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The Petite Anse-Diamant Geothermal System (Martinique Island, Lesser Antilles): Results of the 2012-2013 Exploration

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ABSTRACT

A 2012-2013 additional and combined – geological, hydrogeological, geochemical, geophysical - surface exploration results in a new insight of the Martinique geothermal systems, including Petite Anse – Diamant area.

The Petite Anse – Diamant hot spring is located at the foot of a small volcano - Morne Jacqueline – part of a NW-SE volcano-tectonic corridor. The Southern flank of this volcano collapsed leading to the outcrop:

1) A previous neutral, high temperature hydrothermal activity corresponding to a MT conductive layer interpreted as a clay cap of the present geothermal system. The bottom of the conductive layer displays also a doming shape, characterizing the top of geothermal system;
2) A dyke of diorite coinciding with the top of a huge MT resistive body, following the volcanic corridor, and interpreted as a magma intrusion; it generates several on and off-shore spots of magmatic degassing; this intrusive gas –rock may act as a heat source and interact with the geothermal fluid.

The Petite Anse spring water is of Na-Cl type due to a seawater contribution. The associated geothermal reservoir temperature is estimated at 190-210°C.

The recharge of the system is likely to be low, because of both a bad permeability resulting from the extensive acidic alteration related to previous fumarolic expression, and limited rainfalls.

An exploration drilling area is proposed at the North of the Petite Anse village.

1. INTRODUCTION

The project of “Additional geothermal exploration of Martinique Island (Lesser Antilles)” lies within the framework of the revival and development of renewable energy in French overseas territories (50% share of these energies in these territories by 2020). On volcanic islands such as Martinique, geothermal energy is *a priori* the most promising renewable energy. This project joined the will of the French Government and the Region Martinique to go toward the energy independence of the island in 2030.

The project was co-financed by the ERDF (European Regional Development Fund), ADEME (French Agency for Environment and Energy Management), the Regional Council of Martinique, the Joint Union of Electricity in Martinique (MEMS) and BRGM (French Geological Survey).

1.1. Geothermal exploration of the Martinique island

Geothermal exploration, in Martinique, began there more than 40 years ago. It can be divided into three steps: (1) late 60s, focused mainly on the plain of Lamentin (*e.g.* Cormy et al, 1970.), (2) late 70s - early 80s, incorporating plain of Lamentin and Morne Rouge area between Mount Pelée and Pitons du Carbet (*e.g.* Westercamp 1978; Iundt, 1984) and (3) the early 2000s when it was targeted to the south and SW flanks of Mount Pelée, the Petite Anse sector (*e.g.* Sanjuan et al., 2003a) and, moreover, the NW of plain Lamentin. The 2003 campaign (Sanjuan *et al.*, 2003a) led to identify the vicinity of the Petite Anse hot spring as one of the two areas of "priority 1" because of the combination of geophysical anomalies, geochemical and geologic indices.

1.2. 2012-2013 Exploration campaign

Scientifically geophysical methods have had a major contribution in this campaign (Coppo *et al* , 2015). The magnetotelluric (MT) data acquisition, their processing and inversion / modeling used the latest methods and software. Overflying the island of Martinique by helicopter electromagnetic method (MarTEM project) yielded, on the most superficial levels (<200 m), results of an exceptional resolution, and made possible a calibration of the two methods (MT and TEM) for the resistivity distribution of the investigated areas. New means of data processing and modeling also allowed to update the processing of the old data (acquired in 2003 and in the 80s) in MT, gravimetry and magnetism. Coupled modeling MT- gravimetry and integration of reinterpreted old data helped to highlight coincidence of anomalies, including Petite Anse. Concerning the geochemistry, the use of some isotopic analyses (Li, C , O, H , He) has completed our information on magmatic signatures or on their absence. The mineralogical characterization of hydrothermal alteration, in geology, led to identify stages of old hydrothermal activity as possible indicators of the surveyed current systems.

Beyond the innovative techniques and methods, this project sought to develop, at each stage, a synergy between the different methods by comparing the results obtained by geology, hydrogeology, water and gas geochemistry and geophysics. Eventually, this multidisciplinary exchange helped to build conceptual models that can be useful in later stages of investigation such as exploration by deep drilling. Among the four areas that were surveyed two are proposed for further exploration drilling including the Petite Anse area. Concerning the nomenclature: "Les Anses d'Arlet" represent the larger surveyed area while "Petite Anse" (or Petite Anse – Diamant) is restricted to the area of interest for further investigations and "Les Eaux Ferrées" is the local name for the studied hot spring.

The work presented here by the BRGM has completed surface exploration with three main objectives:

- Secure the implementation and execution of future exploration drilling (mitigation of the geological risk)

- Better assess the geothermal resources of the island,

- Open drilling opportunities in an environment where there are many constraints.

2. GEOLOGICAL SURVEY

New observations and analyzes (Traineau *et al*., 2013) have clarified the geological context of the Petite Anse / Diamant prospect. As follows:

- Extending the investigation area to the whole volcano- tectonic NW-SE axis, between Pointe Burgos and Diamant Rock , a consistent framework was given to magmatic and hydrothermal activity of the SW Trois -Ilets peninsula ;

- Highlighting a spatio- temporal continuum of hydrothermal activity between -1.5 My and today from a detailed mapping of fossil alteration zones related to their tectonic controls, the targeted geothermal reservoir was better constrained at this stage of its evolution (Bouchot *et al*., 2014.)

- Clarifying the close relations between the volcano- magmatic activity and the hydrothermal activity, particularly at the Morne Jacqueline, the context of the identified geothermal reservoir was defined.

A three stages evolution is proposed in line with the work of Germa *et al*. (2011) and Westercamp *et al*. (1990).

2.1 Initial stage

2.1.1 Volcanism

Between 1.5 and 0.35 My, a "hydrothermal magmatic system" is developing more or less related to the multi-staged activity of Roches Genty eruptive center (undated). Many volcanoes were then built, from North to South (Figure 1):

- the Pointe Burgos Strombolian cone and its quartz basalt flow (dated at 1.72 ± 0.2 My), which can be related to the Morne La Plaine thick basaltic andesites flows (1.175 ± 0.020 My) ;

- the Morne Champagne lava dome of the (0.617 ± 0.052 My);

- the Roches Genty eruptive center (undated);

- the Morne Clochette andesitic dome (1.33 ± 0.03 My);

- the mainly dacitic Morne Jacqueline volcano (undated) followed by a pipe explosion at its Western flank;

- the Morne Larcher strato-volcano (0.346 ± 0.027 My);

- the Sec and Diamant Rock domes / intrusions and (1.097 ± 0.018 My).

Volcanism, often explosive and marked by interaction with water (hydro-magmatic), was expressed by persistent coexistence (or even the mixture) of deep-originated basaltic lavas and shallower quartz dacitic ones (Gourgaud et al., 1982 and Gourgaud *et al*., 1991). This feature reflected the existence of magma chamber (s) where the magma can differentiate at shallow depth (6 km according the mineralogy).

This volcanism has a consistency in several ways:

- spatial and temporal restricted distribution;

- associated tectonic system, characterized by two groups of sub-perpendicular faults (the regional one corresponding to the volcano-tectonic axis and the one forming a NE-SW "en échelon" network);

- similar petrographic properties subject to the same bimodal magmatic mixture with a similar mineralogy (Gourgaud *et al*, 1982 and Gourgaud *et al*, 1991...)

There is, however, no evidence that a single magma chamber is at the origin of all this volcanism; several may have coexisted. Recurrent ascents of deep basaltic magma (Gourgaud *et al*., 1991), thanks to the crossing of tectonic directions NE-SW and NW-

SE, may have helped to maintain the volcanic system of the SW peninsula Trois Ilets, active for at least 1.1 My. These magma chambers and associated subsurface intrusions would, then, formed the heat source(s) of a hydrothermal system.

2.1.2. Early hydrothermal system

Among the water-magma interactions that characterize this volcanic area, some geological formations (La Charmeuse) contain elements of an ancient underground hydrothermal alteration (undated but clearly preceding the Morne Larcher terminal activity), probably associated with the activity of the Roches Genty eruptive center. Altered blocks (with jasper and natro-alunite, ...) have been raised due to a hydro-magmatic eruption and may indicate an acidic alteration forming the swept part of a magmatic hydrothermal system.

2.2 . Intermediate stage

2.2.1 . Fossil hydrothermal

It is represented by the decline of magmatic component and the evolution of " hydrothermal - magmatic " acid system (described above) toward a wide High Temperature geothermal system dominantly neutral. It develops a clayey cap (caprock) and a surface fumarolic activity along a strip linking Anse d' Arlet and Petite Anse , demonstrating the existence of a fossil high temperature geothermal reservoir (Figure 1). This corridor parallel to the volcanic axis NW-SE is crossed by faults and fractures which have oblique or perpendicular directions (NNW -SSE to WSW -ENE) regarding it. Examination of these faults and joints shows that they frequently worked in tension, creating favorable conditions for the opening and fluid flowing. Locally, the circulation of hydrothermal fluids could coincide with the operation of a N150 °E fracture, as at Anse Chaudière.

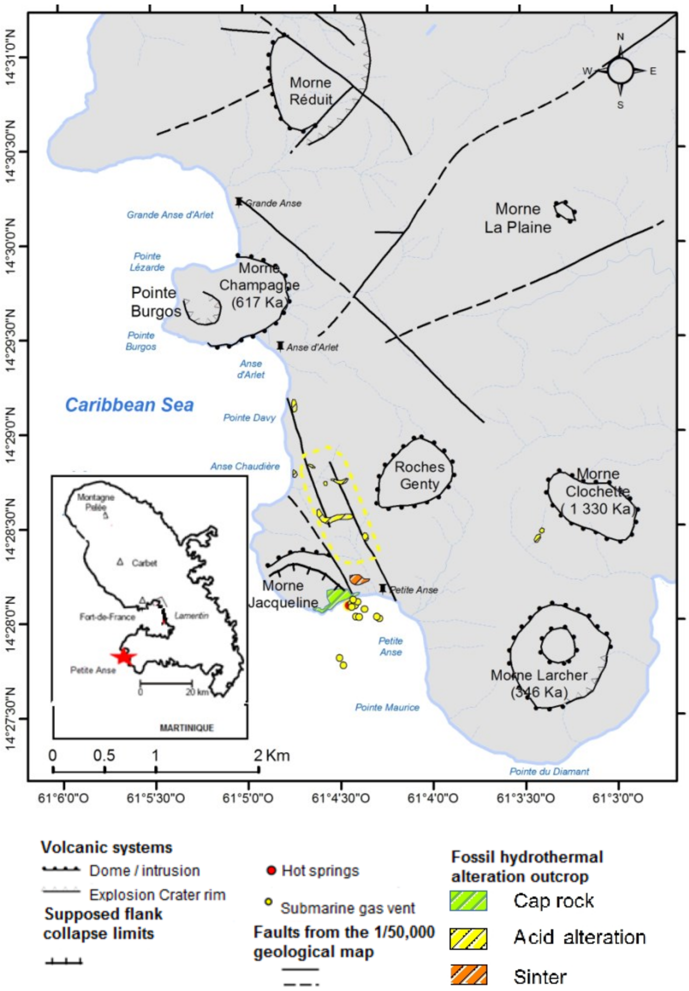

Figure 1: Location of sources and outcrops impacted by a fossil hydrothermal alteration, identified in the area of Les Anses d'Arlet.

This hydrothermalism can be summarized into three types of alteration, spatially distinct:

• kaolinite-alunite alteration : it is observed in several places from the Morne La Capote pass to les Anses d'Arlet village and is symptomatic of a fumarolic activity (boiling fluid within shallow aquifers or an old geothermal reservoir) and therefore temperature conditions above 100 ° C;

• silica deposits (sinter): observed on the uphill Petite Anse village, they are formed from neutral (sodium chloride) and silica-rich fluids and coming from high temperature geothermal reservoirs;

• clay minerals illite and interstratified illite / smectite: in the area of Les Eaux Ferrées, they reflect circulation of hydrothermal fluids at temperatures of about 150-180 ° C and characterize a fossil caprock area.

2.2.2 Flank collapse of the Morne Jacqueline volcano

During the activity of the geothermal system or later on, the clayey cap that could have been used as slip sole as in other cases (e.g. Belousov *et al*., 1999. Boudon *et al*., 2007.), the Southern flank of Morne Jacqueline was destabilized. This flank collapse led to outcropping at least part of the cap of the geothermal reservoir as well as intrusions (igneous dyke crossed by volcanic micro-dykes of the same composition). These intrusions reveal a greater proximity to a magmatic stock and are NW-SE oriented, along the regional direction. Morphological freshness of Morne Jacqueline volcano suggests that this collapse must have happened there only a few hundred thousand years ago.

2.3. Current geothermal activity

It is primarily represented by the thermo-mineral spring of Les Eaux Ferrées. This spring and the small water and gas emergences together with it 200m along beachfront, display degassing and travertine deposits. Several features lead to assume a reduction in the extent and intensity of surface manifestations:

- the low flow rate (0.03 l / s) of the springs with respect to the extension of the area impacted by hydrothermal alterations;

- the fossil fumarolic and high temperature system of alunite-kaolinite acid alteration is taken over today by low temperature springlets, confined to the vicinity of the main spring of Les Eaux Ferrées but always from the same fractures and therefore circulation system.

This may suggest a contraction or possibly a migration of high-temperature geothermal system southward. The current reservoir is assumed to be located under the alteration zone of Petite Anse. There is a network of faults likely to display conditions of hydrothermal circulation between the Petite Anse area and les Eaux Ferrées hot spring.

Finally, the investigated area was expanded and new springs were studied. The synthesis of these geological data allowed integrating the Petite Anse geothermal system in a larger magmatic and hydrothermal frame (within the axis Pointe-Burgos - Diamant Rock) and in the evolution of this set over 1.5 Ma. The present hydrothermal activity seems more limited in space and its intensity lower than in the past.

3. HYDROGEOLOGICAL SURVEY

Hydrogeological investigations in the area of Petite Anse focused on:

- seeking areas likely to feed seaside springs and possible associated geothermal system;

- locating any outfalls, thermal anomalies or degassing sites in the Bay of Petite Anse through underwater investigations;

Only degassing zones (of mainly CO_2) could be identified without being associated with water ingress nor thermal anomalies (Vittecoq *et al.,* 2012).

The low infiltration rate estimated on the Morne Jacqueline is compatible with the low flow rate of the springs (<1 l / s). The precise location of the deep water ascent may lie a few tens or hundreds of meters upstream the springs.

The area of la Charmeuse and the western flank of Morne Larcher are formed with permeable breccias and pyroclastic flows that may (i) constitute a prime infiltration zone and (ii) contribute to the recharge of the geothermal system.

However, two factors can strongly limit the infiltration at depth:

- the low rainfall and the high evapotranspiration lead to assess the infiltration values between 50 and 75 mm / year, or 20 to 30 times less than on the Mount Pelée; what to add, however, a likely contribution, roughly equivalent seawater;

- a uniform conductive level from 200 m depth, highlighted by the MT survey (Coppo *et al*., 2013) and probably corresponding to a clay cap (cap rock), therefore, slightly permeable.

It is therefore very likely that the natural recharge of the geothermal system is limited. Without more precise evaluation, we think it is limited by a precipitation regime at least 4 times "drier" than on Mount Pelée (less than 80 km northward) and a priori less permeable (Vittecoq *et al*., 2012).

Conversely, for the same reason highlighted by the MT survey, the presence of a clay cap may explain the rarity of leaks of the geothermal system.

4. HYDROGEOCHEMICAL SURVEY

4.1. History of works and geological context of the Petite Anse / Diamant spring

Geothermal significance of this spring began to be reported during the exploration of the 1980s (Iundt 1984) on hydrogeochemical criteria. Exceptional chemical and isotopic properties of this source, in the Caribbean context, and its close association with gas ascents of clearly magmatic origin were then highlighted (Pedroni *et al*., 1999). The pursuit of geothermal exploration, then confirmed the interest of the "Diamant spring" area (Sanjuan et al., 2003b) while a geochronological study (e.g. Germa *et al*., 2011) rejuvenated from 1 My to a little more than 300 000 years the surrounding volcanism.

The close association with the activity of the Morne Jacqueline volcano is underlined by the geological survey (see § 1):

Other springs located near the axis of past hydrothermal activity were studied. From North to South, it is Colette, Sucrerie, Colibri and Larcher springs. Their possible link to "les Eaux Ferrées" spring is discussed.

4.2. Characteristics and origins of water

4.2.1. "Les Eaux Ferrées" spring (Petite Anse)

The physico-chemical (including temperature), chemical as well as isotopic characteristics and the source of water Railways have not significantly changed since the first available analyses: a relatively high mineralization (between 19 and 20 g / l) of dominantly sodium chloride type, a temperature between 34 and 35 ° C and a pH between 5.99 and 6.3 (the higher uncertainty is due to CO_2 degassing).

Among the trace elements, characteristic of water-rock interaction at high temperature, the concentrations of As, Cs, Rb vary little. The increase in boron is consistent with other indicators of interaction as $\delta^{18}O$ (which also increases). On the other hand, the decrease of lithium concentration (about 20% compared to the expected trend) cannot be explained.

"Les Eaux Ferrées" spring is located in the area of the"mature" waters of the Cl - SO_4 - HCO_3 Giggenbach's chart (1988) (Figure 3). Their chlorinated feature may be due to mixing with the seawater. However, such waters differ from the mixing line between fresh waters and seawater in a Br / Cl chart. This difference may represent an excess of chloride of 34%. Given the other parameters and the δ D / $\delta^{18}O$ chart (Figure 5), it seems legitimate to attribute this chlorine excess to a magmatic origin.

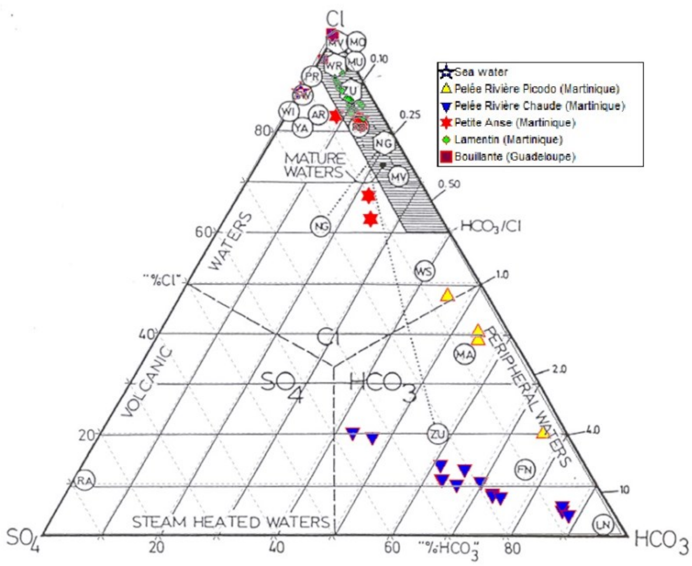

Figure 2: Giggenbach's chart (1991) displaying the distribution of major anions of the springs in the area of les Anses d'Arlet.

Gases isotopic ratios of (see § 5) clearly indicate a magmatic contribution to both the helium and CO_2 carbon and both on land and at sea The high value of "Les Eaux Ferrées" spring water $\delta^{13}C$ (4.7 ‰ *vs* PDB) is most likely due to a magmatic origin rather than a marine one ; there would be a fractionation by CO_2 degassing together with a precipitation of carbonate (Rive , 2013 , pers. comm.). Travertine can be seen, indeed, around the spring.

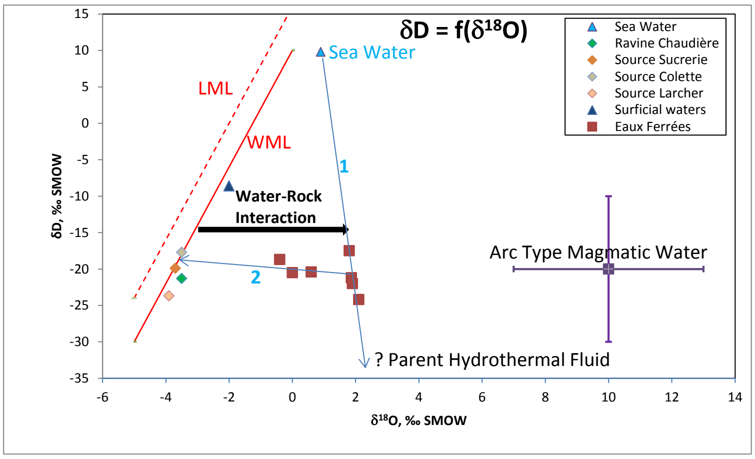

Figure 3: Water stable isotopes of les Anses d'Arlet area. Legend: WML: World Meteoric Line, y = 8x + 10); LML: Local Meteoric Line (Guadeloupe), y = 8x + 10; supposed mixing lines are listed (1) between seawater and deep center for "Les Eaux Ferrées" spring, (2) between "Les Eaux Ferrées" spring and local groundwater

An additional clue to the rise of deep fluids in this area is provided by the few measurements on gas springs sampled underwater in the bay of Petite Anse , in the extension of the anomalous zone of "Les Eaux Ferrées" spring. It is essentially composed of CO_2 (> 60 %) but with locally abnormal concentrations of helium (2.2 to 15.8 ppm for 5.24 ppm in the atmosphere). The helium isotope ratios ($^3He/^4He$) of the sample reaches 7.26 Ra . This is a high value, greater than (7.2 Ra) at the Rivière Chaude hot springs (Jean-Baptiste , 2013 , pers. comm.) under the Mount Pelee dome, close to the gases (8.2 Ra) emitted by the Soufrière of Guadeloupe (Ruzié *et al*. , 2013) and similar (7.9 Ra) than those found by Pedroni *et al*. (1999), at the same "Les Eaux Ferrées" spring. This may confirm the permanence of a mantle feeding and thus of a magmatic activity at this level.

The high concentrations of certain trace elements (As, B, Cs, Li, Rb, ...) and $\delta^{18}O$ (Figure 3), δ^7Li (6.3 to 7.1 ‰) isotopic ratios are compatible with water-rock interaction - at high temperature. The isotopic ratio of hydrogen (δD) does not display any anomaly relative to the local groundwater. A simple mixture between a seawater and a magmatic pole as proposed in other island arc settings (Dotsika , 2009; Giggenbach , 1992) seems hardly feasible in view , inter alia, the diagram δD / $\delta^{18}O$. Chlorine mineralization is still not compatible with such a mixing of sea water / magmatic water. Magmatic signature of CO_2 and He, Cl excess and a trend towards a deuterium deficit suggest, however, that this magmatic contribution does exist. The parent geothermal fluid of "Les Eaux Ferrées" spring could then be the result of a mixing of seawater, meteoric water that interacted strongly with the rock at 200 ° C and a magmatic component. Comparison of chemical and isotopic compositions of different thermal springs and fumaroles from the Aegean volcanic arc suggests that the presence of such a magmatic component characterizes geothermal fields in more active context (Dotsika , 2009). Such a component would be present in Montserrat (Chiodini *et al*., 1996) and in Wotten Waven, Dominica (Traineau, pers. comm., 2014), two volcanically active sites of the Caribbean arc. The confirmation of such a component on Petite Anse would result in, at least, maintaining some magmatic activity without prejudice to the status of the geothermal system itself (Gadalia *et al*. , 2014)

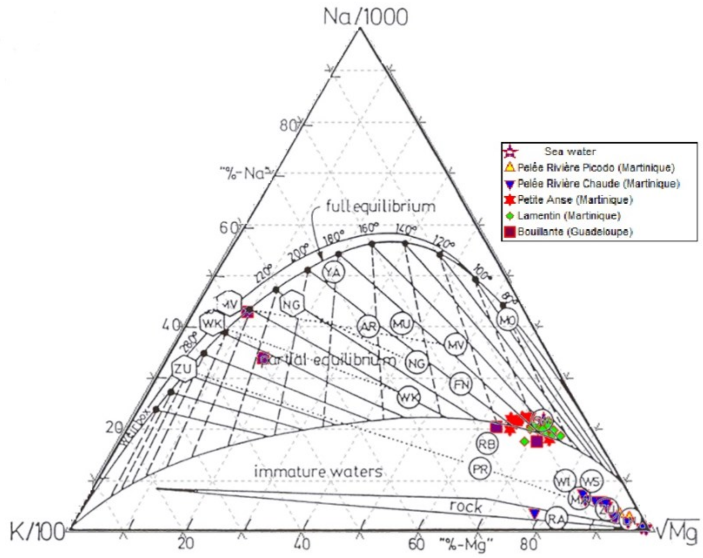

Figure 4: Giggenbach's chart - geothermometer (1988) displaying the major cations distribution of the springs in the area of Les Anses d'Arlet.

The estimate of the temperature by water-rock interaction geothermometry is illustrated by the Na-K-Mg Giggenbach's chart (Figure 4). Several geothermometers converge to a temperature range of 190 to 210°C (Sanjuan *et al*, 2003b;. Gadalia *et al*, 2014.). The silica geothermometers significantly underestimate the temperatures due to:

- either the likely dilution of this species with surface waters;

- or precipitation of silica during an ascent where cooling (most likely) occurs.

The absence of tritium in water in 2003 (Sanjuan *et al*., 2003b) indicates a circulation / transit time exceeding 50 years. It is possible to interpret the trace elements and isotopes anomalies with a low water-rock ratio and a significant interaction time. This would be consistent with geological findings suggesting a contraction of the system.

4.2.2 . Other sources sector Anses d'Arlet (Colette, Sucrerie, Ravine Chaudière and Larcher)

Observations and physico- chemical measurements were made on ten water points, including 3 wells beachfront. The 7 sources , not studied before, have in common a low flow rate (<2 l / min), a temperature close to the average local air (24-26 ° C , depending on altitude), significantly lower mineralization than "Les Eaux Ferrées" spring , the absence of degassing and a sodium chloride dominant mineralization (Traineau *et al*., 2013 . Rad *et al*., 2013).

Colibri and Sucrerie springs display travertine deposits and are located either in the environment or at the intersection of listed faults. The Larcher spring has no deposit and, as the Colibri spring, has a very light thermal character, given its altitude of emergence. Other springs (Bellevue, Colette , Charmeuse, Colibri) have relatively high conductivity for surface waters (300 to 2300 S / cm), probably reflecting leaching of fossil hydrothermal alteration.

Their composition bears the trace or a water-rock interaction at high temperature, or a magmatic contribution. The Giggenbach's chart (1988) (Figure 4) is symptomatic : these waters are near the "superficial" magnesium end member and are distinguished , in fact, from "Les Eaux Ferrées" spring (Gadalia *et al* , 2014.). Conversely, among the emergences of "Les Eaux Ferrées" some of them may have mixed with local groundwater as the mixing line N° 2 of Figure 3 can display it.

These sources have four $\delta^{13}C$ values of a typical biogenic origin and very low levels of high temperature water-rock interaction indicators. Relatively negative deuterium values can be compared to those found in some local rain water (e.g. Arnaud *et al*., 2013), or other groundwaters (such as Habitation Dizac at Diamant village, in Brenot *et al*., 2008).

The absence of links between these sources and "Les Eaux Ferrées" spring goes in the direction of a limited and / or deep hydrothermal system, centered on Petite Anse.

The hydrogeochemical study leads to the following conclusions:

- the "Les Eaux Ferrées" spring displays, in its chemical and isotopic composition, a signature of an interaction with magmatic rocks at high temperature;

- the temperature of the interaction, estimated by geothermometry, rises to 190-210°C;

- we can assume that the interaction is made with a very low water-rock ratio and / or on a long-term;

- the geothermal fluid likely results from a mixing between a meteoric water, a seawater and a magmatic components;

- some new analyzed springs, although neighboring "Les Eaux Ferrées" spring and the former hydrothermal system do not reveal any mixing link with "Les Eaux Ferrées" spring. It seems that none of these waters has known or interaction at high temperature, or contribution of magmatic gases.

5. SOIL GAS GEOCHEMICAL MAPPING

The available data for the area of Les Anses d'Arlet are derived from previous (Sanjuan *et al*., 2003b) and recent (Gal, 2012) investigations.

In most cases it is not possible to demonstrate deep gas ascent (CO_2 and / or helium). Some stations (as in Anse Dufour, northern Morne Reduit) may indicate abnormally high CO_2 without being marked by a helium anomaly (content close to the atmosphere one), and with a value clearly biogenic for this CO_2 (-24.6 ‰ *vs* PDB).

However, the area of Petite Anse, where flows carbonated mineral water of "Les Eaux Ferrées" spring can undoubtedly be linked to phenomena of gas ascents from deep origin (mantle). Near the spring, many CO_2 vents are identifiable and allow highlighting these ascents of deep originated gas:

- the presence of high concentrations of CO_2 (up to 100%);

- the presence of helium anomalies with a strong enrichment relative to the atmosphere (from 5.24 to 7.56 ppm);

- Isotopic signatures of -1.7 to -5.5 ‰ vs PDB for ^{13}C of CO_2 and $^3He/^4He$ ratios clearly of mantle origin (> 7Ra).

The combination of these three indicators used to characterize this Petite Anse area as an upflowing zone of deep fluids. It is possible to say that the surface anomaly has a relatively small geographic expression, indicating that the ascent of the fluids occur through drains having a reduced lateral extension and / or that the permeability is space-limited.

Groundwaters use, in general, the same conduits (faults) as deep originated gases. They are also sometimes vectors. However, measurements carried out close to some springs in the vicinity of les Anses d'Arlet (Colibri, ...) give no positive anomaly neither in helium, nor in CO_2. This is in line with the conclusions of § 5.3 about these springs.

6. GEOPHYSICAL SURVEY

This major part of the 2012-2013 exploration campaign is more specifically developed by Coppo *et al*. (2015).

The Figure 5 (from Coppo *et al*., 2013) summarizes most of the observations and measurements (MT, TEM, gravity and magnetism) that guided the interpretation of these data in terms of geothermal exploration.

The interpretation of these geophysical results leads to the following considerations:

- the cap of a possible geothermal system would be provided by the conductive superficial layer (<10 Ωm), a few hundred meters thick, present throughout the area. The thickest cap layer, located between the resistive "intrusion" at the NW and the Morne Larcher at the SE, indicates the most active geothermal system. The thinnest cap layer, North, could correspond to an older system and would be partially eroded. At the boundary between the two places, a weakness area of this cap allows the emergence of Petite Anse hot springs. It is also on the edge of the resistive intrusion and this border zone could be a priority way of channeling for the geothermal fluids;

- the resistivity area (10 to 50 ohm.m) developed under the thickest conductive cap layer and located between the resistive "intrusion" and the conductive magmatic conduit of Morne Larcher leads, constitutes a favorable area for the development of a geothermal system . This would be in agreement with the Raharjo' synthetic model (2012);

- the potential heat source of the geothermal system (not imaged by the geophysical survey) could be either a magma chamber located beneath the Morne Larcher (which is the newest volcanic edifice in the area with an activity dated at 0.346 ± 0.27 My) or more probably related to the resistive intrusion at the NW.

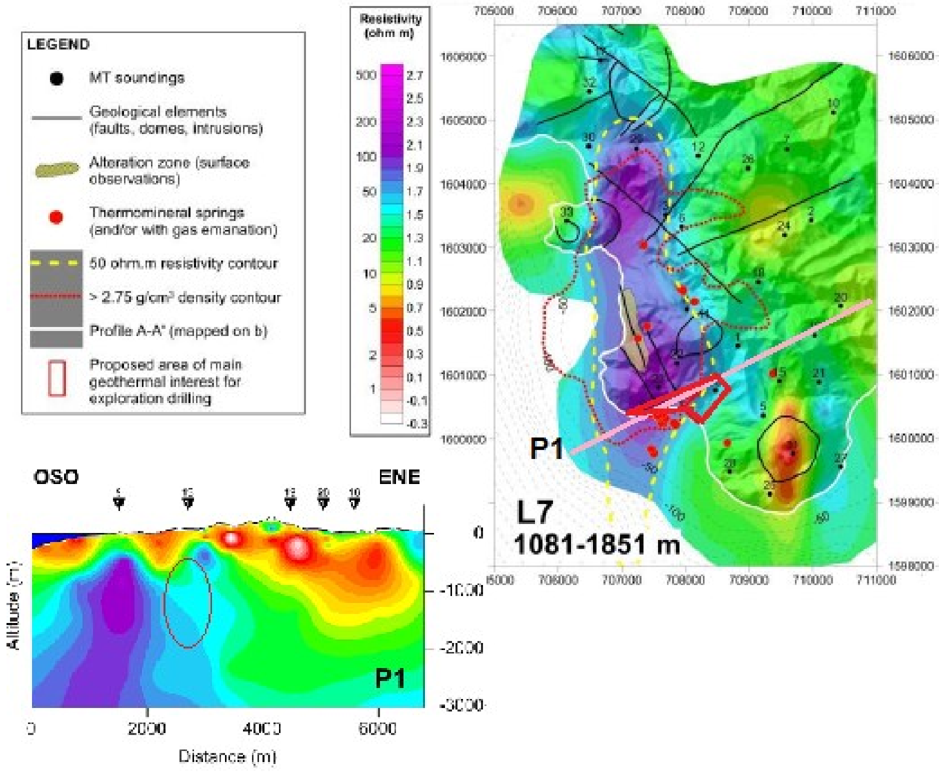

Figure 5: Representations in cross-section and in plan of the resistivity and density distributions on Les Anses d' Arlet area.

Exploration drilling is recommended to target the favorable zone with a minimum depth of 500 m to exceed the shallow clay cap. They should reach at least 2000 m to intersect the whole reservoir zone.

7. CONCLUSIONS

7.1. Conceptual model of geothermal exploration of Les Anses d'Arlet area

The area of les Anses d'Arlets presents a convergence of geological, hydrogeological geochemical and geophysical clues indicating:

- the existence of a high temperature geothermal system characterized by a strong water-rock and magmatic gases interaction ;

- a hydrothermal circulation system that would have been intensely developed in the past but is now smaller in space;

- the existence of a high temperature geothermal reservoir is initially suggested by the geochemical characteristics of “Les Eaux Ferrées” spring showing a water-rock interaction estimated by geothermometers at 190-200 ° C within a deep reservoir fed by seawater, meteoric fluids and a magmatic contribution;

- The geology highlighted fossil hydrothermal alterations suggesting that the geothermal reservoir has been active for a long time and was much more active in the past. This is why the conceptual model (Figure 6) considers a contraction of the reservoir and the development of a thick clay cap over the time;

- this reservoir would be located along the NW-SE oriented volcano- tectonic axis where focused the magmatic activity since 1.5 My. Specifically, the geophysical methods (MT and gravimetry) identified a dense resistive body, NNW- SSW oriented, underlying volcanic units from Morne Bigot to Morne Jacqueline (Figure 5). This shallow mass is interpreted as a magmatic intrusion according to the geological observations. The presence of dykes, adjacent to “Les Eaux Ferrées” spring could be its surface expression, as a result of a flank collapse that would have impacted the southern flank of Morne Jacqueline;

- this intrusion, as it is cooling, could play, at depth, the role of the heat source in the geothermal system and would go on emitting gases (CO_2, He) with clear magmatic signature;

- the eastward resistive extension, developed under a doming of the conductive layer (caprock) is interpreted as the site of an existing geothermal reservoir;

- this geothermal system would now lean on the SE flank of this intrusion that would have acted as a hydraulic barrier. To the East, the Morne Larcher volcanic system limits the development of this field.

- the conductive level (<10 Ω.m) of variable thickness and outcropping in the area of "Les Eaux Ferrées" spring may be the clay cap (caprock) of the current geothermal reservoir while having previously been initiated in a context of higher temperature.

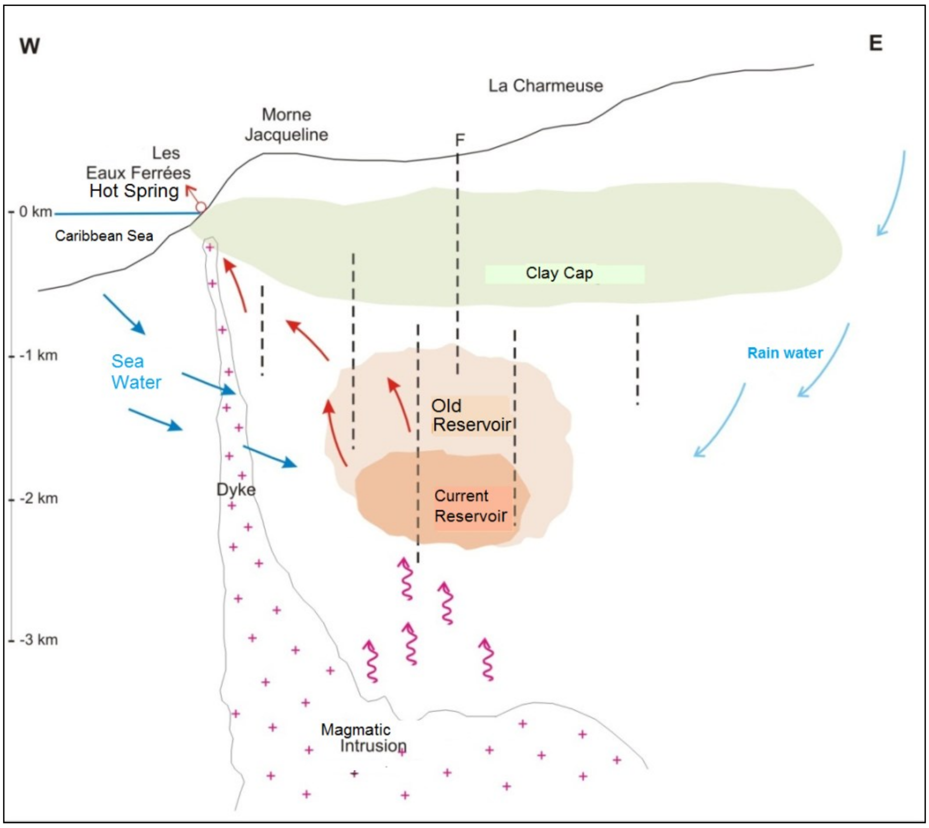

Figure 6: Proposed Conceptual Model of the Petite Anse geothermal system. Depths are given for information only

Several questions remain about this reservoir including its recharging and therefore its capacity, volume and depth.

"Les Eaux Ferrées" spring would be a leak of this reservoir largely guided by a dyke crossing the Morne Jacqueline volcanic formations.

The other explored springs during this additional exploration are unrelated to this geothermal system, confirming its limits.

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