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GEOCHEMICAL INVESTIGATIONS DURING A NEW GEOTHERMAL EXPLORATION PHASE IN THE LAMENTIN PLAIN (MARTINIQUE, FRENCH WEST INDIES)

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ABSTRACT

A new exploration phase was carried out in the Lamentin plain (Martinique, French West Indies) in 2001. On the three bore-holes drilled by CFG in this area, only the bore-hole located more at north (Californie bore-hole) and near the old LA-101 bore-hole, indicated the presence of inflows of hot fluid close to 90°C starting from 400 m of depth. The main inflow was observed at about this depth. A similar geothermal fluid was also found at a depth of about 400 m in the Carrère bore-hole, situated near thermal springs, but with a lower temperature (50°C).

The geochemical monitoring carried out by BRGM made it possible to find some surface inflows of cold fluid with often a probable marine influence in the three bore-holes and to characterise the chemical and isotopic composition of the low temperature geothermal fluid. According to the geochemical data, this Na-Cl geothermal fluid (TDS ≈ 10-11 g/l; pH ≈ 6.2-6.3) is a mixing of 20-25% sea water and 80-75% fresh water, which could mainly come from the massif of the Pitons du Carbet, following a general structural NW-SE direction. This mixing has reacted with the surrounding volcanic rocks and with magmatic CO_2 emanations (minimum CO_2 partial pressure estimated to 1 bar). Relative to a diluted sea water, it is enriched in dissolved Ca, HCO_3, SiO_2, Sr, Ba, B, As, Fe, Mn, Li, Rb, Cs and Ge and depleted in SO_4 and Mg. Additional chemical and isotopic analyses performed on the fluids of neighbouring thermal springs confirm these results and indicate that the geothermal fluid sampled in the bore-holes has been slightly diluted probably by the drilling fluid. When applied on all these fluids, numerous chemical geothermometers yield concordant values of deep temperature around 90-130°C, which are close to the measured temperatures and to those estimated using the gas geothermometers. The relatively high Mg and SO_4 concentrations of these waters and their absence of a ^{18}O enrichment from the rocks are rather in agreement with the moderate temperature estimated using the geothermometers.

All the results suggest that the temperature gradient increases towards the north of the Lamentin plain where the geothermal reservoir would be rather located. According to the geochemical results, the geothermal fluid would derive from a reservoir situated near sea water, somewhere between the Lamentin plain and the Absalon-Didier area. This fluid would flow out laterally from NW to SE at relatively low depths. No major evidence of a high temperature geothermal reservoir was observed in the Lamentin and Absalon-Didier areas.

INTRODUCTION

During the first geothermal exploration phase, that occurred between 1966 and 1971 in the Lamentin plain, a mangrove area situated south of Fort de France city, a low temperature aquifer (about 94°C) was intersected at a depth of 150-250 m by the only deep bore-hole (LA-101, 771 m) drilled in this area. Later geochemical studies carried out in 1976, 1984 and 1985 showed no major shallow evidences of the occurrence of an high temperature reservoir in this area.

The aim of the new geothermal exploration phase (Dec. 2000- Dec. 2001) in the Lamentin plain was (1) to complete the knowledge and the understanding of the superficial low temperature aquifer previously discovered and (2) to investigate deeper formations to evidence a hot reservoir (T > 180°C).

For this purpose, the drilling of three deep bore-holes (around 1,000 m) was conducted by CFG. BRGM was in charge of the scientific programme accompanying the bore-hole drilling. This programme was constituted of a geological and geochemical monitoring and measurements of static temperature and pressure logs. It also included additional chemical and isotopic analyses performed on the fluids of neighbouring thermal springs in the Lamentin and Absalon-Didier areas. The objective of this paper is to present and to discuss the main geochemical results obtained in this programme.

MAIN RESULTS OBTAINED DURING THE DRILLING OF THE THREE EXPLORATORY BORE-HOLES

The main results obtained during the geological and geochemical monitoring, which accompanied the drilling of these bore-holes, and during the series of measurements of static profiles of pressure and temperature, performed in july 2001, are quickly presented in this chapter. All the bore-holes were drilled using a polymeric mud and fresh water. The detailed results obtained during the geochemical monitoring of the drilling fluid and the series of measurements of static P-T profiles are reported in a technical report (Sanjuan *et al.*, 2001). A more detailed study of the geological results is presented by Genter *et al.* (2002).

Pointe Desgras bore-hole

The first bore-hole (Pointe Desgras; Fig. 1) was drilled between November 2000 and January 2001 down to a depth of 939.55 m and was cored from 392 m. Located in an area considered as the centre of a hydrothermal system by previous studies (silica travertine observations and main mercury and gas anomalies), this bore-hole was dry and relatively cold (58°C at 930 m of depth). The geological monitoring revealed the existence of strongly fractured, massive andesitic lava but one can note that these fractures are completely sealed by carbonate deposits, in particular to 710 m of depth. The presence of epidote observed on some cores suggests conditions of high paleo-temperatures. The chemical monitoring of the drilling fluid only highlighted some small inflows of relatively cold and saline water with most probably a marine influence. No significant inflow of hot water was observed. Measurements of the static profile of temperature, carried out 6.5 months after the end of the bore-hole drilling, confirmed the data obtained during drilling (Genter *et al.*, 2002) and are characteristic of a temperature conductive pattern along the bore-hole (Fig. 2). This is concordant with the absence of inflows of hot water in the bore-hole. On the whole, one can consider that this bore-hole crossed a fossil hydrothermal system. The absence of thermal anomalies and the lack of permeability noted all along the bore-hole lead to the conclusion that there is no exploitable geothermal resource on the site of Pointe Desgras.

Habitation Carrère bore-hole

The second bore-hole (Habitation Carrère) was drilled between January and February 2001. It reached a 816.15 m depth and was cored from 386 m. Located close to several thermal springs, it was slightly hotter than the first bore-hole (measured maximum temperature of 50°C) and showed the existence of a zone more fractured than that of the site of Pointe Desgras. Moreover, an inflow of moderately hot and saline fluid was observed at 380-400 m of depth and could be directly sampled. The chemical and isotopic characteristics of this fluid will be later described. This permeable zone corresponds to the presence of a fault, characterised by a strong hydrothermal alteration in the massive lava (presence of quartz, carbonate and sulphide minerals).

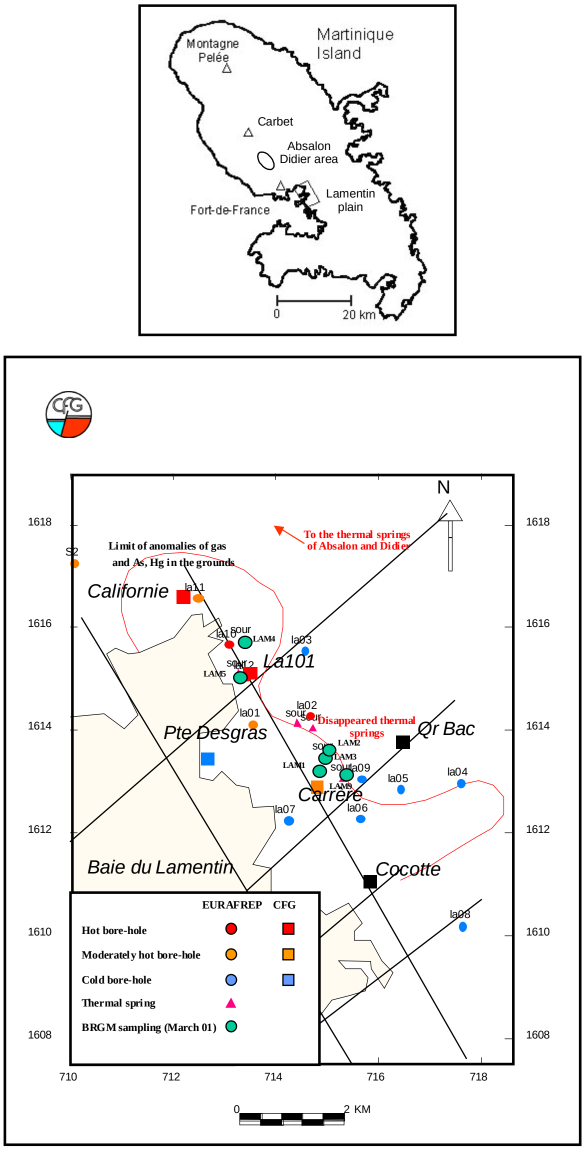

Figure 1. Map of the Martinique and Lamentin plain showing the location of the three new exploratory bore-holes and the sampled neighbouring thermal springs.

The geochemical monitoring of the drilling fluid also made it possible to highlight several small inflows of cold and relatively saline water, indicating a probable marine influence, between 60 and 200 m of depth. No significant inflow of hot water was observed in the major part of the bore-hole but, according to the geochemical results obtained on the drilling fluid, another inflow of fluid with a chemical composition similar to that found between 380-400 m of depth also seems to be present at 600-700 m. Measurements of the static profile of temperature, carried out approximately 5 months after the end of the drilling of the bore-hole (Fig. 2), also confirmed the data obtained during drilling (Genter *et al.*, 2002). They are in a good agreement with the data of the geochemical monitoring insofar as they highlight the existence of two main aquifers: one, between 300 and 425 m of depth (isothermal zone at 50°C) and the other one, between 600 and 650 m of depth (isothermal zone at 46°C). One can, therefore, conclude that no high temperature resources have been found on the site of Carrère.

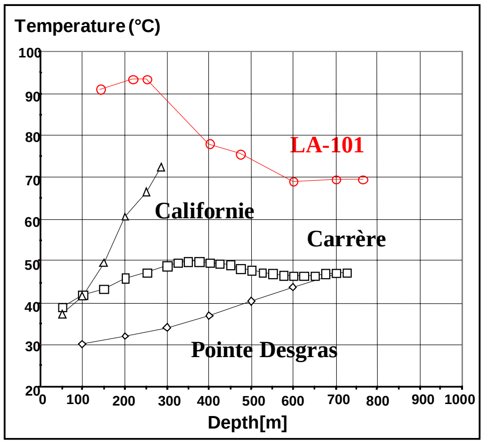

Figure 2. Static profiles of temperature measured in the three new exploratory bore-holes.

Californie bore-hole

The third bore-hole (Californie) was drilled between March and April 2001. It has a depth of 1,000.25 m and was cored from 396.15 m. Located at the north of the Lamentin plain, it was the hottest one. The maximum extrapolated temperature was about 88°C between 400 and 500 m of depth and the temperature at the bottom hole, at 997 m, was 83°C. Geology is slightly different from that observed in the previous bore-hole because the volcano-clastic successions, characterised by volcanic and sedimentary breccia, are developed. The geochemical monitoring of the drilling fluid made it possible to highlight, again, several small inflows of cold and relatively saline water, indicating a probable marine influence between 40 and 200 m of depth. It also showed that from 400 m, several inflows of hot water were crossed by this bore-hole. The main one, observed around 400 m and associated to the highest extrapolated temperature, could be directly sampled and analysed. The analytical results will be later discussed. Because of an obstruction met to 286 m of depth, measurements of the static T profile, carried out approximately 3.5 months after the end of the bore-hole drilling, could be done only down to this depth (Fig. 2). These measurements confirmed, once again, the data obtained during drilling (Genter *et al.*, 2002). A static P-T profile will have to be carried out as soon as the obstruction is eliminated.

FLUID SAMPLING AND ANALYSES

Fluid sampling

During the geochemical monitoring, three fluid samples were collected from the Carrère and Californie bore-holes (two and one samples, respectively). These samples come from the aquifer found at a depth of about 400 m in both bore-holes. A critical analysis of the results obtained during the previous campaigns carried out on the thermal springs of the Lamentin plain (Lopoukhine and Mouret, 1977; Iundt, 1984; Fabriol and Ouzounian, 1985) and the acquisition of new data on elements traces and some isotopes (^{3}H, ^{13}C, ^{14}C, ^{34}S and ^{18}O of the aqueous sulphate, ^{87}Sr/^{86}Sr) were necessary. For this purpose, a campaign of fluid sampling from the thermal springs of the Lamentin plain (LAM 1, 2, 3, 4, 5), neighbouring to the exploratory bore-holes (Fig. 1), and from the thermal springs of Didier and Absalon (LAM 6, 7, 8), located at about 10 km north-west of the Lamentin plain and at the south of the Pitons du Carbet (Fig. 1), was carried out in March 2001. The thermal springs situated on the Lamentin airport zone could not be found because of works done for the new the air terminal. The majority of the thermal springs of the Lamentin plain are characterised by a low flow rate at their emergences. Moreover, these emergences can be numerous and diffuse, which makes difficult any attempt to measure their flow rate and to sample the gases associated with these springs correctly. Two water samples (LAM 9 from the Caleçon river and LAM 10 coming from a 135 m deep bore-hole, at Habitation Carrère), were chosen as reference samples of local surface fresh waters. The local sea water was not again analysed because chemical and isotopic analyses had already performed by Fabriol and Ouzounian (1985).

The results of physico-chemical parameters measured on site such as temperature, pH, Redox potential (Eh) and alkalinity are reported in Table 1 for only some representative fluid samples. The other results are presented in a technical report (Sanjuan *et al.*, 2001). Absolute uncertainty on the measurements of temperature and pH is 0.1°C and 0.05 unit pH, respectively. For the other parameters, relative uncertainty is about 5%. The samples were conditioned on site according to the required specifications for analyses (Sanjuan *et al.*, 2001).

Fluid analyses

With the exception of the isotopic ^{14}C and ^{13}C analyses, which were performed in the BETA ANALYTIC laboratory (Florida, USA), all the chemical and isotopic analyses were carried out in the BRGM laboratories, at Orleans. 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 ± 5% and 15% respectively. The precision on the δD, $\delta^{18}O$ values and ^{3}H activity is ± 0.8‰, ± 0.1‰ and ± 1UT respectively. That on the determination of the $^{87}Sr/^{86}Sr$ isotopic ratio, $\delta^{34}S$ and $\delta^{18}O$ of the aqueous SO_4 and $\delta^{13}C$ is 0.00001, 0.3‰, 0.3‰ and 0.1‰ respectively. Relative uncertainty on the analysis of the ^{14}C activity is around 1 to 2%. Ion balance values lower than 5% suggested a good quality and coherence of the analyses of the aqueous major species. The main analytical results obtained on the fluid samples collected from the exploratory bore-holes during drilling are reported in Table 1. Because of the low amount of water sampled in the bore-holes, the analyses of $\delta^{34}S$ and $\delta^{18}O$ (SO_4), $\delta^{13}C$ and ^{14}C could not be performed. In this table, the results of one analysis representative of the thermal springs of the Lamentin plain (LAM 3) and Absalon-Didier area (LAM 8) are also presented. More detailed results can be found in Sanjuan *et al.* (2001).

INTERPRETATION AND DISCUSSION

Fluid chemical characteristics

In spite of the difference in temperature of the fluids collected from the two exploratory bore-holes, their chemical compositions are very close and homogeneous (Table 1). These Na-Cl fluids have a salinity of about 10-11 g/l and a measured pH around 6.2-6.3. The value of this pH in the formation fluid is most probably lower if it is considered that a CO_2 degassing (acid gas) can have occurred before the fluid sampling. Many gas emanations, made up primarily of CO_2, are observed in the Lamentin plain (Fabriol and Ouzounian, 1985) and CO_2 escapes occurred from the Californie bore-hole, at the end of drilling. The chemical compositions of these fluids are also similar to those of the fluids analysed in the old LA-101 bore-hole and in the neighbouring thermal springs of the Lamentin plain ($T_{emergence}$ ranging from 37 to 58°C). The latter have salinities of about 12-13 g/l and values of pH ranging from 5.8 to 6.3. Once more, these pH values are probably lower because of a CO_2 degassing before fluid sampling.

Carbonate and iron hydroxide deposits, observed at the emergences of the majority of these springs, testify to these phenomena of CO_2 degassing and oxidation of the fluids in contact with the atmosphere. The ternary diagram of the Figure 2 shows that the fluids collected from the two exploratory bore-holes and the thermal springs of the Lamentin plain belong to the same group of waters. This diagram suggests a marked marine influence of these fluids.

Parameter	**CAR b-hole**	**CALIF b-hole**	**LAM3**	**LAM8**
T (°C)	44.0	48.0	58.0	36.3
pH	6.29	6.27	5.87	6.12
Eh (mV)			-109	-2
Alk. (mg/l HCO_3)	1826	1351	738	1345
δD (‰)	-5.5	-5.3	-5.2	-6.7
$\delta^{18}O$ (‰)	-2.1	-1.9	-1.7	-2.8
^{3}H (UT)			< 1	< 1
$\delta^{34}S$ (SO_4) (‰)			20.2	20.8
$\delta^{18}O$ (SO_4) (‰)			10.9	12.2
$\delta^{13}C$ (‰)			-3.5	-2.1
^{14}C age (years)			38000	29740
$^{87}Sr/^{86}Sr$	0.705134	0.705766	0.704944	0.704609
Na (mg/l)	2504	2650	3523	113
K (mg/l)	101	168	175	15.6
Ca (mg/l)	880	824	853	209
Mg (mg/l)	134	138	138	90
Cl (mg/l)	4715	4915	6730	16
SO_4 (mg/l)	285	274	311	2.8
SiO_2 (mg/l)	112	100	79.1	161
NH_4 (mg/l)			2.5	< 0.1
Br (mg/l)	16.5	18.5	22.4	0.041
F (mg/l)	0.2	0.3	0.3	< 0.1
B (mg/l)	6.29	33.3	41.0	0.35
Fe (mg/l)	23.0	90.2	< 0.02	4.82
Sr (mg/l)	13.9	17.6	19.4	0.74
Li (mg/l)	1.18	1.55	0.91	0.04
Ba (µg/l)	330	470	183	104
Mn (µg/l)	2030	1720	332	388
Al (µg/l)	12.0	10.5	< 300	60
Cs (µg/l)	103	182	285	1.0
Rb (µg/l)	450	510	603	35
Ge (µg/l)			12	2
As (µg/l)	73	90	555	35
Cr (µg/l)	< 4.5	< 4.5	150	31
Zn (µg/l)	128	2436	102	11
TDS (g/l)	10.6	10.4	12.6	1.95

Table 1. Selected chemical and isotopic compositions of fluids collected from the Lamentin and Absalon-Didier areas.

The thermal fluids collected from the Absalon-Didier area have very close chemical and isotopic compositions. These $Na\text{-}Ca\text{-}Mg\text{-}HCO_3$ fluids have a moderate salinity (~ 2 g/l) and values of pH between 6.1 and 6.3 (Table 1). These values are probably lower because these fluids are rich in CO_2. Carbonate and iron hydroxide deposits are also observed at the emergences of these springs. The chemical compositions of these fluids are very different from those of the Lamentin plain and classify them in Figure 2, close to the pole bicarbonate, among the group of the fluids considered as peripheral thermal fluids of a geothermal system. The results of the chemical analyses obtained during this study tend to confirm those of the previous studies. This shows a stability of the chemical composition of all the fluids as a function of time, and a relatively low influence of the mixture processes by very superficial waters, during the rise of the thermal fluids at surface.

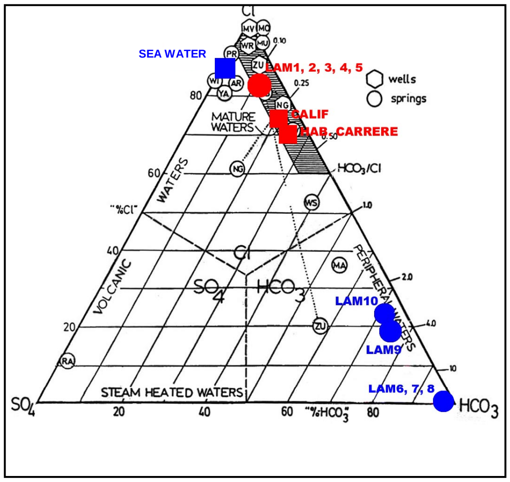

Figure 2. Position of the fluids in a ternary Cl-HCO$_3$-SO$_4$ diagram (Giggenbach, 1991).

Fluid origin and residence time

The concentrations of aqueous Cl, Br and Na as well as the D and ^{18}O contents of the thermal fluids collected from the Lamentin plain indicate they result from a process of mixture between sea water and a fresh water of meteoric origin (Fig. 3). For the fluids sampled from the thermal springs and LA-101, the proportions of mixture are about 30-35% sea water, 70-65% fresh water. For the fluids collected from the new exploratory bore-holes, they are rather about 20-25% sea water and 80-75% fresh water. The process of dilution observed for these last fluids is most probably due to the presence of residual drilling fluid. However, a higher proportion of fresh water of meteoric origin could also explain this dilution. Only a consequent production of these bore-holes, which would ensure the elimination of the drilling fluid, can solve this question.

The linear relations obtained in the diagrams δD-Cl and δ^{18}O-Cl (Fig. 3) allow to estimate the δD and δ^{18}O values corresponding to the fresh water (Cl concentration close to zero), which mixes with sea water. These values are around -8/-6 and -2,4‰, respectively, and are close to those of the fluids collected from the thermal springs of Didier and Absalon. This suggests that the fresh water end-member, which constitutes a part of the thermal fluids collected from the Lamentin plain, may come from an area of water supply similar to that of the thermal springs of Didier and Absalon. This area could be situated in the massif of the Pitons du Carbet (Fig. 1). The use of an isotopic altitude gradient and thus, the determination of the altitude of the area of fresh water supply, were not possible.

The linear relations of the diagrams Cl-Mg, Cl-SO$_4$, Cl-Sr, Cl-B, Cl-Rb and Cl-Cs (Fig. 4; Sanjuan *et al.*, 2001), in which sea water is not one of the end-members of mixture, indicate that the difference in salinity between the fluids collected from the bore-holes and the thermal springs of the Lamentin plain is not caused by superficial infiltrations of sea water.

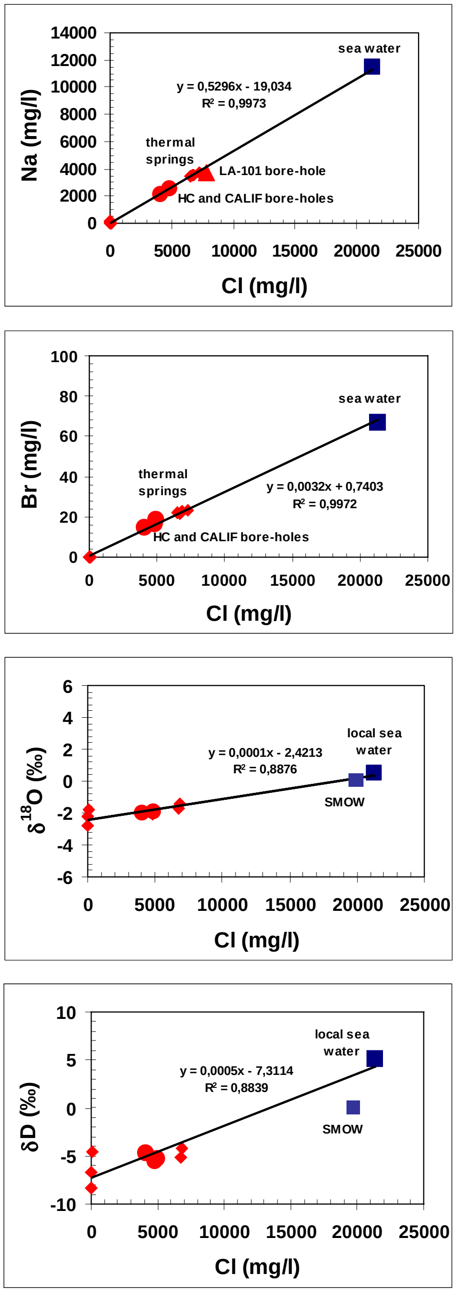

Figure 3. Cl-Na, Cl-Br, Cl-δD, Cl-δ^{18}O diagrams for the fluids collected from the exploratory bore-holes and the thermal springs.

The surface water samples (LAM 9 and 10) have ^{3}H activities equal to 2, which seems in agreement with the values measured on current precipitations from San Juan (Puerto Rico). The analytical results show the ^{3}H absence in the fluids collected from the thermal springs of the Lamentin plain. Given the low ^{3}H activities of the current rainfalls, it is difficult to conclude about the residence time for the thermal fluids. The ^{3}H activity measured in the water of Didier in 1994 (3 UT) and that analysed on the water of Absalon (< 1UT) in this study make also difficult any conclusion on the residence time of these fluids. As the ^{14}C activities analysed on the fluids collected from the thermal springs of the Lamentin plain and Didier are significantly influenced by CO_2 emanations of magmatic origin (null ^{14}C activity; see next chapter), the ages estimated for these fluids cannot be regarded as representative (Table 1). These activities rather reflect the carbon abundance of magmatic CO_2, which is dissolved in water.

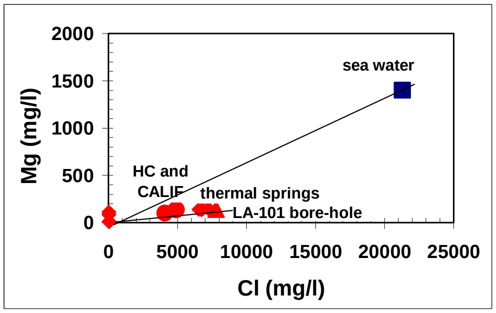

Figure 4. Cl-Mg diagram for the fluids collected from the exploratory bore-holes and the thermal springs.

Water-rock-gas interaction processes

Compared to a sea water diluted by fresh water, the fluids collected from the two exploratory bore-holes and the thermal springs of the Lamentin plain are enriched in Ca, HCO_3, SiO_2, Sr, Ba, B, As, Fe, Mn, Li, Rb, Cs and Ge. They are depleted in Mg and SO_4 (Fig. 4). These results are characteristic of interaction processes between water and volcanic rocks (basalts, andesites...), which have been observed in laboratory and in natural environment (Sanjuan *et al.*, 1990). The relatively high concentrations of dissolved SO_4 and Mg, compared with those of a high temperature fluid (concentrations close to zero), suggest the existence of moderate deep temperatures. The absence of ^{18}O enrichment from the rocks, in the fluids (Fig. 3), consolidates this assumption but can also indicate a high water-rock ratio. In spite of the sea water presence ($^{87}Sr/^{86}Sr \approx 0.709$), the isotopic Sr ratios of the fluids collected from the two bore-holes and from the thermal springs of the Lamentin plain are close to those of the andesites (0.704-0.705), which suggests that these fluids have a relatively significant degree of interaction with the surrounding rocks and that their residence time must be rather long. This confirms, in addition, that there is no sea water infiltration at surface and that the relatively high SO_4 and Mg concentrations are rather due to a moderate temperature. The values of $\delta^{34}S$ and $\delta^{18}O$ of the dissolved SO_4 measured on the fluids collected from the thermal springs of the Lamentin plain show that the dissolved SO_4, in spite of the presence of reactions which tend to decrease its concentration in solution, still keeps its marine signature (Faure, 1986; $\delta^{34}S \approx 20‰$ and $\delta^{18}O \approx 9.7‰$ for sea water). Consequently, it can be concluded that the isotopic ^{18}O exchanges between SO_4 and water are rather rare.

The values of partial pressure of CO_2 (P_{CO2}) computed at surface conditions for the exploratory bore-holes and thermal springs using the EQ3NR geochemical code vary from 0.7 to 1.2 bar (Sanjuan *et al.*, 2001). Because CO_2 degassing could occurred before the pH measurement (before or at the emergence of the thermal springs, at the well head), it is probable that the pH values are lower and that the P_{CO2} are higher. After calculation, the isotopic ^{13}C values measured in the fluids collected from the thermal springs of the Lamentin plain and Didier-Absalon lead to ^{13}C signatures in the CO_2 gas emanations ranging between -6 and -4.5‰. These are characteristic of a deep magmatic origin (Faure, 1986; $-8.6‰ < \delta^{13}C < -2.3‰$). All these data are in a relatively good agreement with those found by Pedroni *et al.* (1999) for ^{13}C and $^{3}He/^{4}He$, directly measured on the gases from the thermal springs of the Lamentin plain, Didier and Absalon. However, these authors sometimes suggest the existence of a slight contamination of these emanations by local organic sediments.

As indicated by the saturation calculations performed using the EQ3NR code at temperature conditions of spring emergences or well head, all the fluids are saturated or over-saturated with respect to carbonate minerals such as calcite, disordered dolomite, strontianite or witherite. This explains why one observes the formation of this type of minerals at the emergence of many springs. The high values of P_{CO2} and degassing, at surface, are mainly in charge of these precipitations. All the fluids are under-saturated with respect to anhydrite, fluorite and celestite and over-saturated with respect to chalcedony and quartz. The Redox reactions were not considered in this study. If we assume that the aqueous Al is controlled by an equilibrium between kaolinite and water, the majority of the fluids is under-saturated with respect to albite but is saturated or over-saturated with respect to K-feldspar and montmorillonites (smectites). As that is observed on numerous CO_2 thermal springs, the formation of smectites at the emergence of these springs is strongly probable. The fluids from the Lamentin plain are saturated or over-saturated with respect to muscovite and barite whereas the fluids of the Absalon-Didier area are under-saturated with respect to these minerals. Saturation calculations performed at 90-120°C using the EQ3NR geochemical code and assuming that all the fluids are in equilibrium with respect to calcite and kaolinite show that the values of deep P_{CO2} can be relatively high (about 7 to 24 bar). The temperatures for the saturation calculations were selected by considering the deep temperatures estimated using the chemical geothermometers (see next chapter). If these values had been higher, the P_{CO2} would be still higher, which makes improbable the existence of deep temperatures higher than 120-130°C. All the fluids are saturated with respect to disordered dolomite and chalcedony (or quartz, if calculations performed at 120°C). The Lamentin fluids are saturated with respect to Ca-Mg-Na montmorillonites and muscovite while the fluids from the Absalon-Didier area are only saturated with respect to Na-K montmorillonites. All the fluids are under-saturated with respect to albite, K-feldspar and strontianite. They remain under-saturated with respect to anhydrite, fluorite and celestite. Only the fluids collected from the exploratory bore-hole are saturated with respect to barite and witherite.

Chemical Geothermometers

The triangular diagram of the Figure 5 indicates that all the fluids are located in the zone classified like that of immature fluids, out of a full equilibrium with the rock. This is not an indication of high deep temperature. However, all the thermal fluids collected from the Lamentin plain are closer to the qualified zone of partial equilibrium than those of the Absalon-Didier area, which are near the Mg pole. These properties often characterise CO_2-rich waters and result in a significant discordance between the results obtained using the chemical geothermometers. The application of the latter must thus be carried out with much caution.

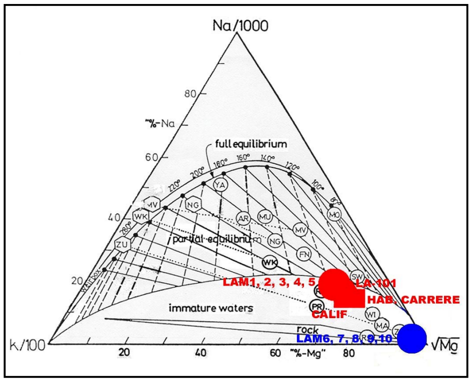

Figure 5. Position of the fluids in a ternary Na-K-Mg diagram (Giggenbach, 1991).

The main chemical geothermometers were used in this study. Only the temperatures estimated for some representative fluids are reported in Table 2. The geothermometers such as Na/Li of Kharaka *et al.* (1982), SiO_2, Na/K/Ca(Mg), K/Mg (Nicholson, 1993), Na/Rb, FK and Mn/K (Michard, 1990), applied on all the Lamentin fluids, give concordant temperatures of about 90-130°C (Table 2). These values are close to the measured values in the LA-101 and Californie bore-holes.

Temperature (°C)	CAR b-hole	CALIF b-hole	LAM3	LAM8
T_{surface}	44	48	58	36
T_{Quartz}	144	138	125	166
$T_{\text{Chalced.}}$	116	109	96	138
$T_{\text{Na/K (Michard)}}$	117	154	133	235
$T_{\text{Na/K (Fournier)}}$	149	180	163	246
$T_{\text{Na/K/Ca}\ (\beta=4/3)}$	148	172	164	170
$T_{\text{Na/K/Ca}\ (\beta=1/3)}$	134	161	166	64
$T_{\text{Na/K/Ca (Mg)}}$	87	87	88	30
$T_{\text{Ca/K}}$	173	208	210	114
$T_{\text{K/Mg}}$	91	104	105	52
$T_{\text{Na/Li (Kharaka)}}$	112	121	89	103
$T_{\text{Na/Li (Fouillac)}}$	41	50	17	31
$T_{\text{Mg/Li}}$	67	73	61	8
$T_{\text{K/Sr}}$	148	174	174	125
$T_{\text{Na/Rb}}$	88	90	87	105
$T_{\text{Na/Cs}}$	69	79	83	46
T_{FK}	103	130	132	< 42
$T_{\text{Fe/K}}$	70	63	> 425	30
$T_{\text{Mn/K}}$	70	93	131	37
$T_{\text{18O (SO4-H2O)}}$			142	115
$T_{\text{estimated}}$	110 ± 20	110 ± 20	110 ± 20	110 ± 20

Table 2. Deep fluid temperatures estimated using the main chemical geothermometers (Nicholson, 1993; Michard, 1990; Sanjuan et al., 2001).

On the other hand, the Na/Li geothermometer of Fouillac and Michard (1981) established from a statistical study of data obtained in granitic and volcanic medium yields temperatures about 40-50°C (Table 2). Apparently, the relationship determined by Kharaka *et al.* (1982), using chemical compositions of fluids collected from oil sedimentary basins, seems to be more reliable in the present case and indicates the strong influence of the CO_2 system on this geothermometer. The K/Mg geothermometer gives relatively good results because it is rather based on an equilibrium reaction between alumino-silicate minerals. According to the saturation calculations, the fluids seem to be close to the equilibrium with respect to muscovite and Mg-montmorillonite. The Na/K and Na/K/Ca geothermometers give overestimated temperatures when applied on sea water (about 140-180°C). As aqueous Na and K are strongly influenced by the sea water-fresh water mixture in the fluids of the Lamentin plain, these geothermometers rather yield higher values, even if a slight enrichment in K is observed compared to a diluted sea water. The isotopic ^{18}O (H_2O-SO_4) geothermometer gives slightly higher values of temperature. However, as the marine signature of this isotope remains still very pronounced, it is not sure that the isotopic equilibrium is fully reached. The gas geothermometers such as $CO_2/H_2/CH_4$, H_2/Ar; CO_2/CH_4, used on results of previous studies, also give concordant temperatures (T < 120°C; Sanjuan *et al.*, 2001). For the fluids from the Absalon-Didier area, only the geothermometers such as silica (chalcedony), Na/Li of Kharaka, Ca/K, Sr/K, Na/Rb and ^{18}O(H_2O-SO_4) give convergent values of temperature, ranging from 100 to 130°C (Table 2). As these fluids are not saturated with respect to muscovite, contrary to the fluids of the Lamentin plain, one can note that the K-Mg geothermometer is not applicable. It is obvious that the fluids collected from the Absalon-Didier area and Lamentin plain do not derive from the same deep reservoir.

CONCLUSION

Compared with the previous geochemical data obtained on the fluids of the old LA-101 well and the thermal springs of the Lamentin plain, these new results have allowed to better know and understand the geothermal system of this area with regard to the temperature of the deep fluids, their origin, their residence time and their mode of circulation, the nature of the rocks constituting the reservoir and the processes which can take place during the fluid rise and the fluid cooling (mineral deposits, degassing…). No major evidence of a high temperature geothermal reservoir was observed in the Lamentin and Absalon-Didier areas. The deep temperature of the geothermal fluid in both areas was estimated to be about 90-130°C. All the results suggest that the temperature gradient increases towards the north of the Lamentin plain where the geothermal reservoir would be rather located. According to the geochemical results, the Na-Cl and CO_2-rich geothermal fluid, constituted around 30% sea water and 70% fresh water, would derive from a reservoir situated near sea water, between the Lamentin plain and the Absalon-Didier area. This fluid would flow out laterally from NW to SE at relatively low depths. Additional works performed in the Carrère and Californie bore-holes, such as relatively long term production tests, would permit to obtain more hydrodynamic characteristics (estimations of flow and reservoir capacity, etc.) and a more accurate chemical and isotopic composition of the low temperature geothermal fluid.

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