Toward a Continuum Geothermal Model to Explain Coexistence of Medium to High (100 to 250°C) Temperature Geothermal Systems in Martinique and Guadeloupe, French West Indies

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Keywords
Martinique, Guadeloupe, Lesser Antilles, Bouillante, Montagne Pelée, high to medium temperature geothermal systems, continuum geothermal model, evolution in space and time, magmatic heat source, exploration guidelines, fluid equilibrium

ABSTRACT
The recent surface exploration data acquired in Martinique led to revisiting the conceptual models of three geothermal systems in active volcanic arc context: Petite Anse in the Southwest of the island, Lamentin in the center, Montagne Pelée in the North. These three explored systems are compared with each other and with the developed Bouillante geothermal field in Guadeloupe (15 MWe). From parameters, such as reservoir temperature, duration of the geothermal system using fossils events, age and duration of magmatism, degree of equilibrium of geothermal fluid, we propose a continuum model of geothermal system including three successive stages: prograde, peak and retrograde.

Introduction
Recent surface exploration data acquired in Martinique, French West Indies, between 2012 and 2014, led to revisiting the conceptual models of three geothermal systems in this active volcanic arc setting: Petite Anse in the Southwest of the island, Lamentin (close to Pitons du Carbet) in the centre, and Montagne Pelée in the north (Gadalia et al., 2014) (Figure 1).

The three systems being explored in Martinique are compared with each other and with the Bouillante geothermal field (Guadeloupe, France) (Figure 1), the only exploited geothermal field in the Caribbean, with an installed capacity of 15 MWe (Bouchot et al., 2010). So while Bouillante is a classical system of high temperature (250°C), according to geothermometers it appears that the geothermal systems in Martinique show lower temperature reservoirs between 100°C and 220°C. These different reservoir temperatures coupled with their variations in time pose several questions. Do these temperature differences indicate different stages of the same type of geothermal development (with successive prograde, peak or retrograde stages)? What impacts can the age, position, volume and duration of the magmatic activity as source of heat, have on the evolution of the geothermal system (duration, extension) and the temperature of its reservoir?

The comparison of different systems, based on selected parameters such as reservoir temperature, duration of the geothermal system using fossils events, age and duration of magmatism, degree of equilibrium of geothermal fluid, should provide relevant answers to these questions. This comparative synthesis should thus allow a better understanding of the temporal and spatial evolution of these systems and contribute to better exploration of them in the Lesser Antilles island volcanic arc (Table 1).

A geothermal system associated with an active volcanic arc is, a priori, controlled by a magmatic source of heat. It is

Figure 1. Location of the four studied geothermal fields (red star), in Guadeloupe and in Martinique (French Lesser Antilles).
characterized by i) a geothermal reservoir resulting from hydrothermal convective circulation, ii) leaks from the reservoir to the surface and associated surface expressions (thermo-mineral springs, fumarole) and iii) recharge of the system involving, as on islands in the Lesser Antilles, meteoric and marine waters.

Geothermal Fluids and Reservoir Temperatures

In Martinique and Guadeloupe, geothermal reservoirs show little variations in terms of chemical composition of geothermal waters. They are usually close to the pole chlorinated sodium mainly because of the strong influence of seawater in the reservoir recharge (Figure 2). In fact, the involvement of seawater with a salinity around 35 g/l, complicates the interpretation of geothermal fluids in terms of water maturity. To do this, it favors the use of isotopic analysis of fluids (O, C), binary diagrams (e.g. Cl/Br), and the ternary diagram [Na-K-Mg] rather than the reaction diagram [Cl-HCO₃-SO₄₂⁻] (Giggenbach, 1988) whose concept of “mature waters” is inappropriate because of sea water influence (Figure 2).

Table 1. Comparison between the geothermal systems of Martinique and Guadeloupe French islands.

<table>
<thead>
<tr>
<th>Geothermal Field</th>
<th>Montagne Pelée</th>
<th>Bouillante</th>
<th>Petite Anse</th>
<th>Lamentin-Carbet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage of the geothermal evolution</td>
<td>Prograde stage</td>
<td>Peak stage (with plateau)</td>
<td>Retrograde stage (trend)</td>
<td>Advanced retrograde stage</td>
</tr>
<tr>
<td>Duration of the magmatic activity in the region</td>
<td>125 ky (550 ky if Mont-Conol included)</td>
<td>1 Ma (between 1.2 My and 230 ky ago)</td>
<td>~1.1 Ma (between 1.5 My and 350 ky ago)</td>
<td>700 ky (between 1 Ma and 337 ky ago)</td>
</tr>
<tr>
<td>Latest volcanic activity recorded in the field</td>
<td>Active volcanism (1929, last event)</td>
<td>~500 ky ago</td>
<td>~350 ky ago</td>
<td>&gt; 600 ky ago</td>
</tr>
<tr>
<td>³He/⁴He signature (from hot spring)</td>
<td>7.2 Ra</td>
<td>4 - 4.7 Ra</td>
<td>7.75 - 7.93 Ra</td>
<td>2.2 Ra</td>
</tr>
<tr>
<td>Temperature of the reservoir (geothermometer or measured)</td>
<td>180-200°C (R2)</td>
<td>200-220°C (R1) (estimated)</td>
<td>250°C (measured)</td>
<td>190-210°C (estimated)</td>
</tr>
<tr>
<td>Fossil geothermal stage</td>
<td>No identify</td>
<td>Adularia and quartz breccia (250 ± 50 ky by ⁴₀Ar-¹³₇Ar)</td>
<td>Palaeo-caprock and palaeo-acidic alteration (fumarole) with evidence of boiling (undated)</td>
<td>Illicite alteration in depth and palaeo-silica sinters (300 to 250 ky by U/Pb)</td>
</tr>
<tr>
<td>Duration of the geothermal system</td>
<td>~100 ky (from 125 ky ago to today)</td>
<td>&gt; 350 ky</td>
<td>~200 ky</td>
<td>&gt;&gt; 500 ky</td>
</tr>
<tr>
<td>Current fluid composition with pH and TDS</td>
<td>Na-HCO₃ to Na-Cl</td>
<td>Na-Cl</td>
<td>Na-Cl</td>
<td>Na-Cl</td>
</tr>
<tr>
<td></td>
<td>5.6 &lt;pH&lt; 6.2</td>
<td>pH&lt; 5.3</td>
<td>6.3 &lt;pH&lt; 7</td>
<td>5.6 &lt;pH&lt; 6.2</td>
</tr>
<tr>
<td></td>
<td>0.4 to 1.4 g/l</td>
<td>20 g/l</td>
<td>20 g/l</td>
<td>10-11 g/l</td>
</tr>
<tr>
<td>Degree of fluid-rock interaction</td>
<td>Immature waters</td>
<td>Full equilibrium</td>
<td>Partial equilibrium</td>
<td>Partial equilibrium</td>
</tr>
<tr>
<td>Recharge of the geothermal system</td>
<td>Only 2% of sea water</td>
<td>Sea water (58%)</td>
<td>Sea water (54%)</td>
<td>Sea water (30-35%)</td>
</tr>
<tr>
<td>Spatial extension of the geothermal activity</td>
<td>Supposed expansion in the future</td>
<td>Spatial stabilization of the geothermal since 300 ky</td>
<td>Contraction of the system (in progress)</td>
<td>Contraction of the system since 250 ky (from 10 to 1 km²)</td>
</tr>
</tbody>
</table>

In Montagne Pelée, two reservoirs are distinguished: a first reservoir, located on the SW flank of Pelée stratovolcano, is of sodium-chloride bicarbonate-type with an outflow feeding the springs of Rivière Picodo (0.4 g/l, pH 7.7 - 8.4), while a second reservoir, located in the apex area is composed of bicarbonate fluids with an outlet at the springs of Rivière Chaude (1.4 g/l, pH 6.4-6.8), and which appeared after the 1902 eruption. The proportion of seawater in the Picodo reservoir is estimated around 2% (Gadalia et al. 2014). Unlike conventional magmatic-hydrothermal model associated with an active stratovolcano, the summit reservoir (Rivière chaude), whose waters probably borrow the eruptive conduit, is not acid. Bicarbonate character reflects a neutralization of the water. According to the ternary diagram [Na-K-Mg] (Figure 2), theses geothermal waters (Rivière Picodo and Rivière Chaude) are clearly in the field of “immature waters”.

In Petite Anse, Eaux Ferrées springs are of sodium-chloride water type, marked
by a salinity of 20 g/l at pH 7 to 6.3. The reservoir waters could result from a mixture of sea water (54%) and freshwater (46%), as in Bouillante. According to the Br/C diagram, a large excess of chloride (34%) could have a magmatic origin (Gadalia et al., 2014). According to the ternary diagram Na-K-Mg, the geothermal water is partially equilibrated (Figure 2) but close to “immature waters” field. In addition, high concentrations of certain trace elements (As, B, Cs, Li, Rb, ...) and the isotopic ratios of $^{18}$O water indicates a water-rock interaction at high temperature.

In Bouillante, the geothermal fluid, taken from the reservoir or reconstituted from hot springs, is homogeneous in its composition. It corresponds to sodium chloride brine with a salinity approaching 20 g/l and a pH of 5.3 ± 0.3 at 250°C. Its chemical and isotopic compositions indicate that the reservoir is supplied both by sea water (58%) and fresh surface water (42%), the mixture of which is at chemical equilibrium with the host rock at a temperature of 250 °C (Sanjuan et al., 2001). According to the ternary diagram [Na-K-Mg] (Figure 2), these sodium-chloride waters reach the “full equilibrium” field.

Geothermometers calculated from hot spring and wells waters of the four studied fields show strong variations in temperature of the geothermal reservoirs, ranging from 100 to 250°C.

In Lamentin, the current reservoir is a low temperature type (100-140°C) according to geothermometers from Lamentin hot water (90°C) (Figure 3), while fossil reservoir known in Lamentin 250 ky is of high temperature type (>200°C).

In Montagne Pelée, where at least two high temperature reservoir have been characterized (Gadalia et al., 2014), the chloride-bicarbonate reservoir (related to Rivière Picodo) would have an estimated temperature of 155-180°C while the bicarbonate reservoir (in relationship with Rivière Chaude spring) would be a little warmer around 180-200°C.

In Petite Anse, the reservoir is a high temperature type, between 190-210 °C (Sanjuan et al., 2003), according to the geothermometers obtained from the Eaux Ferrées springs (close to Petite Anse village).

In Bouillante, the measured temperature in the developed reservoir, up to 250°C, is the highest of the four study geothermal fields.

In terms of fluid equilibrium, it appears that the dominantly chloride-sodium type reservoir waters, characterized by a strong recharge of sea water (except for Montagne Pelée) show: i) a full equilibrium for Bouillante reservoir fluid (250°C), ii) only partial equilibrium for Petite Anse and Lamentin hot spring (close to immature field), and, ii) clearly immature waters for Montagne Pelée (Rivière Picodo and Rivière Chaude).

**Early Hydrothermal Stages as Fossil Witnesses of the Geothermal Systems**

Identification of early fossil stages of the geothermal systems can make a relevant contribution to explain their evolution in time and space (Figure 3): i) determining how long they are active, ii) estimating their thermal temporal evolution (cooling, heating or thermal peak?) and iii) assessing if their spatial extent varies with time.

In Lamentin (Figure 3), prominent fossil silica sinter as high temperature occurrences, emplaced 250-300 ky ago (dated by U/Th, in Chovelon et al., 1984) and chlorite-epidote and illite-I/S assemblages identified in wells (~200°C) in total imbalance with the temperatures (80-90°C) of the current fluid, testify to a high temperature palaeo-system active 300 ky ago in the plain of Lamentin (Mas et al. 2003). In addition, in the Morne Rouge area, a large siliceous hydrothermal breccia (explosion breccia type), associated with silica sinter, suggests that the HT palaeo-system came into sharp boiling 300 ky ago. Later, temperatures inferior to 200°C, expressing the beginning collapse of the palaeo-system, has been suspected due to the presence of laumontite and corrensite in the wells (Mas et al. 2003). Today, kaolinite and smectite assemblage is stable with geothermal water (80-90°C). From a spatial point of view, the witnesses of the high temperature palaeo-system (silica sinters, explosion breccia, hydrothermal alteration and related arsenic anomaly) are distributed over a wide area of approximately 10 km² (at the surface), while the current water flow at 90°C and related kaolinite-smectite alteration (in wells) and conductive signature (CSEM method, Gadalia et al., 2014) are very limited in space (~ 1 km² at the surface). Therefore, assuming that both geothermal stages (fossil and current) are connected to the same geothermal system and comparing the current low temperature reservoir to the fossil high temperature reservoir, it can be seen that, between 250 ky and today, the Lamentin geothermal system gradually cooled (from ~250°C to 100°C in the reservoir) while contracting in space (from 10 km² to 1 km² according to surficial expressions).

In Petite Anse (Figure 3), the warm springs of Eaux Ferrées, located on the coast, are hosted in an intense argillic alteration with pyrite-montmorillonite smectite dominant (indicating ~100°C), which forms the caprock of a fossil geothermal system (Traineau et al., 2013). The scarce presence of interstratified illite-smectite and illite (>200°C) in this palaeo-caprock is interpreted as the result of warmer fluid upflow coming from the underlying geothermal fossil reservoir. Above this caprock (Figure 3), a typical kaolinite-alunite palaeo-alteration was identified, on the relief, in several sites distributed along a 2 km long NNW-SSE corridor between Petite Anse and Anse d’Arlet. This acid alteration is symptomatic of a palaeo-fumarolic activity, likely related to an early boiling event of a larger and / or shallower reservoir than the current one. These undated palaeo-alterations (neutral caprock on the sea level and acidic alteration on the relief) are the witnesses of an intense high temperature geothermal palaeo-system, whose the caprock is today at the surface, because of the flank collapse of the Morne Jacqueline volcano (Traineau et al., 2013) (Figure 3). Therefore in Petite Anse, we suggest that the geothermal system could begin several hundreds of thousands of years ago (300-500 ky?) with an intense geothermal activity recognized on several kilometers (under boiling conditions), whereas the current activity seems to have decreased in intensity (and perhaps slightly in temperature 190-210°C) and is contracted around Morne Jacqueline volcano. We interpreted this evolution as a retrograde trend of the system. However, strong magmatic signature of the $^3$He/$^4$He ratio (7.3-7.9 Ra according to Pedroni et al., 1999 and Gadalia et al., 2014) suggests a continuation (or renewal) of magmatic activity in the region despite the absence of volcano less than 350 ky, which could eventually maintain the current geothermal system at high temperature (~200°C).
In Bouillante, the high temperature geothermal system (250°C) is existing for at least 300 ky as indicated by an adularia-silica bearing breccia, partially eroded, and visible in outcrop above the current reservoir (Patrier et al., 2013). Recently dated at 250 ± 50 ky by 40Ar/39Ar on adularia (Vérati et al., 2014), this explosion breccia contains mainly adularia emplaced at >200°C, which is compatible with the current reservoir temperature. Thus, since 250-300 ky, the Bouillante geothermal system has maintained at high temperature (~250°C) without modification of its spatial extension, centered on the Bouillante Bay. This system appears particularly stable during a long period.

In Montagne Pelée, geothermal activity appears at most as old as the building of Pelée stratovolcano, which began 127 ky ago (Germa et al., 2011; Boudon et al., 2013). Thus, the stratovolcano is the main host rock of the geothermal reservoirs, located between 1000 and 2000 m in depth.

Comparing the spatial and temporal evolution of the four studied geothermal systems, it appears that the system of Bouillante remains stable in temperature (250°C) and in space during 300 ky, while the geothermal system of Petite Anse is marked by a spatial contraction of its reservoir and a reduction of its hydrothermal activity, which could be combined with a slight decrease of the temperature around 200°C. More advanced is the retrograde thermal evolution of the system Lamentin which gradually cools since 250 ky to reach 100°C today. The system of Montagne Pelée, as a still immature geothermal system, is likely to show a prograde evolution in the future (next 100 ky?).

### Magmatism as a Heat Source for Geothermal Systems

Recent magmatic activity has been recorded in Martinique (Westercamp et al., 1990; Germa et al., 2011) and is thought to be providing the required heat sources for the development of geothermal systems. Relationship between magmatic activity and hydrothermal systems can be tentatively analyzed even if ages are not well-constrained.

Petite Anse. The area of active and fossil hydrothermal activity is located within a volcano-tectonic corridor extending from Pointe Bouchot, et al.

Bouillante. The volcanic activity observed in the area of Bouillante belongs to the so-called Bouillante volcanic Chain which

### Figure 3. Surficial expressions as witness of fossil and active geothermal (hot springs) stages of the Lamentin (left) and Petite Anse (right) fields (Martinique).
has been active between 1.2-0.2 My (Gadalia et al., 1988). The most recent magmatic activity recorded at Bouillante is dated at 0.5My (500 ky): it is considered has the probable heat source of the high temperature geothermal system. The ^3He/^4He ratios of gas collected in the thermal fluids (4-4.7 Ra) is consistent with a rather long-lived degassing magma.

Finally, comparison of the four hydrothermal systems shows:
- the age of the magmatic activity considered as the heat source varies: 600 ky (Lamentin), 500 ky (Bouillante), 350 ky (Petite Anse), actual (Montagne Pelée),
- the duration of the magmatic activity varies: 1.1 My (Petite Anse), 0.7-0.8 My (Lamentin, Bouillante), 130 ky (Montagne Pelée),
- a time lag exists between the latest magmatic activity and the development of the (mature) hydrothermal system. It is estimated at 200 ky (Bouillante), 100-200 ky (Petite Anse, Lamentin), and more than 100 ky because the mature stage is not yet reached (Montagne Pelée).

**Toward a Continuum Geothermal Model**

From comparative parameters, summarized in Table 1, we propose a continuum model of geothermal system with three successive stages, prograde, peak and retrograde stages (Figure 4):
- The early hydrothermal stage is characterized by a rise in temperature of the system (prograde conditions) that follows an intense magmatic activity. During this prograde stage, the reservoir temperature reaches 220 °C (at Montagne Pelée) but the partial equilibrium of fluids with the rock is not yet reached (“immature waters”). At this stage, we can assume that the extension of system is limited and it will tend to be expanding later (if permeability and recharge are effective). This is the case of the system of Pelée stratovolcano; it is difficult to estimate the duration of this prograde stage but could be around 100 to 200 ky.
- The thermal peak stage reach 250°C in Bouillante system. This high temperature stage should be sustainable during at least 300 ky (plateau) and occupying the same volume of geothermal reservoir. This is the case of the system of Bouillante.
- A retrograde trend of the system could be characterized by a slight cooling of the resource (250 °C to 200 °C) coupled with a decrease of hydrothermal activity, partial equilibrium of the fluid and a contraction of the reservoir. This is the case of Petite Anse geothermal system.
- Advanced retrograde stage is marked by a significant cooling of the reservoir to reach 140-100 °C (Lamentin), coupled with an important contraction of the system. In this case, we can assume that the magmatic heat source is at the end of cooling because of its old age (> 600 ky) and that the geothermal system is progressively dying. This is the case of geothermal system of the Lamentin.

**Summary**

Such a continuum model should contribute to exploration in active volcanic arc setting such as the Lesser Antilles volcanic arc. It appears that a magmatic environment, both sustainable (700 ky to 1 Ma) and wedged in the time around 500 ky (magmatic peak), appears more favorable to the development of active high temperature geothermal system (peak stage).

To conclude, this model allows characterization of different geothermal systems, explored or exploited, according to their degree of evolution. Each stage of this development (prograde to retrograde) is associated with a specific use of the geothermal resource: production of cold or heat (around 100 °C), plus/or electricity production by binary cycle for temperature <180 °C, plus/or power generation by flash turbine as in Bouillante geothermal plant (> 200 °C).

**References**


