Multimodal geothermal exploration in the Lesser Antilles Arc at the Lamentin lowland (Martinique)

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1. Introduction

Geothermal energy is an opportunity for numerous parts of the world cut off from the power distribution networks. This is particularly the case of many islands and some peninsulas impacted by volcanic activity. While geothermal energy has a lot of environmental and economic advantages with respect to other traditional or renewable sources of energy, its sustainable development implies a greater component of geoscientific research adapted to the site to be exploited. The case of the Lamentin lowland, in Martinique (Lesser Antilles) is emblematic in this regard.
Figure 1. Martinique island and the Lesser Antilles arc modified from [25]. The inset is a simplified Martinique geological map from [8] where the investigation area is located. Ages are from Germa (2008) and figures from Labanieh (2008).

Geothermal exploration started more than 50 years ago (eg. [1], [2], [3], [4], [5]) and this study [6], constitutes its fifth session. This zone presented, at the beginning of the investigations, two major interests.

(i) There are the most obvious hydrothermal indices of the Martinique island: most numerous and hottest springs, massive deposits of hydrothermal silica and ubiquitous degassing.

(ii) The area of economic activity is in full expansion at the gates of the two main cities of Martinique, with high energy needs. Exploration, however, soon ran into difficulties, first of all due to the lack of geological outcrops as sediments, mangrove or sea cover most of the area. The urbanization also contributed to limit its access in particular to electromagnetic exploration. Additionally the geological complexity was gradually discovered:
(i) 5 volcanic complexes surround this lowland (eg. [7], [8], [9], figure1) and 4 fault directions, that played repeatedly in different ways, intersect them (eg. [10]);
(ii) a succession of hydrothermal activity phases [11], downshifted this zone from a high energy level (fluid over 200 °C) into an area of medium energy [12].

On the threshold of an announced development of renewable energies, of which geothermal energy is prominent in Martinique, it was important to overcome those obstacles by gathering the acquired knowledge and specifying some of them in order to move to the feasibility stage of the geothermal exploitation.

The objectives of this study lie in this context and should improve our understanding of the operation of the Lamentin geothermal system:

- clarifying the role of the faults from the recharge to the fluid circulation in the reservoir;
- defining the heat source(s);
- specifying the extent of the geothermal system.

Once the conceptual model of the Lamentin geothermal system has been updated, sites for implementing new exploration and even production drilling would be proposed.

2. Means and methods

2.1. GIS and 3D Geological modeling

The successive geothermal exploration campaigns but also other works inherent to the suburban growth of this zone, have produced a quantity of various data, strengthening the geological knowledge both on the surface and in depth. In particular, 13 thermal gradient boreholes [13] and 4 geothermal exploration wells [14], [15], [4] have largely been used as bases for building a Geographic Information System (GIS) and, beyond, a 3D geological model. This initiated space organizing and putting in coherence the numerous existing geoscientific data [16].

2.2. Electromagnetic surveys

The relevance of the CSEM in urban and marine environments was demonstrated during the 2013 geothermal exploration campaign [17], and an additional survey was carried out to better constrain the conductivity underground distribution. Those new measurements were

(i) compared to data acquired in 2013 by TEM (transient electromagnetic method) carried out by an helicopter-borne survey [18] and
(ii) supplemented by reprocessing AMT and MT (Audio-MagnetoTelluric and MagnetoTelluric methods) data, on the one hand, and on the other hand, “dipole-dipole” (electric method) data acquired during previous campaigns (years 80 and 2013) [17].

The spatial organization of the conductive layers allowed:

(i) understanding better the old high-temperature geothermal system the structure of which still largely conditions the current system;
(ii) highlighting conductivity contrasts between formations to structure the Lamentin geothermal field and its major north and south boundaries.

2.3. Gravimetric survey

Additional gravimetric survey, allowed emphasizing the density contrasts between formations and to image an underground set compartmentalized by network fractures.
2.4. Geological survey
Additional geological studies (field observations and measurements, thin sections microscope examination) led to

(i) specify the respective orientations and type of the various tectonic episodes, including the most recent with the seismicity examination [19];
(ii) characterize a possible magmatic activity that can be used to trace a heat source;
(iii) specify the thermodynamic and paleogeographic conditions as well as the extent of the previous hydrothermal phenomena to better qualify the old high temperature phase of the Lamentin geothermal system.

Examination of underwater bathymetric (eg. [20]) and sedimentological maps as well as low penetration seismic reflection profiles allowed highlighting the extent off shore of some structures identified on shore.

2.5. Fluids geochemical survey
New water sampling and analyzes, in the surroundings of and within the Lamentin lowland, were carried out to better understand (i) the possible links between the different groups of groundwater with the geothermal fluid, and (ii) the processes occurring during the ascent of this fluid to the surface.

The set of soil volatile species concentrations (As, Hg, CO$_2$, CO, He, Rn) has been integrated (eg. [21], [22], [23]) and reinterpreted. The identified anomalies highlight the zones of leakage of a deep circulation probably corresponding to active faults.

2.6. Hydrogeological synthesis
Taking into account the hydrogeological knowledge on the "Lamentin" aquifer of medium depth is useful to understand the hardly deeper circulation of the geothermal system.

3. Results and interpretations

3.1. Structural context of the geothermal system
The Lamentin depression is controlled by a complex and deep system of faults: since the beginning of its collapse (around 6.5 Ma), several successive tectonic episodes occurred and the same faults could have played in different ways (sometimes in opening, sometimes in shear). The opening gave birth to the Lamentin depression, which itself changed direction. This tectonic evolution is related to the subduction of the Saint Lucia aseismic ridge affecting the plunging Atlantic plate and impacting the lithospheric fractures system of southern Martinique and its volcanism (eg. [24], [9], [25] and figure 1). Seismicity confirms the depth and active directions of the involved mechanisms.

Together with the 3D geological modeling, the hydrogeological study [24] revealed, under the Lamentin lowland, a relatively "rugged" relief of the top of the old volcanic basement where more pronounced areas of subsidence follow up with marked uplifts.

The Lamentin depression is thus defined as a collapsed area, the subsidence of which continues, intersected and limited by different faults probably of lithospheric magnitude; some of them (NW-SE) are currently working in extension whereas others (NE-SW) have rather a role of accommodation.

3.2. Identification of a heat source for the geothermal system
What are the signs of a thermal anomaly in the Lamentin lowland?

3.2.1. Thermal manifestations.
Hot springs
More than a dozen of springs with surface temperatures exceeding 35 °C are recorded within the investigated area (figure 2). The contribution of gases to the warming of the thermal or surface waters they cross is highlighted; other species (arsenic, boron, ...), detected in thermal (and gaseous) waters (eg [12] and [15]), and possibly in soils (arsenic, mercury, ...) [21] may have been driven by high temperature gases. The thermal spring outlets are marked out by carbonate travertine and ferric oxyhydroxide deposits in relation with their degassing.

Anomalous thermal gradients in drill-holes
The spatial distribution of the thermal springs corresponds to that of the strong thermal anomalies; abnormally high thermal gradients (from 1 to 3 °C / 10 m), measured in boreholes [13] are generally related to current circulations of hot water at depth (figure 2). This distribution seems consistent with a convective circulation in a network of faults. The core of these thermal anomalies is located between Morne Cabrit in the west and the Petit-Bourg fault in the east, with an extension to Chateauboeuf in the northwest and Habitation Carrère in the southeast (figure 2). This thermal maximum corresponds to a deepening of the old volcanic basement (zone of greater subsidence) reflecting an area of lithospheric weakness where deep contributions are facilitated.

Gas emanations (springs and soils)
The chemical and isotopic analyses of the gas phase (helium, CO₂) display a magmatic signature [27]. A component of magmatic water, can also, marginally, contribute to the mixture. Radon and carbon monoxide (CO), with reduced lifetimes, are part of the series joining the deep gases during their ascent [22]. Arsenic and mercury [21] may be derived, at least partly, from the superficial leaching of deposits of the previous high temperature hydrothermal episode. Their association with other gas anomalies suggests that they may have been, also, driven, at depth, at high temperature by ascending gases.

The spatial extent of the soil gas anomalies exceeds that of thermal springs but remains limited (figure 2). Two compatible origins can be considered for this heat source of the Lamentin geothermal system:

(i) a magma body releasing gases during its cooling;
(ii) a deep fault allowing the rise of mantle fluids.

North and west of Chateauboeuf, thermal anomalies are still detected by drilling without reaching the thermal gradient levels of the northern Lamentin lowland. On the other hand, no soil gas anomaly has been detected beyond the North-Lamentin fault [23] and the mineral springs water in this zone (Moutte, ...) are not gaseous, unlike those from the Lamentin lowland. Further north, the mineral spring waters (Didier and Absalon) are enriched in carbon dioxide (CO₂), but have different geochemical characteristics [15] (figure 2). The North-Lamentin fault, in its new layout, forms, in this case, a boundary between two thermal and gas pressure domains. South of Petit-Bourg, in the southern part of the Lamentin lowland, only a few anomalies in soil gas concentrations remain, sparse, with no sign of hot groundwater. They may nevertheless reveal the remaining activity of the Rivière Salée volcanism.

3.2.2. Recent volcanism in the Lamentin lowland.
The hypothesis of a restricted volcanism in the Lamentin lowland, like other neighboring and quasi-contemporary small volcanoes (Rivière Salée, peninsula of Trois-Ilets) in the Center and South-West Martinique ([8], [9]) is confirmed from field observations, notably at Morne Rouge and geological descriptions of drilling logs, near the airport (figure 2). At Morne Rouge, volcanism is expressed by base surge deposits, typical of hydro-volcanism and is intimately associated with phreatic eruption breccias and voluminous hydrothermal deposits emitted during the previous geothermal high
temperature episode dated from 300 to 250 ka [10]. Those phenomena coincide with a crossing of NW-SE faults, parallel to the Petit-Bourg fault, and N-S one.

**Figure 2.** Synthetic map of the Lamentin lowland 2017 geothermal exploration results (gravimetric residual anomaly map in background)
The existence of such a volcanism, associated here with carbon monoxide (CO) and arsenic (As) anomalies, is consistent with the presence of a cooling deep magma body. However, its dimensions, at depth, must be limited enough so that it is not detected on the gravimetric anomaly maps. The current zone of major thermal anomalies coinciding with the Petit-Bourg Fault is located about 2 km east of those volcanic formations as well as the various and massive hydrothermal deposits of the previous hydrothermal phase. This shift can be explained by the sealing phenomena that affected the peripheral sectors of the Lamentin lowland.

This local volcanism, as an expression of a deeper magmatism, makes it possible to envisage, at the Lamentin level, a heat source closer from the Lamentin thermal manifestations than the Pitons du Carbet volcano (figure 1), a massif with a larger magmatic root and whose activity is slightly older (998 to 320 Ka) [9]. This change, more in line with the other data, will lead to a new conceptual model of the Lamentin geothermal system (figure 3).

3.2.3. Older hydrothermal episode.

The volume of hydrothermal deposits (sinters), forming the main reliefs of the Lamentin lowland, their association with phreatic explosions, and hydro-volcanism, their chemical composition [28] and the nature of the minerals forming them (silica, sulphides, barite, tourmaline, ...) show that the old phase of geothermal activity exceeded 200 °C and suggest that there has been a direct geothermal upflow from the reservoir, 250 - 300 ka ago.

Among the minerals of this high temperature hydrothermal phase, clays, studied in the cores of geothermal exploration drilling [11], allowed calibrating the conductivity measurements obtained during the electromagnetism campaigns. We will rely on this conductivity spatial distribution to define the geothermal system structure.

3.3. Hydrothermal circulation system and reservoir extent

3.3.1. Water quality evolution from recharge to spring outlet

The qualitative evolution of the Lamentin thermal water can be described by the following geochemical model:

- Step 1: infiltration of meteoric waters on the flanks of the Pitons du Carbet massif (annual rainfall reaching there 4 to 5 m), more than ten kilometers north of the Lamentin lowland, recharges the system in fresh water;
- Step 2: fresh water is mixed with about 25 – 30 % of seawater, interacts at depth with dominantly andesitic lavas and is heated at a temperature of 115 ± 25 °C, under a pressure of mantle-derived gas phase, leading to the formation of the geothermal fluid;
- Step 3: during its ascent towards the surface through some leakages, the geothermal fluid may be chemically reduced leaching the sulphides formed during the preceding hydrothermal high temperature phase;
- Step 4: at a sub-surface level, the geothermal fluid is mixed with some mangrove water, composed in approximately equal parts of river fresh water and sea water; sulphide are then oxidized and dissolved, leading to acidification and desorption of elements fixed on the clays as well as ions exchange from low temperature and high cation exchange capacity (CEC) clays (smectites).

The overall composition of the fluid, however, remains stable in time (over the last 50 years of analyzing it) and identical in the various thermal springs and productive boreholes of the Lamentin lowland (eg [2], [12]), taking into account variations resulting from shallow processes. This supposes a renewed homogenization at depth, probably obtained by convection, in agreement with the thermal measurements carried out in drillings. This homogeneity was, moreover, also present during the old high temperature geothermal phase, as far as we can judge from the chemical composition of the sinters [28]. This constitutes a sign of good circulation for both the old and the current geothermal resources.
3.3.2. Way of circulation of the geothermal fluid

Infiltration
Initially, between the recharge area and the geothermal reservoir, the water circulates in preferential underground channels consisting of fractured lava flows, pyroclastic deposits or clastic formations from the volcanic edifices of Pitons du Carbet and Morne Jacob. The water reaches deep through the faults, sometimes active, which intersect these formations.

Network of faults
The analogy with the groundwater of the aquifer located at medium depth (-20 to -75 m) in the Lamentin lowland and the lower valley of the Lézarde river [24] makes it possible to envisage, a similar type of circulation for the Lamentin geothermal reservoir intercepted in drilling (200-400 m):

- faults of various directions, connected with each other in a network, delimit panels;
- these panels consist mainly of fractured lava flows of the old basement;
- fluid during its ascent, can follow overlying sedimentary levels according to their permeability, with possible superposition of circulation layers.

In addition, convection in the Lamentin geothermal reservoir can explain thermal gradient inversions in some boreholes and temperature gaps between some thermal springs and neighboring drillings. It may be stimulated by the upflow of mantle-derived gases. The NW-SE Petit Bourg fault appears as the major geothermal circulation structure where probably most of the mixing with seawater and the interaction with the basement rocks under gas pressure occur. The distribution of thermal springs (in particular the numerous springs of Habitation Carrère and those of the airport, figure 2), like soil volatile species anomalies, can deviate slightly from the Petit-Bourg fault. The sinters location (Morne Rouge and others) shows that the core of the geothermal activity may have moved in the past. The current gaps between the main fault and thermal springs can be interpreted as

(i) resulting from the crossing with transverse directions (NE-SW) although those faults do not necessarily play in extension according the field observations
(ii) the expression of a multiple parallel fracturing "gradually moving from Morne Rouge toward Petit-Bourg fault during the last 300-250 ka period;
(iii) a fluid circulation through permeable levels from the Petit-Bourg fault.

Seawater supply
Geothermal system is most likely supplied with seawater, at depth, by the oblique fault of Chateauboeuf (N120 ° E), that crosses the Cohé du Lamentin and joins the Petit-Bourg fault (figure 2). Other transverse faults (N60 ° E), permeable levels of fractured lava flows or coarse clastic sediments can make additional contributions.

Leakages
If the thermal springs are numerous (probably not all are known in the mangrove zone), their respective flow remains low despite the pressure exerted by the ascending CO₂: although not measured, the flow rate of each spring is evaluated at less than 0.01 L/s. Their dispersion and their low flow rates illustrate the current difficulty of "leaking" through layers largely sealed by clay alteration and / or clogged with hydrothermal silica deposits.

Limits
The circulation of the geothermal system itself, at depth, is likely limited, to the north, by the North-Lamentin fault. The southern limit is the Center-Lamentin fault; this southern border, like the eastern
(Vauclin-Pitault massif, figure 1) and western (Morne Rouge to MorneCabrit) ones, are characterized by significant silicification affecting formations in contact with the fluid. These limits are mostly imaged by electromagnetic and gravimetric surveys. Permanence of the seismic activity probably allows keeping the circulation at the core of the Lamentin system.

3.3.3. Spatial extent of the Lamentin geothermal resource
The clay minerals study of the formations crossed by the geothermal exploration drilling [10] displays a superposition of two geothermal phases: an old high temperature one (≥ 200 °C) followed by a thermal collapse and a more recent phase of medium temperature (120 °C); this last result [11] coincides with the geothermometric calculations on the current fluid (115 ± 25 °C) [15], [29].

Electromagnetic records are determined by the clays Cation Exchange Capacity (CEC) and cannot discriminate those two episodes and will display the remaining conductive structure of the old high temperature phase.

In the northern part of the Lamentin lowland, a very conductive (<10 Ω.m), relatively thin (<100m) and superficial layer is highlighted. It is well discriminated from the seawater intrusion, quite limited in this littoral zone because of the hydrostatic pressure exerted by the waters coming from Pitons du Carbet. This level contains clays of strong CEC, characteristic of a high temperature geothermal caprock (smectites).

The underlying layer is moderately conductive (between 10 and 100 Ω.m) reflecting clays typical of a high temperature geothermal reservoir zone (illites, chlorites). More recently formed medium temperature clays do not impact significantly the electromagnetic measurements.

An underlying resistant zone corresponds to the resistivity of the old volcanic basement (> 100 Ω.m).

The spatial extent of the Lamentin geothermal system has probably been reduced during its cooling due to sealing (clay alteration or silica deposits). Dating [29] extends the impact of the silicification episode from the Acajou slopes in the north to near Sainte-Luce, about 8 kilometers south of the Lamentin lowland (figure2).

4. Conclusions : updated conceptual model of the Lamentin geothermal system
In the northern part of the Lamentin lowland took place a subsidence controlled by lithospheric-scale faults, mainly oriented NW-SE, through which mantle derived gases or even small quantities of magma rise. The conditions of operating a high temperature geothermal system were thus gathered there, 250-300 ka ago. The massive hydrothermal silica deposits (sinters) and areas of mercury anomalies show that the Lamentin lowland was then a zone of direct upflow from the geothermal reservoir.

These sinters constitute the signs of important leakages probably induced by a more marked seismic activity and/or, at a lower extent, to more permeable, coarser clastic sediments. Those hydrothermal deposits are characteristic of the older Lamentin geothermal system.

Following a joint decrease in fluid temperature and, likely, in fault activity, the circulation channels partially clogged, particularly to the west and south, leading to a shrinkage of the system. However, seismicity remains sufficient to maintain leaks giving soil gas anomalies as well as thermal and gaseous hot springs at low flow rate.

The current geothermal system has a temperature of 115 ± 25 °C according to chemical geothermometers and its fluid composition includes a 25-30 % share of seawater that has mixed with fresh water coming from the Pitons du Carbet slopes(figure3). The geothermal fluid composition and temperature are relatively stable and homogeneous judging from the thermal springs and the productive drilling, in spite of chemical modifications (mixing, oxidation, desorption, ionic exchange) occurring during its ascent to the surface. This may reflect a mixing of the resource thanks to a convection process within a network of faults.
The absence of thermal anomaly over the entire zone (on several drillings), on the one hand, and the non-detection of positive gravity anomalies in the Lamentin lowland suggest that the magma body, at the origin of volcanism as gas flows, is limited and deep.

**Figure 3.** Conceptual model of the Lamentin geothermal system (modified from Gadalia et al., 2014)

The supply of the system in seawater could be provided, north of the geothermal system by a diverticulum of the Petit-Bourg fault (Chateauboeuf), possibly associated with permeable formations. The NW-SE Petit-Bourg fault, hosting the convection, is the guide to the main current thermal anomaly.

5. **References**

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