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PRELIMINARY GEOLOGICAL RESULTS OF RECENT EXPLORATORY DRILLINGS IN A GEOTHERMAL FRACTURED RESERVOIR AT LAMENTIN (FRENCH WEST INDIES, MARTINIQUE)

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ABSTRACT

A new geothermal exploration survey has been conducted in 2001 within the Lamentin Plain near Fort de France (Martinique, French West Indies. Three vertical wells, which were drilled to 1-km depth, penetrated volcanic and volcano-clastic formations. An exhaustive geological study was carried out on core in order to identify the fracture network in the basement. During the drilling operations, temperature data were also acquired on site. The compilation of the geological and geothermal data collected within these 3 new deep exploration wells shows the superimposition of several hydrothermal events that could explained the present-day geothermal system of the Lamentin in Martinique.

INTRODUCTION

During on a previous geothermal exploration phase done 30 years ago in the Lamentin area in Martinique (Fig. 1), a shallow depth geothermal anomaly was evidenced by Eurafrep (1969). BRGM performed additional survey in 1980-85 (Chovelon, 1984). A recent drilling exploration phase was carried in 2000/2001. The aim of this exploration project was to improve the data on the geothermal reservoir (200-400-m) and to check the occurrence of a possible high enthalpy reservoir at depth. Three vertical wells, namely Pointe Desgras, Carrère and Californie, were drilled (Fig. 2) by rotary mode down to 400 m and then were fully cored to 939.55, 816.15 and 1,000.15 m depth respectively (CFG, 2001).

On the cored sections, a full geologic survey was done on-site. It included a complete structural analysis of the cores in terms of fracture studies (fracture density, hydrothermal filling, fracture geometry) and a detailed lithologic description of the cores.

GEOLOGICAL BACKGROUND

Martinique is a volcanic island belonging to the Lesser Antilles arc, which draws an 850-km length curve. The plain of Lamentin is located on the mid-west part of the Martinique Island, close to Fort de France and constitutes an alluvial zone covering a surface of 100 km^2 approximately (Fig. 1). The surface geology is known from the 1:50,000 geologic map (Westercamp *et al.*, 1989). The area of Lamentin corresponds to a major graben zone (Fig. 2) limited by NW-SE faults and intersected by the NE-SW faults (Chovelon, 1984).

Based on the geological map of Martinique and previous drilling reconnaissance, several cartographic faults are known in the area of Lamentin (Fig. 2). The northern part of the Lamentin graben is limited by the Lamentin fault oriented N60E, which is a normal fault of plurikilometric size. The eastern border of the graben is limited by a hidden fault oriented N140E (Petit Bourg fault). A suspected fault with the same orientation is suspected in the western part of the Lamentin graben. Two parallel faults oriented N115E and dipping north are known close to the Lamentin fault. They cut the Miocene andesitic formation. In the northwestern part, two supposed cartographic faults oriented N140E are also known and cut the Miocene andesitic formations.

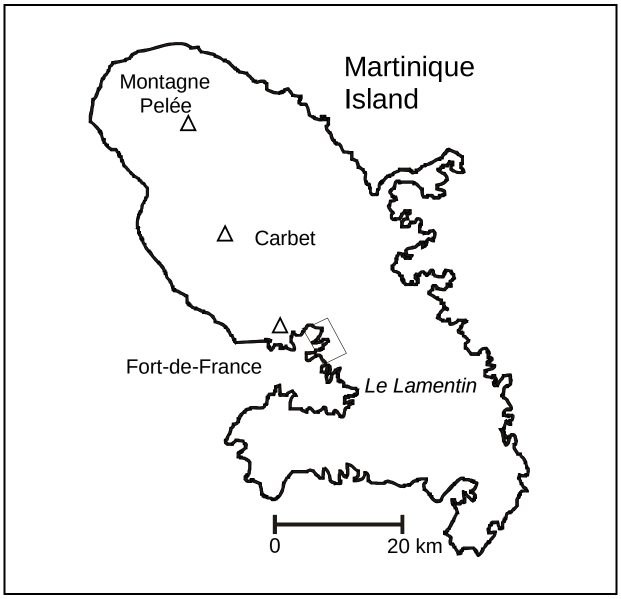

Figure 1. Location of the geothermal exploration zone of Lamentin in Martinique.

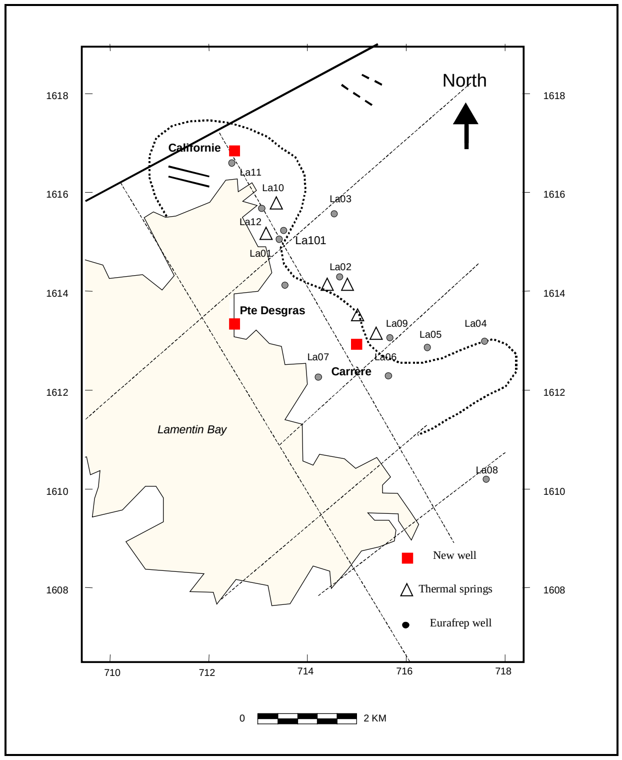

Figure 2. Map showing the locations of the thermal springs, the old and the recent geothermal wells, the fault system and the envelope of the geochemical anomalies in As, Hg, CO_2, Helium (dotted line).

PRESENT-DAY GEOTHERMAL ACTIVITY

The occurrence of many thermal springs localized in the area of Lamentin highlighted the presence of a geothermal resource at depth. The thermal springs whose fluid temperatures vary between 34 and 58°C are aligned along an axis oriented NNW-SSE to NW-SE (Fig. 2). Flow rate is generally low and their chemical compositions are characterized by a CO_2 rich NaCl fluid (Sanjuan *et al*., 2002). Moreover, geochemical studies of surface highlighted anomalies in As, Hg and gas in the grounds (Radon, CO_2, Helium) which form an envelope lengthened according to structural directions NW-SE and NE-SW (Fig. 2). Silica travertine deposits of 300,000 years approximately are known on the surface.

These current hydrothermal activity indicators had led to a first geothermal exploration phase (Eurafrep, 1969). 12 relatively shallow depth wells, La1 to La12, had been drilled (Fig. 2). The wells located in the northern part of the zone (La1, La2, La10, La11, La12) present the most interesting thermal anomalies. A deep well LA101 (771 m) crossed an artesian reservoir between 155 and 250 m of depth producing a CO_2-rich fluid with a temperature close to 90°C rich. Its chemical composition is equivalent to that of the thermal springs of surface. This reservoir zone corresponds to a network of inclined fractures characterized by silica deposit (Eurafrep, 1969).

THE POINTE DESGRAS WELL

The first exploration well was drilled in the central part of the area of interest (Pointe Desgras), where extensive silica travertine was deposited (Fig. 2). It was drilled to 939.55 m. The quality of the coring was excellent and recovery is practically 100%. No circulation loss has been observed during drilling even during the crossing of the major fault to 710 m, which was completely sealed by hydrothermal product. The temperature measured at 931 m at the end of the drilling is 58.7°C. The thermal profile being quasi-rectilinear (Fig. 3) suggests a purely conductive thermal gradient of about 4°C/100 m (CFG, 2001).

Lithologic Characterization

From cuttings and core analysis, this well penetrated in the upper part sands and gravels, and volcano-detritic formations. Deeper, it crossed the volcanic basement characterized by thick andesitic flows and lahar deposits. In the lower part, massive andesitic lavas, intrusions and volcano-clastic formations were encountered.

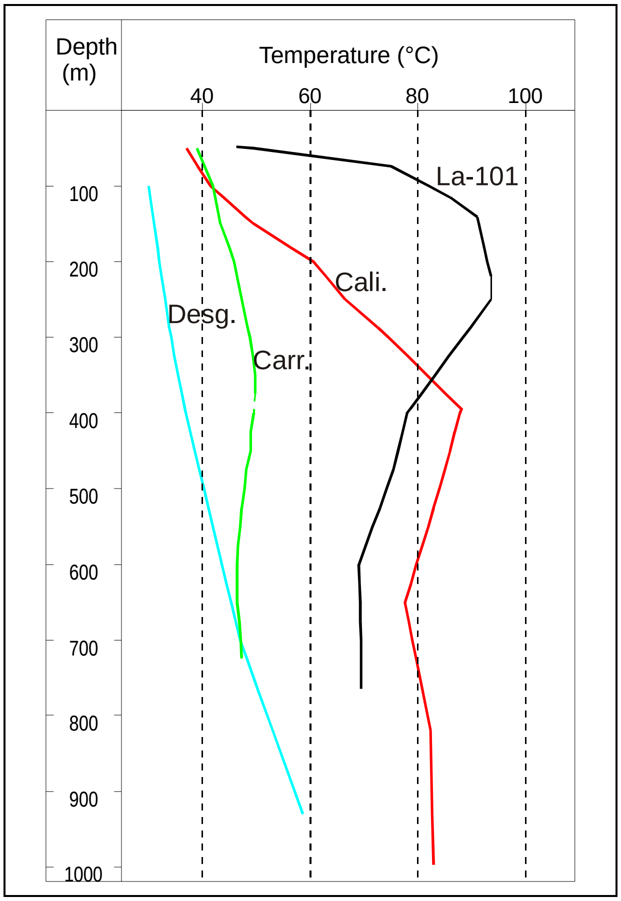

Figure 3. Representative temperature profile measured in the 4 deep wells drilled in the Lamentin area.

Fracture Characterization

Fracture typology

The small-scale fracture types are mainly joints (52), tension gashes (392), faults (76), normal faults (19) and sinistral shears (2). The ratio between the number of faults and the total number of the fractures is about 18%. Most of the faults observed on cores correspond to highly dipping normal faults. The tension gashes filled with calcite also shows a geometry consistent with an apparent normal fault movement. In the thickest fault zones, there is a systematic tendency to the development of hydraulic breccia with secondary calcite cement.

Several fault zones were identified on cores (Fig. 4). The most significant one is a vertical brecciated fault localized between 692 and 715 m depth (Fig. 4). The hydrothermal white-greenish deposits are geodic with calcite, sulphides and clays. In this zone, the cumulative fracture width reaches approximately 30 cm thick. Residual free aperture is about 10 mm in the geodic part of the calcite filling.

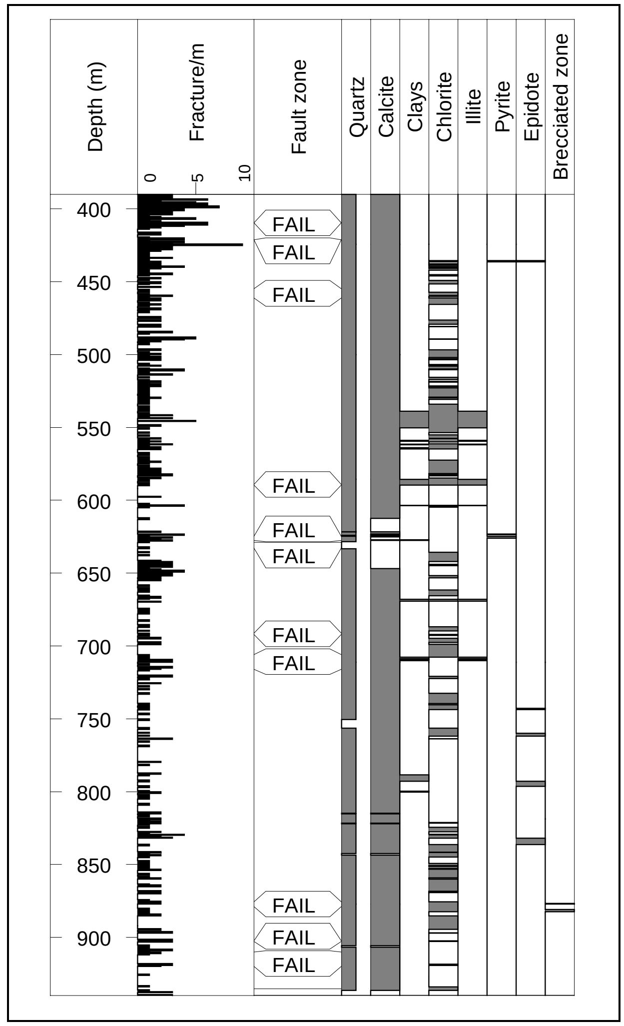

Figure 4. Fracture density, major fault location, and vertical distribution of the hydrothermal fillings sealed fractures in the Pointe Desgras well.

Fracture density and hydrothermal alteration

From core analysis, sealed fractures show an average linear fracture density slightly below 1 fract./m. The density is slightly higher in the upper part of the cored well between 390 and 430 m, then decreases very slightly or remains stable with the depth. However, in some localized sections, some fracture concentrations occur such as to 650 m (Fig. 4). The density of fractures is relatively uniform with depth suggesting a rather homogeneous distribution. Based on core analysis, the cumulative fracture width of the hydrothermal fillings is 2,412 m. This value represents an equivalent fracture porosity of approximately 0.5% now completely sealed.

The fractures are systematically sealed by hydrothermal deposits with calcite and quartz. Epidote appears very locally in the fractures starting from 430 m but is well represented only below 725 m. In the major fracture zones, clays and pyrite are associated with calcite and quartz. Clays of chlorite type are well represented according to the depth. They do not seem specifically associated with the fractures zones.

Fracture geometry

The cores are not oriented. However, we can deduce some relevant structural information on the dips and the relations between families of fractures. The upper part of the Pointe Desgras well between 390 and 450 m is marked by the presence of two nearly-vertical sets of tension gashes and faults. These fracture sets are orthogonal. A nearly horizontal fracture set made of joints is also present (Fig. 5). Below, between 463 and 854 m, only one fracture set steeply dipping is present.

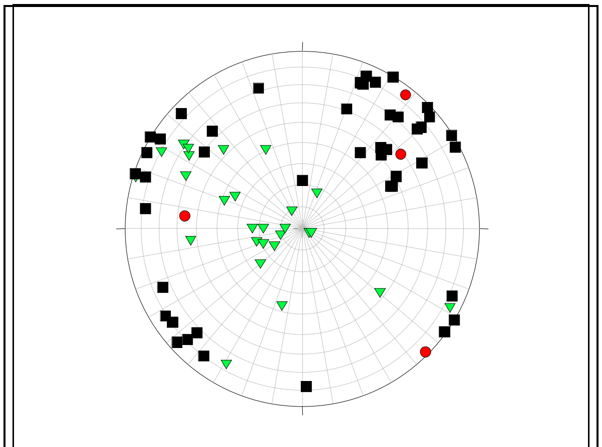

Figure 5. Example of stereographic projection (Schmidt plot, Upper Hemisphere), of fracture poles measured on Pointe Desgras cores. North is fictitious.

Relationship with the Present-Day Geothermal System

There is no evidence of present fluid circulation in the Pointe Desgras well. Temperature conditions are low with a maximum of 58°C. Fractures are sealed by hydrothermal deposits. The occurrence of epidote, which generally crystallizes above 200°C, is ascribed to a previous high temperature, fossil hydrothermal activity.

THE CARRERE WELL

The second well, Carrère, was carried out in the southern part of the area of interest in a zone where there are thermal springs (Fig. 2). It was drilled in destructive mode to 386.70 m and then cored to 816.15 m. The quality of the coring was excellent (96%) except in some fractured zones. Indeed, several permeable zones characterized by partial or total mud losses (386-393, 412-428, 469, 498, 690 m) were observed during drilling. The temperature measured at 100 m depth is about 40°C (Fig. 3). Deeper, the temperature increases regularly down to 350-375 m where it reaches 50°C in the major mud losses zone. At the bottom hole, the temperature remains still low with 47°C.

Lithologic Characterization

In the upper part, this well penetrated the formations similar to those encountered in the Pointe Desgras well (coarse-grained sands, gravels and volcano-detritic formations). Deeper, it crossed the volcanic basement characterized by thick massive andesite lavas belonging to an intrusive complex.

Fracture Characterization

Fracture typology

The small-scale fracture types mainly are tension gashes (475), faults (104), normal faults (12), reverse faults (6) and sinistral shears (5). The ratio between the number of faults and the total number of the fractures is about 21%. Most of the faults are normal faults with high dipping value in agreement with the general graben structure. The shear faults are localized around 517 m depth apart from the major fracture zones. The reverse faults are grouped around 414 m within a wall-rock zone of a major fault or in low fractured zone (431 m).

In the cored section, many fractured and altered zones were encountered. They correspond to geodic mineral-bearing zones with silica, sulphides (pyrite, galena), clays and locally calcite. They are characterized by a significant halo of hydrothermal alteration. For example between 368 and 401 m, this fracture zone is correlated with the mud losses, bad core recovery and outflow of geothermal fluids observed during drilling. The principal permeable zones are localized between 413-428 m, 471-473 m, and 496-502 m. Deeper, other less developed fracture zones occur and they are characterized by hydraulic breccia with calcite cement (645, 725, 777 m).

Fracture density and hydrothermal alteration

In the Carrère well, the distribution of fractures versus depth shows low fracture content zones which alternate with high fracture content zones (Fig. 6). Most of the fractures corresponds to a small-scale fractures plugged showing an average linear fracture density of slightly below 1.5 fract./m. The most fractured zones correspond overall to the zones which present the thickest fractures (500, 610, 645, 730 m).

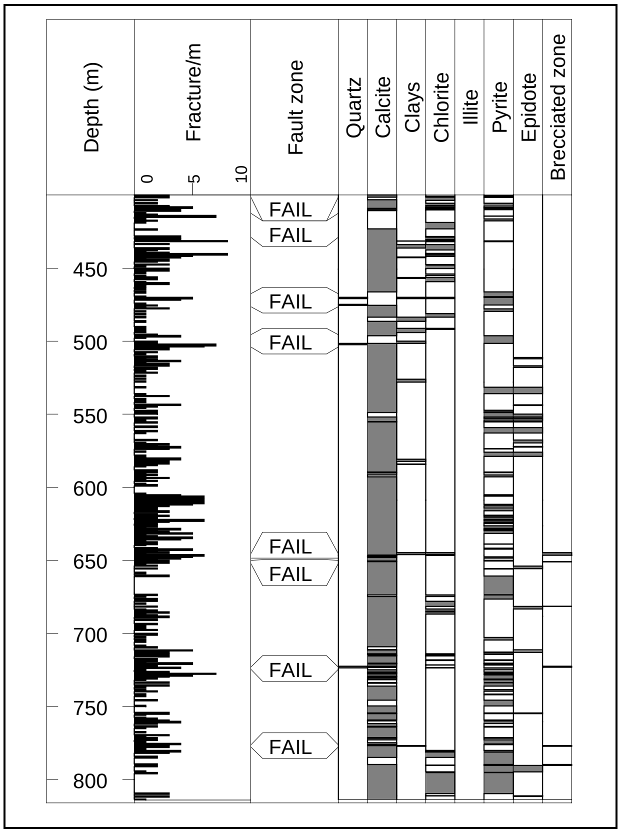

Figure 6. Fracture density, major fault location, and vertical distribution of the hydrothermal fillings sealed fractures in the Carrère well.

Based on core analysis, the cumulative fracture width of the hydrothermal fillings is 3,308 m. This value represents an equivalent fracture porosity of approximately 0.8%. Calcite is ubiquitous and filled tension gashes mainly. The chlorite appears in the upper part of the coring (400-500 m) and more sporadically in-depth towards 670 and between 770 and 800 m (Fig. 6). The pyrite is abundant and seems dominating when the chlorite is lacking except in the major fault zones where these minerals are associated in many microcracks. Epidote is present at 510 m. In the fracture zones, calcite is missing, and silica associated with clays and sulphides dominates in the fractures. In the permeable fault zone located around 390 m, detailed mineralogical studies in progress show the presence of kaolinite.

Fracture geometry

The Carrère well shows at least one vertical fracture set made of tension gashes or faults. Between 407 and 442 m, a nearly horizontal fracture set occur made of calcite joints. Fracture sets with oblique dip are also present (415, 455, 610, 678 m). Very locally, two orthogonal fracture sets with high dipping values are present (412, 716 m).

Relationship with the Present-Day Geothermal System

Temperature profile in the Carrère well shows a maximum temperature of 50°C around 400 m depth (Fig. 3), highlighting a lateral outflow for the shallow hydrothermal system. It is correlated with a large-scale fault characterized by a strong hydrothermal alteration occurring both within the hosted-rock (intense wall-rock effect) and within the fractures (geodic quartz, clays, carbonates, sulphides). Kaolinite minerals seem preferentially associated with the permeable fractures. No significant permeable drain was observed in the deeper part of the well. As in Pointe Desgras well, the occurrence of epidote is related to a previous high temperature hydrothermal event, now extinct.

THE CALIFORNIE WELL

The third well was carried out in the Californie District, in the northern part of the Plain of Lamentin in a marshy ground (Fig. 2). It was drilled in destructive mode to 398.14 m then cored to 1,000.25 m. The coring quality was excellent (97%). The Californie well is the hottest and the most permeable of the three exploratory wells drilled during this reconnaissance phase. The principal zones of losses are localized around 300 m of depth, and between 398 and 413 m where the core recovery was poor. This permeable drain would produce hydrothermal fluids characterized by a temperature of 85-90°C (Fig. 3). Its is correlated with the shallow reservoir evidenced in the neighboring well, LA101, between 150 and 250 m depth (Eurafrep, 1969).

Lithologic Characterization

In its upper part, this well penetrated the same layers that in the other wells (sand, gravel, conglomerate). Deeper, it crossed volcano-clastic formations (silt, sandstone, conglomerate) and brecciated deposits related to sub-marine volcanic activity. As in neighboring LA101 well, no thick massive laves were encountered in the Californie well.

Fracture Characterization

Fracture typology

The small-scale fracture types are mainly tension gashes (380), fractures without filling (25), faults (115), normal faults (14), sinistral shears (3) and dextral shears (3). 34 undetermined faults show a dip slip movement. The ratio between the number of faults and the total number of the fractures is about 25%. Most of the faults observed on cores correspond to highly dipping normal faults. Just below the permeable zone, there are 10 normal faults localized between 427 and 434 m which are associated with the dextral faults. The calcite bearing tension gashes also show a geometry consistent with normal fault kinematics. Sinistral shear faults are localized between 566 and 605 m.

Fracture density and hydrothermal alteration

In the cored section, the average linear fracture density is the lowest of the 3 exploration wells done with 0.92 fract./m. The fracture content versus depth is not homogeneously distributed. There are zones moderately to slightly fractured (505-800, 925-1000 m) which alternate with zones completely depleted in fracture (450-505, 800-880, 900-925 m). The most fractured zone made of many normal faults, located around 430 m, shows the most significant hydrothermal filling width. Fractures are very thin and some of them are characterized by the lack of hydrothermal filling, in particular below 800 m depth. The fracture porosity deduced from fracture width is about 0.4%. The distribution of the fractures is heterogeneous and a relationship to lithology seems dominating. Indeed, there is a vertical zoning between the occurrence of fractures and lithology. This zoning is illustrated on the log of fracture fillings versus depth (Fig. 7). We successively observe some interval of depth with calcite (390-410, 540-600, 740-820, 885-1000 m), then with silica (450-530, 850-885 m), and with clay (445-450, 600-740 m). Those depth intervals match with the encountered lithology formations. For example, calcite deposit is well correlated with occurrence of volcanic clasts.

The zone of permeable outflow where the core recovery was weak (396.15-402.70 m) corresponds to altered sandstone. Mineralogical studies in progress show the occurrence of kaolinite in this permeable zone. Another water outflow is suspected below 770 m. It could correspond to a zone of fault located between 760 and 782 m.

Fracture geometry

Californie well only shows a principal highly dipping fracture set with tension gashes and/or faults. In the upper part (426-435 m), faults define an oblique fracture set. The zone 426-435 m, made of oblique faults, is localized just below the permeable zone and could correspond to the lower part of the permeable drain intersected by the well.

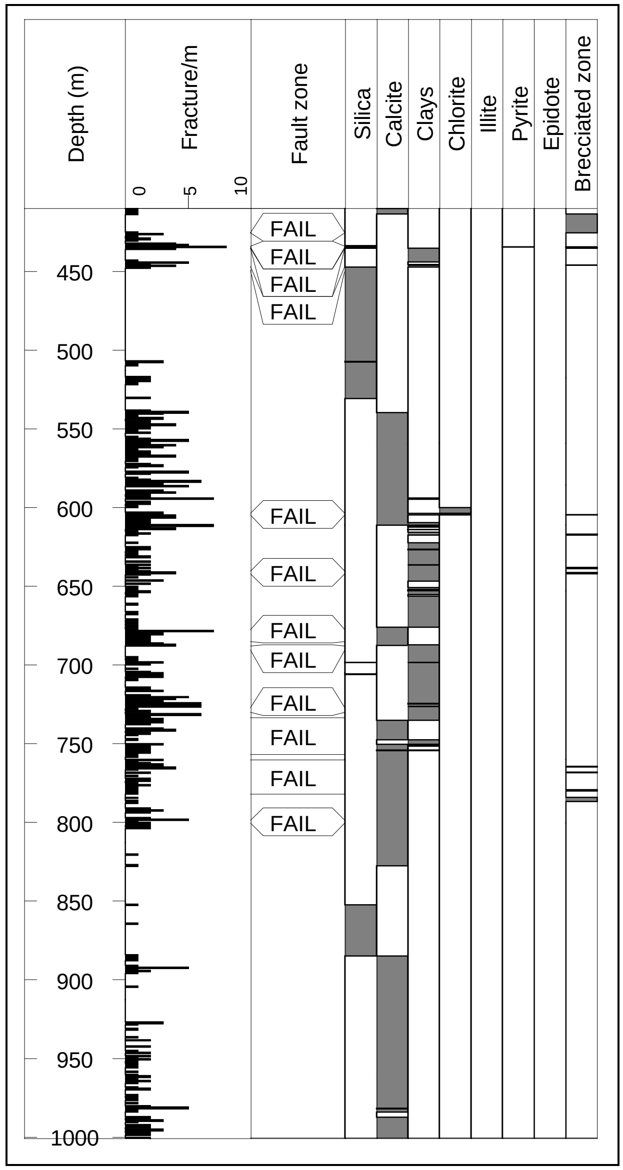

Figure 7. Fracture density, major fault location, and vertical distribution of the hydrothermal fillings sealed fractures in the Californie well.

Relationship with the Present-Day Geothermal System

Within the third well, Californie, geology is slightly different with a more developed volcano-clastic succession characterized by volcanic and sedimentary breccia. The maximum extrapolated temperature is around 88°C around 400 m (Fig. 3). It correlated with a main fault zone which show evidences of permeability during drilling operations. Below 400 m, temperature decreases slightly. Bottom temperature was 83°C at 997 m. This permeable and hot well shows a relatively low fracture content by comparison with the two other exploration wells. However, the fault percentage is highest in the Californie well. As in the Carrère well, mineralogical studies show that the permeable fracture location is well correlated with the occurrence of clay minerals (kaolinite).

MODEL OF THE HYDROTHERMAL SYSTEM

The results of the geothermal exploration done in the Lamentin Bay has improved the knowledge of the shallow geothermal resource evidenced 30 years ago by Eurafrep. The three recent wells intersected shallow permeable faults or fracture zones. Most of the faults or fractures collected on the cores are consistent with normal faulting and thus the structure of the Lamentin graben. Fault zones produced hydrothermal fluids with a maximum temperature of 90°C. Temperature profiles recorded in these wells (Fig. 3) suggest the occurrence of a lateral outflow flowing from the NW to the SE (Fig. 8). This lateral outflow appears to be controlled by the border fault of the Lamentin graben striking N140E (Petit Bourg fault) but also by the N115E fault reported on the geological map located in the vicinity of the Californie well (Westercamp et *al*., 1989). Origin of fluids could be partly related to a water supply coming from the *Pitons du Carbet* volcano (Sanjuan *et al*., 2002). Spatial distribution of the hot springs as well as the shape of the isotherms 40 and 80°C (at 100-m depth) well agrees with this model. Pointe Desgras well appears to be located outside the geothermal outflow (Fig. 8). However, data provided by this well indicate the existence of the fossil, high temperature hydrothermal system developed in the central part of the Lamentin graben. Silica travertine deposits and geochemical anomalies (As, Hg) in soils appear now also to be related to this past hydrothermal activity.

CONCLUSION

The present-day low temperature hydrothermal system is controlled by the fault system oriented NW-SE, which determines the structure of the Lamentin graben. The current indices of the hydrothermal activity are concentrated in the northern part of the tectonic graben in relation to a fluid circulation coming from the NW. The low temperature hydrothermal system of Lamentin is superimposed on a fossil high temperature system which had been active in the central part of the Lamentin graben as exemplified in Pointe Desgras and Carrère wells.

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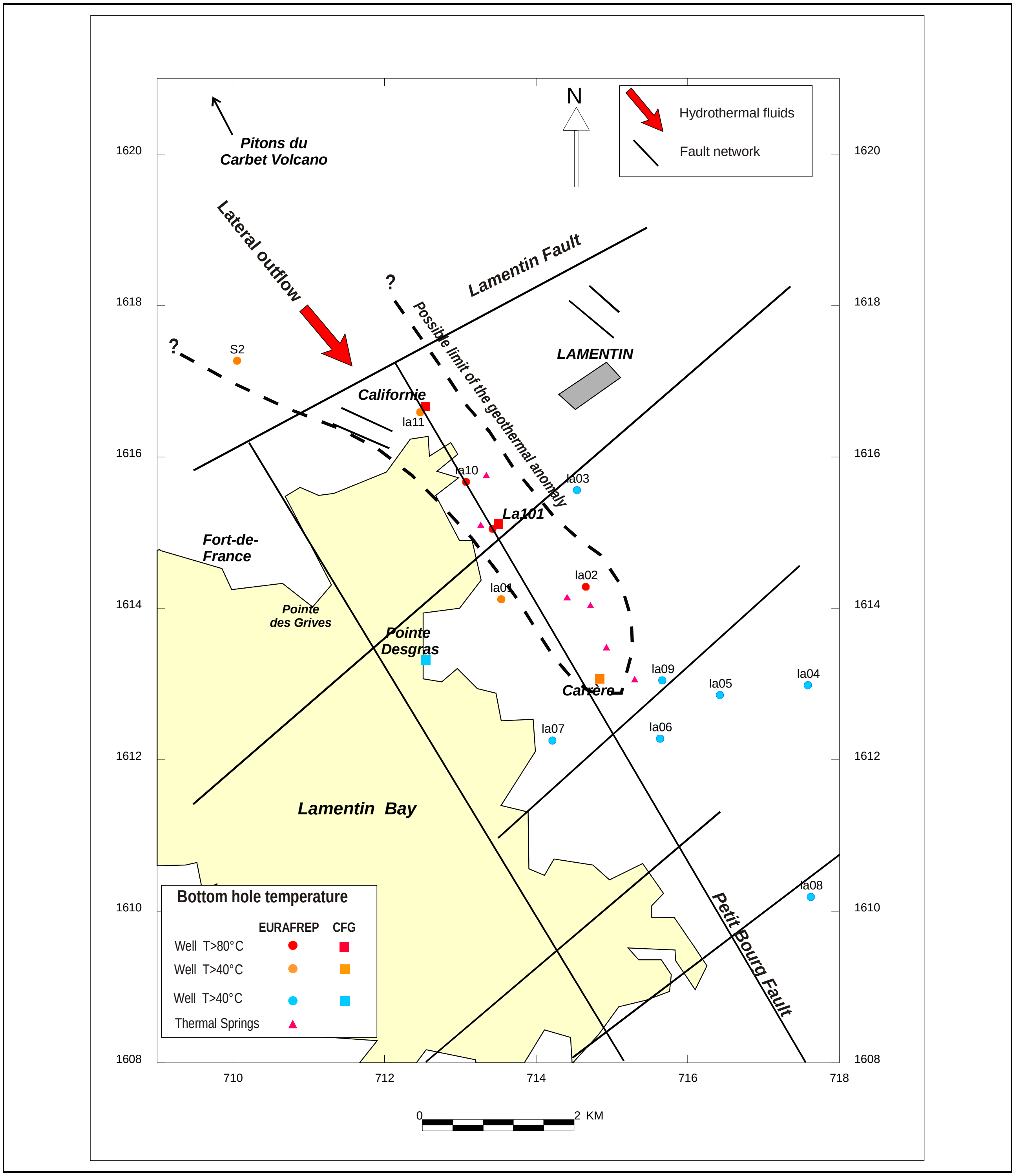

Figure 8. Interpretative model of the low temperature geothermal system showing the lateral outflow in the northern part of the Lamentin graben. The N115E Californie faults as well as the NW-SE Petit Bourg fault are interpreted as the main structures responsible for the fluid circulation.