and from the neighboring marine area.

Water sample	Date	Cl (mg/l)	As (III) (µg/l)	As total analyzed (µg/l)
Discharge canal (production BO-5)	30/11/2002	19840		30
Discharge canal (production BO-6)	15/10/2003	19410		30
Discharge canal (production BO4-5-6)	24/03/2005	20100		26
Discharge canal (production BO4-5-6)	27/05/2005	19500	0	16
Discharge canal (production BO4-5-6)	29/09/2005	19000		23
Discharge canal (production BO4-5-6)	14/12/2005	20300		18
Discharge canal (production BO5-6)	05/04/2006	19469		16
Discharge canal (production BO4-5-6)	22/08/2006	19700		22
Discharge canal (production BO4-5-6)	06/12/2006	19362		14
Discharge canal (production BO4-5-6)	28/02/2007	20302		
Discharge canal (production BO4-5-6)	20/06/2007	19250		42
Discharge canal (production BO4-5-6)	11/12/2007	19509		23
Discharge canal (production BO4-5-6)	08/07/2008	18800		24
Discharge canal (production BO5-6)	09/12/2008	18968		18
Mean sea water		19500	< 1	3-4
Sea (Ponton)	26/06/2004		2.4	10
Sea (Ponton)	26/05/2005			3.8
Sea (Ponton)	30/09/2005			< 10
Sea (Ponton)	14/12/2005			10
Sea (Ponton)	06/04/2006			7.6-7.7
Sea (Ponton)	06/12/2006			11
Sea (Ponton)	28/02/2007			10
Sea (Ponton)	20/06/2007			11 / 12.1
Sea (Ponton)	12/12/2007			7.8
Sea (Ponton)	08/07/2008			12.9
Sea (Ponton)	11/12/2008			6.7
Sea (Face Supermarché)	26/06/2004			2.0
Sea (Face Supermarché)	26/05/2005			4.3
Sea (Face Supermarché)	14/12/2005			6.0
Sea (Face Supermarché)	06/04/2006			5.6-5.9
Sea (Face Supermarché)	06/12/2006			6.0
Sea (Face Supermarché)	28/02/2007			6.8
Sea (Face Supermarché)	20/06/2007			7.2 / 7.1
Sea (Face Supermarché)	12/12/2007			2.7
Sea (Face Supermarché)	08/07/2008			3.2
Sea (Face Supermarché)	11/12/2008			1.5
Sea (Pumping station)	14/12/2005			2.0
Sea (Pumping station)	06/04/2006			2.9
Sea (Pumping station)	06/12/2006			3.0
Sea (Pumping station)	28/02/2007			2.1
Sea (Pumping station)	20/06/2007			2.6 / 2.5
Sea (Pumping station)	12/12/2007			2.6
Sea (Pumping station)	08/07/2008			1.9
Sea (Pumping station)	11/12/2008			1.4
Sea (Marsolle)	06/04/2006			2.0
Sea (Marsolle)	28/02/2007			1.8
Sea (Marsolle)	12/12/2007			1.5
Sea (Marsolle)	08/07/2008			3.4

On the other hand, in this same framework and with the CFG Services collaboration, a long-term geochemical monitoring of some of these thermal manifestations such as the spring Tuyau (S3), the observation drill-hole BO-BS, the springs Cave BO-2 (S4) and Marsolle (S7), was initiated.

The results obtained from the on site measurements, the chemical and isotopic analyses performed in the BRGM laboratories on the water and gases of these thermal manifestations are reported in several reports (Sanjuan and Brach, 1997; Sanjuan, 2001; Correia *et al.*, 1999; Sanjuan *et al.*, 1999; 2002; 2004; 2007; 2008) or papers (Traineau *et al.*, 1997; Sanjuan *et al.*, 2000; Correia *et al.*, 2000; Sanjuan *et al.*, 2001; Mas *et al.*, 2005; Lachassagne *et al.*, 2009).

The chemical and isotopic characteristics of most of these thermal manifestations are described and interpreted in these publications. Among these thermal springs, only the physico-chemical monitoring of the water discharged from Tuyau shows chemical and isotopic variations directly associated with the conditions of geothermal exploitation.

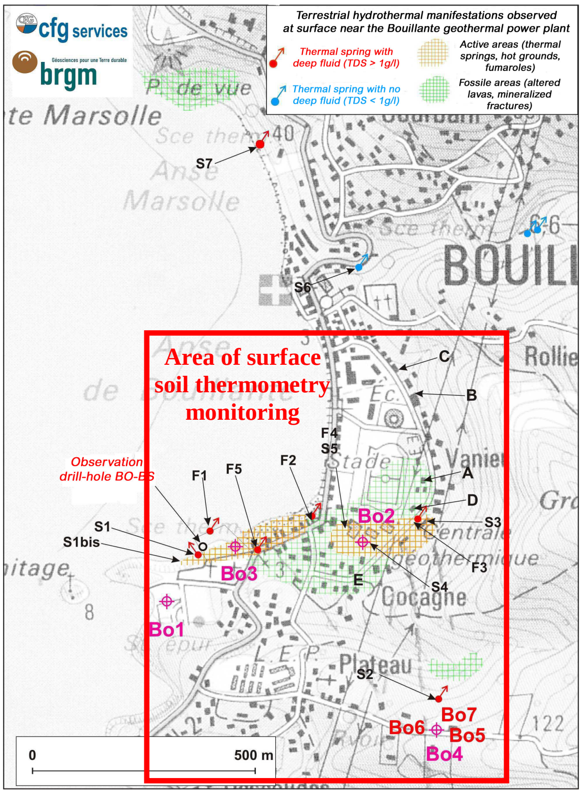

Figure 7: Area selected for fluid geochemical monitoring and surface soil thermometry (map from CFG Services)

a) Spring Tuyau (S3; Fig. 7)

This thermal spring is located near the geothermal power plant and geochemical monitoring of its Na-Cl fluid was initiated in 1998. Since the start of the production at the new power plant in 2005, we can see a progressive increase in temperature and decrease in water salinity (as indicated by the Cl and Ca concentrations; Figs. 8 and 9). A decrease in water salinity from 1.6 to 0.8 g/l had been already observed during the long-term BO-2 production duration between 1998 and 2002. However the water salinity had strongly increased from 0.8 to 2.5 g/l, between 2002 (BO-2 production stopping) and 2005 (production starting of the new power plant; Figs 8 and 9).

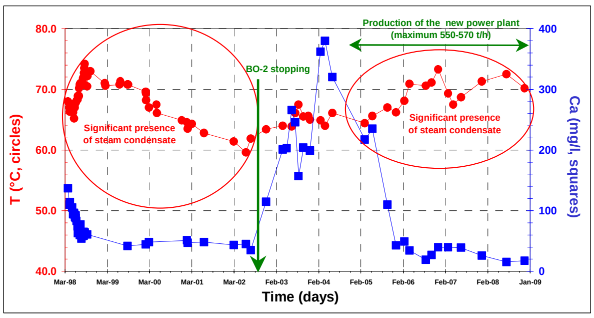

Figure 8: Temperature and Calcium determined in the water discharged from the thermal spring Tuyau (S3)

Using the isotopic δD and $\delta^{18}O$ values (Fig. 10), Sanjuan *et al.* (2004; 2008) mainly attributed these temperature and salinity variations to the presence of variable contributions of reservoir geothermal water, of steam condensate separated from geothermal water and of local surface water, in the fluid discharged from this spring. The reservoir geothermal water has an isotopic signature in δD and $\delta^{18}O$ close to -1.2 and -1.1‰, respectively (Sanjuan *et al.*, 1999; 2001; Mas *et al.*, 2005). The separated geothermal water is characterized by δD ≈ -0.2 to 6.6‰ and $\delta^{18}O$ ≈ -0.7 to 0.4‰, respectively, following the fluid separation temperature. The steam condensate separated from the reservoir geothermal water indicates isotopic values ranging from -19.9 to -6.1‰ for δD and from -4.9 to -3.3‰ for $\delta^{18}O$, following the fluid separation temperature. The local surface waters are characterized by δD values ranging from -12.0 to -6.2‰ and $\delta^{18}O$ values varying from -3.0 to -2.5‰. All these isotopic data were reported in Sanjuan and Brach (1997), Sanjuan (2001), Sanjuan *et al.* (1999; 2000; 2002; 2004; 2007 and 2008), Mas *et al.* (2005) and Guisseau *et al.* (2008).

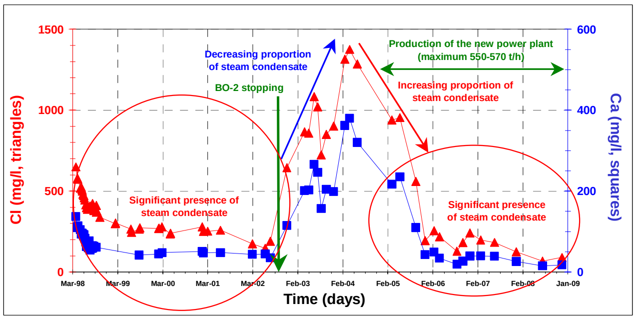

Figure 9: Chloride and Calcium analyzed in the water discharged from the thermal spring Tuyau

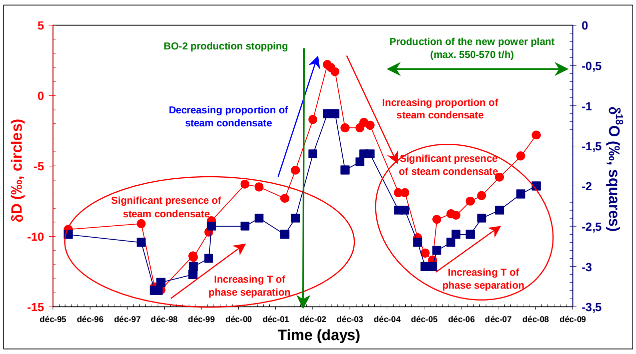

Figure 10: δD and $\delta^{18}O$ values analyzed in the water discharged from the thermal spring Tuyau

Given the salinity and the chemical and isotopic composition of the water of this spring, the contribution of reservoir geothermal water always remains low (< 10%). When there is more production from the geothermal reservoir (BO-2 or deeper wells BO-4, BO-5 and BO-6 producing), the contribution of steam condensate should tend to be more significant (salinity decrease; Figs 8 to 10). When the reservoir is produced less (only a deeper well producing) or production is stopped, the contribution of steam condensate should tend to decrease or even disappear, causing a significant increase in water salinity (Fig. 8 to 10). The progressive increase observed for the δD and $\delta^{18}O$ values between December 2005 and December 2008 (Fig. 10), accompanied by stabilized or slightly decreasing water salinities and increasing temperatures (Fig. 8 and 9), could be explained by the temperature rise of the steam separation from the geothermal water (the isotopic values of steam separated at higher temperatures are less negative).

b) BO-BS observation drill-hole (Fig. 7)

The technical characteristics of the observation BO-BS drill-hole are reported in Sanjuan *et al.* (2002). This drill-hole is located near the old well BO-3 in the area of the pumping station of sea water used for the cooling system of the power plant. The geochemical monitoring of the water discharged from this drill-hole favorably replaced, in 1999, that of the spring Bord de Mer (S1), which was difficult to carry out because of its proximity with the sea and its diffuse emergences on the beach (Sanjuan *et al.*, 2002).

The fluid samples are collected from this drill-hole using a sampling system constituted of a stirrup pump and a tube, which allows the fluid to flow up from the bottom-hole. The fluid for which chemistry suggests a quasi-direct leakage of geothermal fluid after separation from the steam phase (Sanjuan, 2001; Sanjuan *et al.,* 2002) could come from fluid leaks suspected in the old well BO-3, through fissures created in the concrete used to close this well.

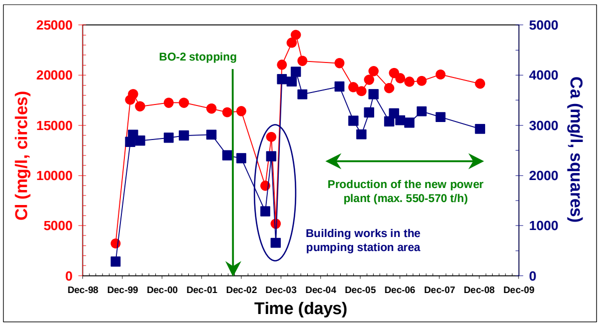

Figure 11: Chloride and Calcium analyzed in the water discharged from the drill-hole BO-BS

Up to December 2002, the fluid collected from this drill-hole indicates a relatively stable chemical and isotopic composition (Fig. 11). This fluid has similar characteristics to the geothermal fluid discharged from the wells BO-2 and BO-4 after vaporization.

The vaporization rate, deduced from the Cl concentrations (about 30%), is similar to that estimated for the fluid collected at 100°C, from the BO-4 weir box (Sanjuan *et al.*, 1999; 2002). The different variations of salinity and chemical composition of this fluid observed between January 2003 and June 2004 were interpreted by Sanjuan *et al.* (2004) and are essentially due to construction work carried out in the pumping station during this period. From May 2005, five months after the start of the new power plant and the new exploitation conditions, there was a decrease in water salinity and in the concentrations of dissolved species, which tended towards the values determined when BO-2 was the only producer well (Fig. 11).

c) Spring Cave-BO2 (S4; Fig. 7)

This thermal spring is located in the cellar of the well BO-2. The high salinities observed in the water discharged from this spring, their significant variations (from 8 to 27 g/l) as well as the changes of chemical composition (even if Na and Cl are the dominant species, Table 5) indicate that this water is made up of variable proportions of geothermal water, sea water and fresh water always with, however, high contributions of geothermal water (Sanjuan *et al.*, 1999; 2004; 2008). The variability of the results is mainly due to the diffuse emergences of this spring in the BO-2 cellar which is often filled with rain water and must be pumped before fluid sampling. Another factor of variability is the proximity of the BO-2 cellar with the cooling system in which sea water circulates.

A direct and very quick connection between the well BO-2 and the spring Cave BO-2 was observed during a tracer test carried out in 2005 by BRGM and CFG Services in which two organic tracers (sodium benzoate and 1,5-nds) were injected into BO-2 (Sanjuan *et al.*, 2004; 2008).

Table 5. Some examples of chemical and isotopic compositions of the waters discharged from the thermal springs Cave-BO2 (S4) and Marsolle (S7).

Thermal spring	Cave BO-2	Cave BO-2	Cave BO-2	Cave BO-2	Marsolle	Marsolle	Marsolle	Marsolle
Sampling date	Sep-95	10-Dec-03	06-Apr-06	10-Dec-08	May-96	03-Dec-02	06-Apr-06	12-Dec-07
T (°C)	97.4	85.5	61.0	96.6	44.3	45.3	46.7	47.2
Cond. 20°C (mS/cm)	27.2	16.4	17.7	25.2	1.28	1.12	0.98	1.34
TDS (g/l)	15.9	9.9	13.3	16.5	0.80	0.72	0.67	0.86
pH	5.89	6.66	6.74	7.21	7.18	6.85	7.40	7.25
Eh_{nc} (mV)	-165	-150	-40	59	135	172	79	86
Na (mg/l)	4025	2629	3713	4050	171	147	127	191
K (mg/l)	508	252	249	257	15.6	12.4	13	15.5
Ca (mg/l)	1443	840	894	1791	44.1	43.8	47.9	50
Mg (mg/l)	6.6	25	148	93	12.6	8.5	5.8	14.4
Alkalinity (mg/l HCO_3)	73	200	298	90	167	170	155	168
Cl (mg/l)	9572	5832	7190	9564	277	225	201	310
SO_4 (mg/l)	74	150	565	457	28.8	22.0	18.0	28.6
NO_3 (mg/l)			< 0,5	< 0.5	< 0.5	< 0.5	< 0.5	1.8
SiO_2 (mg/l)	144	149	145	140	87	93	100	79
PO_4 (mg/l)			0.1	< 0.1	< 0.1	< 0.1	< 0.1	
Br (mg/l)	33.6	20.6	29.0	33.6	0.93	1.10	1.27	1.00
B (mg/l)	8.4		6.6	5.4	0.22	0.15	0.25	
F (mg/l)			0.2	0.2	0.2	0.2	< 0.1	
NH_4 (mg/l)			< 0.5	7.6		< 0.1	< 0.05	< 0.1
Sr (mg/l)			7.6	15.9	0.30	0.30	0.30	
Li (mg/l)	2.3	1.8	1.0	1.8	0.046	0.040	0.053	
Rb (mg/l)	1.24		0.62	0.91	0.032	0.032	0.036	
Cs (µg/l)	240		85	150	2.8	< 5	< 5	
Ge (µg/l)			6	4.000	< 5	< 5	5	
Ba (µg/l)			770	1190	7.8	5.0	9.0	
Mn (µg/l)			3750	17070	0.18	< 5	< 5	
As (µg/l)	290		135	170	3.5	< 10	< 10	
Fe (µg/l)			610	30	< 20	< 20	< 20	
Al (µg/l)			< 10	5.9	< 10	< 10	< 10	
Ag (µg/l)			< 5	< 0.1	< 2	< 2	< 2	
Pb (µg/l)			< 2	< 0.1	< 2	< 2	< 2	
Ni (µg/l)			< 5	0.5	< 2	< 2	< 2	
Cu (µg/l)			< 2	3020	< 2	< 2	< 2	
Cd (µg/l)			< 2	1.1	< 2	< 2	< 2	
Co (µg/l)			< 2	0.1	< 2	< 2	< 2	
Cr (µg/l)			< 5	< 0.1	< 2	< 2	< 2	
Zn (µg/l)			29	22.8	< 5	< 5	8	
δD (‰)	-3.0		0.3		-8.1	-8.0	-9.5	-7.0
$\delta^{18}O$ (‰)	-1.1		-0.5		-2.6	-2.7	-2.5	-2.6
$\delta^{11}B$ (‰)						22.52		
$\delta^{7}Li$ (‰)					5.8			
$^{87}Sr/^{86}Sr$	0.704783				0.705170			

d) Spring Marsolle (S7; Fig. 7)

The temperatures measured (43-46°C) at the emergence of the thermal spring Marsolle (Fig. 7) and the water salinities (close to 0.7-0.9 g/l) are relatively stable with time (Sanjuan *et al.*, 2008). The chemical and isotopic compositions of the water of this spring, which indicate low variations in the concentrations of some species (Table 5), suggest that this Na-Cl water is the result of mixing between very high proportions of fresh water and very low contributions of sea water and geothermal water, which can be slightly variable following the date or the conditions of fluid sampling (Sanjuan and Brach, 1997; Sanjuan, 2001; Mas *et al.*, 2006; Sanjuan *et al.*, 2008; Millot *et al.*, 2010).

e) Fumaroles (F1 to F5; Fig. 7)

The chemical analyses of the incondensable gases and the very negative values of δD and $\delta^{18}O$ determined in the steam condensates, collected from different fumaroles located near the power plant and sea (Fig. 7), show that (Sanjuan and Brach, 1997; Sanjuan *et al.*, 2002):

- similar results have been obtained and reported by Brombach *et al.* (2000);

- these gases are essentially formed by mixing of deep originating CO_2 and atmospheric air;
- the steam condensates are the result of a vaporization phase at 100°C made up of a mixture of geothermal water and surface fresh water at different proportions.

3. SURFACE SOIL THERMOMETRY NETWORK

During exploration work in 1964, 250 temperature measurements at a depth of 1.25 m and 8 gradient drill-holes (down to a depth of 50 m) were made, and they facilitated the selection of several areas of geothermal interest (Goguel, 1965). In 1999, some surface soil thermometry measurements were again carried out by BRGM (Sanjuan *et al.*, 2002).

Given the interest in these measurements, BRGM and CFG Services initiated a surface soil thermometry monitoring, using a network of 52 measurement points around the power plant (Figs. 7 and 12), in October 2006. These points were selected taking into account the known surface thermal anomalies. They were positioned using GPS and equipped with copper tubes driven to a depth of 0.8 m to avoid atmospheric influence. These measurement points will give complementary information in order to study the evolution of the impact of the power plant exploitation on its immediate surface environment.

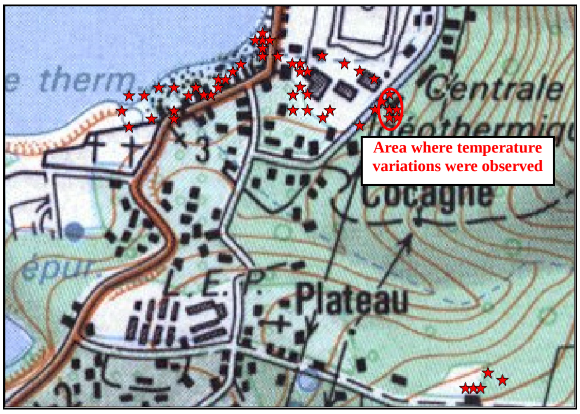

Figure 12: Points of temperature measurements (red stars) of the surface soil thermometry monitoring

In the framework of this monitoring, at least two thermometric campaigns (one during the humid season and the second during the dry season) were performed. The temperature measurements were performed using a thermocouple probe.

The first measurement campaign occurred during the humid season (October and December 2006). The first measurement campaign during the dry season was carried out in March 2007. Other measurements campaigns were conducted in 2007 and 2008, during the dry and humid seasons. The results are reported in Sanjuan *et al.* (2008).

Among the very hot points (> 99°C), very few variations were observed and finally, these points gave no interesting information about the evolution of the impact of the power plant exploitation on its immediate surface environment. These points must be replaced by other more pertinent points. On most of the other points, only some low seasonal variations of temperature were observed. Only two points in an area located behind the power plant, towards East and near the thermal spring Tuyau (Figs. 7 and 12), showed significant increase in temperature (up to 15°C) between the measurements performed in December 2006 and 2007. However, this monitoring is starting and other measurements are necessary to confirm the first observed trends or detect other trends. The location of the measurement points will have to be modified according to the obtained results.

4. GEOPHYSICAL MONITORING

4.1 Broadband Seismometry Network

The main objectives of this monitoring technique were:

- to characterize the seismological activity of the geothermal field. It can give information about the long-term evolution of the constraint field and of the fluid migration in relation to the exploitation conditions;
- to better define the geometry of the geothermal reservoir;
- to better understand the impact of the exploitation of a geothermal field on the location and the characteristics of seismicity in the near field (modification of the seismic hazard; Bommer *et al.*, 2006).

A network of 5 Güralp CMG40-T broadband seismometers located around the production wells has been monitoring the seismic activity in the vicinity of the exploited geothermal system since August 2004 (Fig. 13). The equipment of this network is described in detail in Jousset (2006). The seismometer LB5 quickly failed because of its location in a hot ground area.

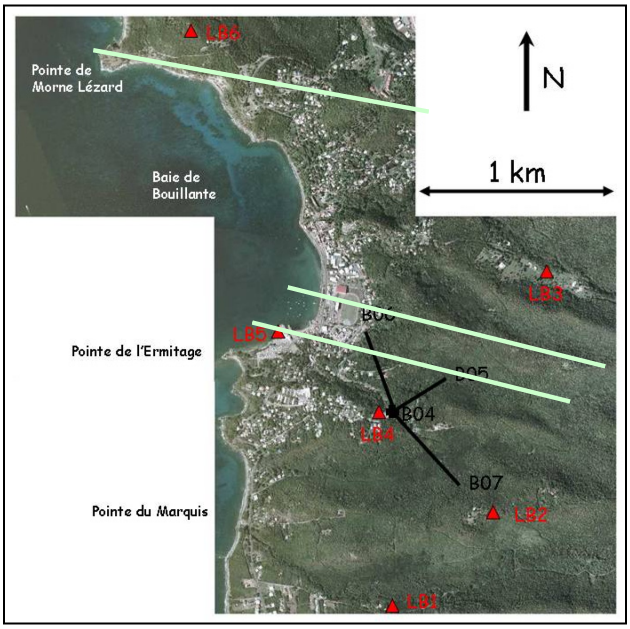

Figure 13: Location of the broadband stations used for the seismological monitoring (map extracted from BD CARTO - (C) IGN Paris 2005 - Licence n°6 CUI - dom 0100). The main faults are represented by green straight lines

It appears that the detection of seismological events at Bouillante is made difficult because of at least three factors:

- the strong regional seismological activity;
- the strong seismic ambient noise in Guadeloupe;

- the choice of the location of the stations with respect to the signal due to the first two factors.

In spite of these difficulties, the data analysis has found different types of signals, which enhances understanding of the geothermal field at structural and dynamical levels.

The network has recorded:

- some very close earthquakes (some kilometres of depth), with well-marked P and S waves, and recorded on all the stations in form of a majority of high frequency signals (5-20 Hz). These tectonic earthquakes indicate that the Bouillante area is seismically active, in relation to the major tectonic accident located near the geothermal field (Fig. 1), but these events are independent of the fluid exploitation activity. In contrast, the analysis of these events contributes to the structural knowledge of the Bouillante field: the signature of an impedance contrast is visible on the local (and regional) earthquakes, leading the proposal of the existence of a stratiform interface at a depth of about 500 m which can be related with the lithological changes observed in the well logs (interface between the breccia-tuff and submarine volcanic units; Sanjuan *et al.*, 2004);
- on the stations close to the production wells (LB4) and out of the production periods, harmonic signals (4 and 8 Hz frequency) probably corresponding to “tube waves”, caused by the resonance of the production wells under the effect of pressure source (bubble cavitation?);
- a dominant 2 to 3 Hz frequency continuous signal recorded on all the network with temporal modulations and different amplitudes. These tremors (volcanic pulsations associated with fluid circulation in the edifice) are recorded on other hydrothermal and oil fields (Ohminato, 2006; Dangel *et al.*, 2003), but their origin is still not well understood;
- very long period signals (about 8-10 s) during the crossing of seismological waves of tectonic earthquakes corresponding to the after-shocks of a 6.3 Mw magnitude earthquake which occurred on November 21, 2004 in the Saintes island. These signals have been associated with aftershock source processes (Jousset and Douglas, 2007).

In contrast, in the analyzed data, it can be noticed that the network has not recorded the following signals:

- microseismic events directly induced by the exploitation, in accordance with the previous seismic studies (Gaucher *et al.*, 1998);
- large magnitude and long period well-individualized signals. However, the variable amplitude continuous signal could be an expression of this type of signals.

These results have several implications:

- no induced microsismicity could be explained by the fact that the fluid extraction does not generate significant short term changes in the pressure of the geothermal reservoir. The volume of the reservoir seems to be important. The hydrogeological and geochemical models indicate both sea water and fresh water recharge. However, seismic activity associated with long-term exploitation could be observed in combination, for example, with a higher proportion of incondensable gases in the geothermal fluid;
- the seismic hazard during the observed period has been low insofar as the major tectonic accident which is near the Bouillante geothermal field is an active area and that tectonic earthquakes independent on the geothermal exploitation can occur;
- concerning the monitoring methodology, the network was not focused enough to concurrently record long period events at the Bouillante noise conditions. If the network was tightened around a production well, the corresponding events could be recorded on several stations and the mechanical properties of this well could be deduced.

We can conclude that few local tectonic events were observed. The seismicity associated with the geothermal exploitation is very probably low and consequently, the seismic hazard induced by the geothermal exploitation is also low. The major problem remaining is to develop a 3D-model of the velocities in the Bouillante area, and its relationship with the major tectonic structures and the reservoir geometry. Its knowledge at the reservoir scale would allow better locating of the local events, in order to follow and understand the detailed temporal evolution of the observed frequency. In spite of all the care dedicated to the data processing, the introduction of more effective algorithms to discriminate the wave forms would allow improvement of event classification and establishment of statistics on the event occurrences.

The installation of this network must allow monitoring the long-term geothermal exploitation and some broadband seismometers will be moved to improve this monitoring technique. Seismological networks are used in numerous world geothermal fields (Iceland, Italy, USA, etc.) to monitor the seismic activity of these fields. On the other hand, if a part of the production fluids was soon re-injected in the underground to support the pressure in the Bouillante geothermal reservoir, this technique would be very useful in monitoring the microseismicity induced by the fluid re-injection.

Another broadband seismometer (station LB6) has been installed in the non-exploited northern part of the Bouillante geothermal field (Fig. 13) in order to test this technique for geothermal exploration. This station records very numerous small amplitude earthquakes (1 to 5 10^{-6} m/s), which are identically repeated with a long period of about 10 s and present all the characteristics of the resonance of a fluid contained in a fracture or a fracture network. The location of these long period micro-earthquakes is made possible thanks to their abundance and similarity and the use of an additional seismometer successively positioned at different stations located around the permanent station of the network. The location of these micro-earthquakes corresponds to an area where hydrothermal manifestations had been recognized with, in particular, submarine emissions of thermal waters and gas bubbles, and terrestrial helium anomalies. The depth of these events was estimated to be in the first hundred meters and would be located in the known Marsolle fault. In comparison with the seismological signals recorded for the geysers, a hypothesis for the formation mechanism of these earthquakes could be the cavitation/collapse of gas bubbles in the geothermal fluid (degassing area), which ascends along the Marsolle fault. If validated, this technique can be very useful for geothermal exploration.

4.2 Microgravity Monitoring

The gravity monitoring of a geothermal reservoir using measurement reiterations (« time-lapse » or 4D) can give useful information about the mass transfers in this reservoir. It allows the fluid movements during geothermal exploitation to be monitored, locating the recharge and outflow areas that control, in the time, the continuity of the resource (mass balance of the system). It can be also used for the geometric and dynamic modeling of a reservoir. Combined with monitoring of the altimetric data, the microgravity can contribute to the study of possible vertical surface ground deformations induced by geothermal exploitation.

Microgravity monitoring started in February 2006 with the setting up of a network of about 31 measurement stations, located with an accurate differential GPS. Most of the stations are situated in the geothermal field area but nine of them are outside for gravimeter calibration (Fig. 14). Since 2006, a campaign of gravity and GPS measurements has been performed each year, between February and March.

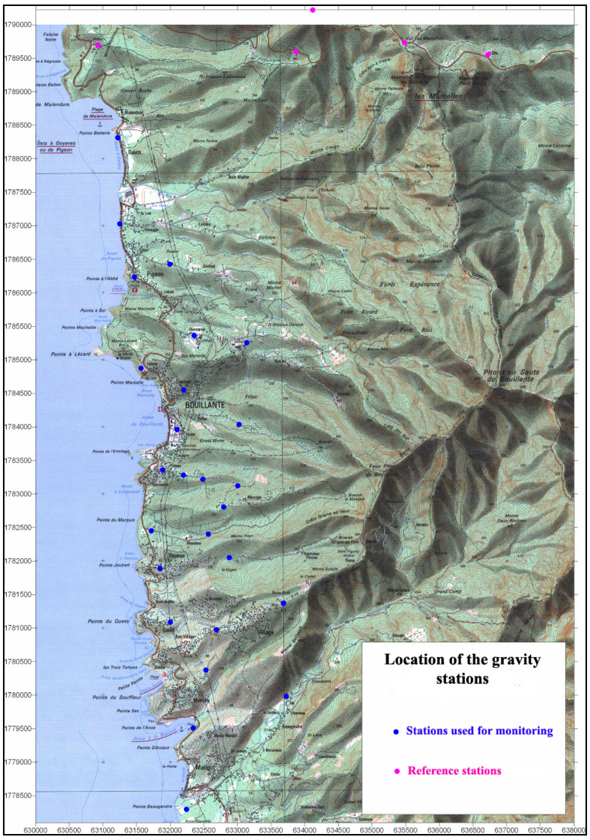

Figure 14: Location of the stations of the microgravity network

The material used for these measurements and the main results obtained in 2006 and 2007 are presented in detail in Debeglia *et al.* (2007). During the first iteration of the gravity and altimetry measurements carried out in February-March 2007, and after comparison with the 2006 measurements, some differences in gravity, ranging from -37 to 42 µGal and higher than the analytical uncertainties, were identified (Fig. 15). No altimetric variation higher than 8 cm (precision) was observed. The repartition of the gravity variations in the studied area is complex and cannot be induced only by a mass depletion induced by the geothermal exploitation. Several positive and negative anomalies are observed and cannot be always explained. The overall mass balance on the exploited area was estimated to be around -1.9 millions of tons during the period considered. However, we do not know if this mass depletion is fully associated with the geothermal exploitation because other unknown origin anomalies, such as the positive anomaly Cocagne-Muscade, are integrated into this estimation. This mass depletion is lower than the annual fluid production estimated at about 4.5 millions of tons and would be in agreement with a relative quick recharge of the reservoir, observed on the well-head increasing pressures when the fluid production is stopped. Between 2007 and 2009, few gravity variations were recorded. An attenuated negative trend could be mentioned in the area of the power plant but needs confirmation.

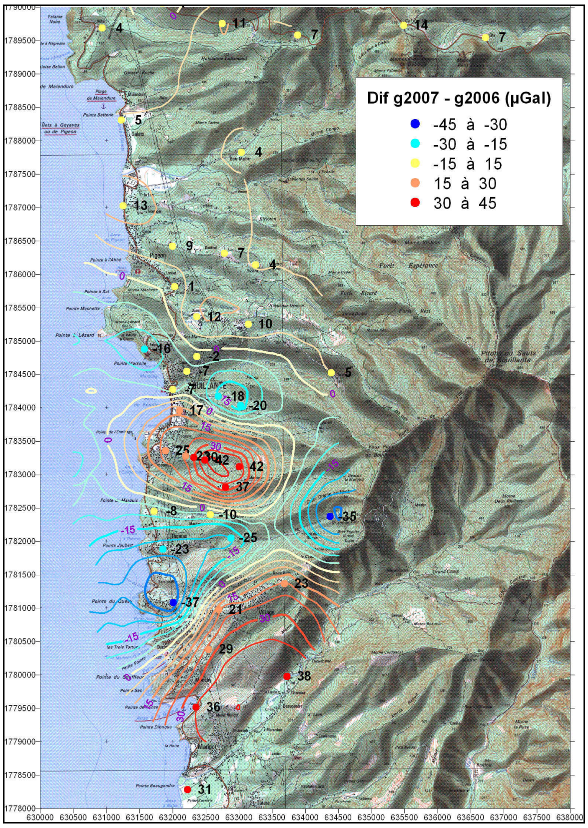

Figure 15: Map showing the gravity variations between 2006 and 2007, measured using a CG3 gravimeter and superposed on a IGN topographic background

Mass supply corresponding to fluid inflows in the studied area will be observed by new iterations. Disruptive influences can be also related to the existence of surface aquifers or small amplitude vertical movements. Compared to disruptive effects, the gravity variations induced by the geothermal exploitation will be more significant on a longer observation period and the continuity of the monitoring will allow reinforcement of the mass balance estimation of the system. On the other hand, the precision of the gravity and altimetry measurements can be improved. An intensification of the stations of the monitoring network would be useful because a better delineation of the anomalies would allow more precise interpretations.

The presence of continuous gravity and environmental recording using a permanent or semi-permanent observatory would help to better interpret the obtained results. This observatory, which would be installed near the production zones, could consist of a gravimeter (Earth Tide Meter or G-phone from Scintrex/Microg-Solution), a meteorological station, a permanent GPS and a system of data acquisition and telemetry. The vertical gradient would be measured every 5 years in order to have an additional constraint.

4.3 SAR Interferometry

In the framework of a study of Synthetic Aperture Radar (SAR) interferometry which allows detecting and measuring possible vertical surface ground deformations induced by the geothermal exploitation, 24 SAR images taken over the whole Guadeloupe Island from the sensor ASAR ENSIVAT of ESA, between 2003 and 2006, were processed.

Two SAR interferometric methods were used: conventional interferometry (DInSAR) and Phase Shift Interferometry (PSI). The description of these methods and the main results are reported in De Michele and Raucoules (2007).

These methods do not seem to detect vertical ground movements induced by the Bouillante geothermal exploitation. It is difficult to read and interpret the interferograms in the context of the Bouillante area. As the vegetation is abundant in this area, the response in the SAR signal is inconsistent with time. In the Bouillante town, the duration of the SAR signal coherence is short (between 35 and 175 days). However, in conventional interferograms calculated on a short period, no vertical surface ground deformation was detected.

Given the context of this area, L-band interferometry would be more appropriate because this band is less sensible to the vegetation presence. This technique can detect ground deformations up to about 1 centimetre. A new L-band SAR sensor (ALOS-PalSAR) has been placed in orbit and could be used for the monitoring of the vertical ground deformations at Bouillante. However, archives must be preliminary constituted for this new sensor in order to use the PSI technique. L-band interferometry will be probably tested in the Bouillante area after this year.

CONCLUSIONS

Several geochemical and geophysical techniques have been used and tested in order to monitor the evolution of the Bouillante geothermal reservoir and its immediate surface environment during its exploitation. The results obtained during this work have been and will be used in the conceptual geological models which have been established and must be developed. They will be also used for hydrodynamic and geochemical modeling.

On the whole and despite the pressure decrease observed in the geothermal reservoir due to an annual fluid production estimated at about 4.5 millions tons, no significant variation of the monitored parameters has been detected from these methods over four quasi-continuous years of geothermal exploitation. Only the fluid discharged from the thermal spring Tuyau, located close to the power plant, and an area situated near this spring, seem to show focused shallow changes induced by the geothermal exploitation. The microgravity monitoring indicates a mass depletion of about -1.9 millions of tons between March 2006 and February 2007. Even if this mass depletion is poorly defined, its value compared with the annual fluid production seems to be in good agreement with a relatively quick recharge of the reservoir, which is also supported by the rapid increases in well-head pressure when fluid production is stopped.

For the moment, it is difficult to conclude if these monitoring methods are the most appropriate because more time is necessary to evaluate them. Most of them will be continued and probably developed in the next few years, especially if the produced fluids are re-injected, in order to anticipate and/or quickly take into account problems related to a chemical change in the reservoir fluid or induced microseismicity, for example.

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