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Assessment of the Bouillante Geothermal Field (Guadeloupe, French West Indies): Toward a Conceptual Model of the High Temperature Geothermal System

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ABSTRACT

The Bouillante geothermal field is located on the west coast of the French West Indies island of Guadeloupe (France, Lesser Antilles). The large range of scientific (geology, geochemistry, geophysics, hydrogeology) results obtained over the last 10 years on this field have made it possible to develop an innovative conceptual model of this high-temperature geothermal system; a reference for island-arc environments. The model highlights the major influence of structural control on the development of the recent volcanism and subsequent geothermal activity at different scales, and also explores new ideas concerning the Bouillante system in terms of heat source, deep fluid flow and reservoir geometry. In addition, a spatio-temporal scenario takes into account all events from the early magmatic activity of the Bouillante volcanic Chain complex (estimated at ~0.5 Ma) up to the development of the geothermal field some 200,000 years later.

1. INTRODUCTION

The Bouillante geothermal field, located on the west coast of the French West Indies island of Guadeloupe (Lesser Antilles), was explored in the 1970s, developed in the 1980s, brought into production in 1986, and expanded in 2005 to currently produce up to 15 MWe, or 7 % of the island's annual electricity needs (Sanjuan and Traineau, 2008). In addition to its electricity-producing role, the Bouillante field is an outstanding research laboratory for improving our knowledge of a reference high temperature (250-260°C) geothermal system in island-arc environment.

A great deal of scientific research has been carried out on the Bouillante field since the synthesis of past work published 10 years ago, including a structural analysis of the geothermal conduits, geophysical investigations both offshore (magnetics and high-resolution shallow seismics) and onshore (gravimetry, electrical resistivity tomography profile and passive seismic), characterization of the geothermal alteration, numeric geological modelling of the developed field, fluid geochemistry and tracer tests and hydrogeological modelling (e.g. Fabriol *et al.*, 2005; Guisseau *et al.*, 2007; Mas *et al.*, 2006; Thion *et al.*, in press; Lachassagne *et al.*, in press).

These multidisciplinary studies have substantially improved our knowledge of the geothermal field (reservoir, flowpaths, fluids origin, etc.) from the standpoint both of its geometry and of its dynamic operation. The aim of the present paper is to integrate all this recent knowledge into a preliminary conceptual model of the Bouillante geothermal system.

2. GEOLOGY

2.1 Regional Geology

The Guadeloupe archipelago forms part of the N-S-trending, 850-km-long, Lesser Antilles volcanic arc located at the northeastern edge of the Caribbean plate where the Atlantic lithosphere subducts southwestward beneath the Caribbean plate at a speed of 2 cm/yr (Feuillet *et al.*, 2002). The island-arc is located between the subduction trench and the Tobago submarine plateau to the east, and the Grenada back-arc basin to the west.

The Bouillante field is on the west coast of Basse-Terre Island, the westernmost and highest (1467 m) of the Guadeloupe archipelago. It lies within the area of both the 'axial Chain complex' (1.023 to 0.445 Ma; Samper *et al.*, 2007) and the 'Bouillante Chain complex' (1.1 to 0.2 Ma; Gadhia *et al.*, 1988) whose geographic extension on the western edge of the island is atypical (Fig. 1).

The Bouillante field is at the western end of an WNW-ESE volcano-tectonic depression belonging to the Marie-Galante graben system. At the scale of Basse-Terre Island, the depression is marked notably by the WNW-ESE to NW-SE Bouillante-Capesterre regional fault that passes immediately north of Bouillante where it is known as the Marsolle-Machette corridor. This extensive structure is bounded to the west of Basse-Terre (i.e. offshore) by a major NNW-SSE fault linking the normal-sinistral Montserrat-Bouillante system in the north with the Les Saintes system in the south (Fig. 1; Thion *et al.*, in press).

2.2 Local Geology

The Bouillante field is contained within a volcanic substratum largely attributed to sub-product of the axial Pitons de Bouillante chain cropping out along the axis of Basse-Terre Island.

The partly detrital and dominantly andesitic volcanic substratum is characterized by a succession of four lithological units. From top to bottom of the volcanic pile, these are: 1) the subaerial volcano-detrital unit 'A' (30 to 130 m thick), 2) the subaerial volcanic unit 'B' (160 to 240 m thick), 3) the shallow submarine to coastal volcano-detrital unit 'C' (225 to 400 m thick) and 4) the submarine volcanic unit 'D' (>2500 m thick).

Recent volcanic centres (1.1 Ma and 0.2 Ma) of the 'Bouillante Chain complex' defined by Gadhia *et al.* (1988) lie on this substratum. Aligned along a N-S band of some 20 km by 4 km, the 'Bouillante Chain complex' volcanism follows the offshore N160°E-striking fault of the Montserrat-Bouillante system (Fig. 1, Thion *et al.*, in press). The volcanic rocks have the characteristics of a

weakly potassic tholeiitic series that evolved through fractional crystallization from north to south (basalt, andesite in the north to dacite, rhyolite in the south; Gadalia *et al.*, 1988). The persistence of volcanic activity in the area for almost 1 Ma and the associated magmatic differentiation argue in favour of a common NNW-SSE trending- deep magmatic reservoir below the Bouillante Chain complex. Immediately north of Bouillante city, volcanic centres developed within the E-W to WNW-trending Marsolle-Machette corridor, suggesting a local tectonic control of this volcanism (Figs. 1 and 2).

At the scale of the Bouillante field, the lithological pile is cut by a network of high-angle normal faults striking N90°E to N120°E, including the main south-dipping Bouillante-Capesterre-(Marsolle) fault. This network comprises ~10 faults, spaced approximately 500 m to 1 km apart, with decametre to metre throws delimiting a mini graben. This graben is developed on the horsetail fault end of the regional south-dipping normal fault (Fig. 2). These faults developed in a brittle domain during a regional NNE-SSW-trending extension (Feuillet *et al.*, 2001).

2.3 Magmatic and Structural Controls of the Bouillante Field

The northerly trending Bouillante volcanic Chain complex is probably controlled by the submarine NNW-SSE strike-slip fault, which belongs to the regional normal-sinistral Montserrat-Bouillante-Les Saintes system. The Bouillante field is located at the intersection between this major submarine transfer fault, and the western horsetail fault end of the regional Bouillante-Capesterre normal fault which is a major corridor of the E-W Marie-Galante graben system (Figs. 1 and 2).

In detail, the Bouillante field has developed within a mini-graben. Backing up against the major south-dipping Bouillante-Capesterre-(Marsolle) fault, this graben is made up of a 'piano key' network of E-W antithetic faults which, considering their subvertical dip, favours tension opening subjected to NNE-SSW extension and the circulation of geothermal fluids (Fig. 2).

The most likely heat source of the Bouillante geothermal system is the magmatism of the Bouillante Chain complex:

- a range of arguments justifies the individualization of this volcanic series: i) the petrologically homogeneous character (tholeiitic type series) of the Bouillante Chain complex, ii) its cohesion in space and time, iii) its strong hydromagmatic component, iv) the presence of increasingly differentiated and younger products as one passes southward, and v) the alignment of the chain along a regional N160°E structural trend. Furthermore, these arguments support a connection between the chain's small volcanic centres and a common magmatic reservoir broadly controlled by the sinistral strike-slip movement of the regional Montserrat-Bouillante-Les Saintes fault (Fig. 1). The tholeiitic character of the suite results from a partial melting of the subducted oceanic crust below this fault. The magma from this melting could then be blocked at depth to form a common magma reservoir (at an undetermined depth). Near the southern end of the volcanic chain (absence of surface geothermal manifestations) this common reservoir could ramify into one or several secondary magma chambers with differentiation occurring at a shallower depth;

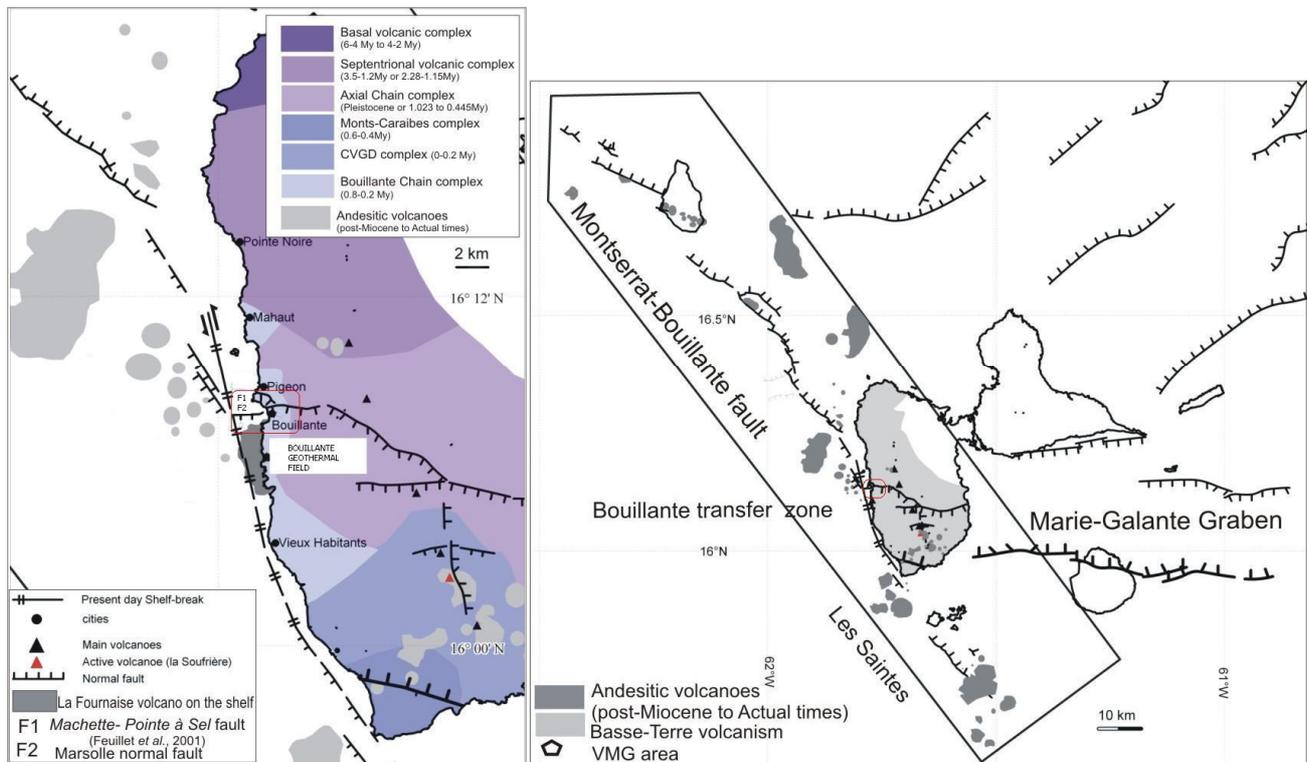


Figure 1: Regional and local tectonic settings of the Bouillante field, and associated volcanism (Thinon *et al.*, in press). (Right) Regional structural sketch of the Montserrat-Bouillante-Les Saintes and Marie-Galante tectonic systems. (Left) Location of the Bouillante geothermal field (western Basse-Terre) at the intersection of the NNW-SSE Montserrat-Bouillante-Les Saintes strike-slip system and the Marie-Galante graben system.

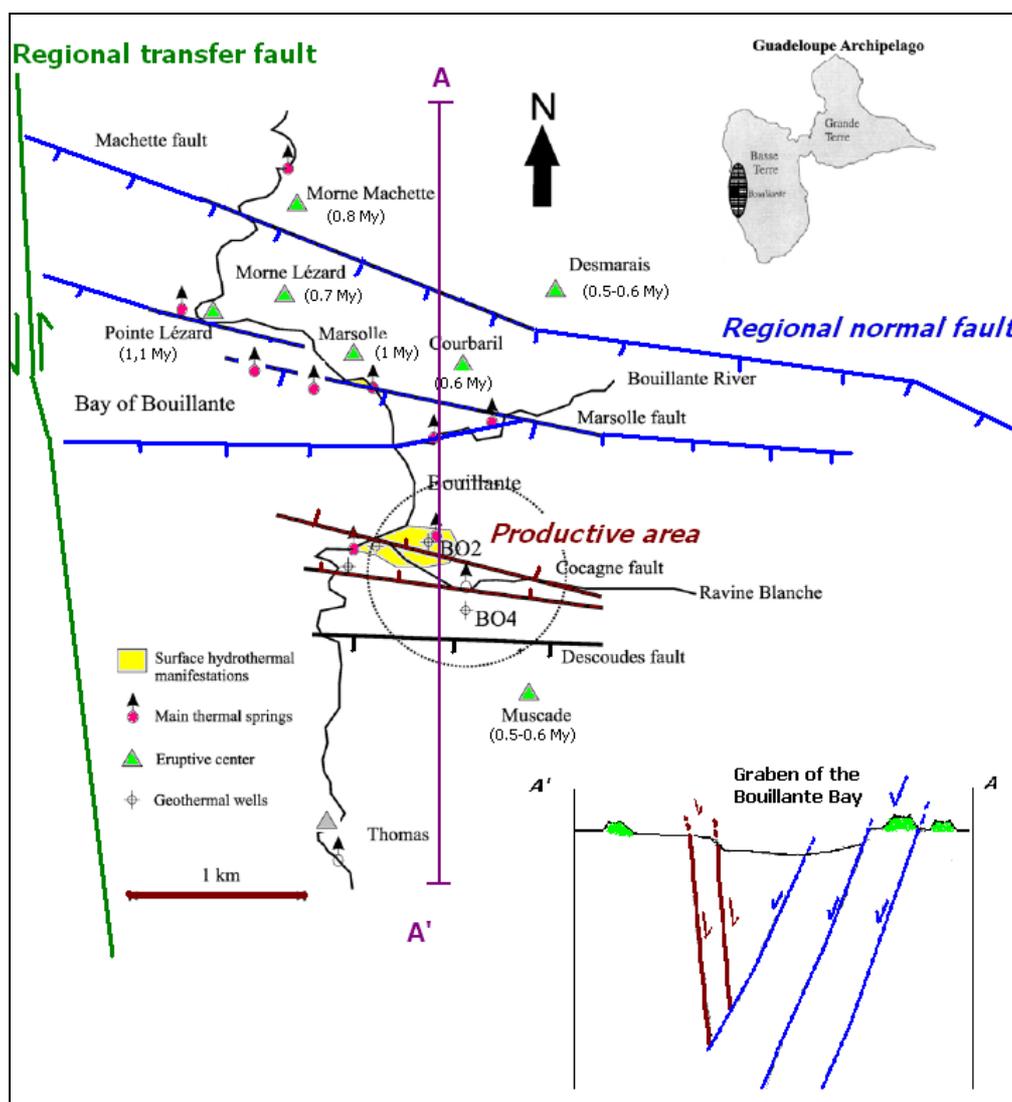


Figure 2: Structural pattern of the Bouillante geothermal field (network of E-W faults) with position of the main surficial geothermal expressions (modified from Mas *et al.*, 2006).

- an 6 km long- N-S alignment of geothermal surface manifestations within the volcanic chain reflects spatial fluid leakage from a high-temperature geothermal reservoir. Conversely, no leakage has been determined from the geochemical results obtained on the thermal spring waters located around the La Soufrière volcano. This volcano is located 15 km southeast of Bouillante field. Moreover, very marked differences exist between the La Soufrière gases and those of the Bouillante geothermal field, notably as regards their $^3\text{He}/^4\text{He}$ signature (Sanjuan *et al.*, 2001).
- the age of the Bouillante Chain complex is about 500,000 years in the Bouillante area, whereas the earliest known age of the geothermal manifestations is about 320,000 years (see below), which de facto excludes the La Soufrière volcanism which is younger than 200,000 years.
- field data: mapping of the volcanism, structural analysis of the outcrops, surface hydrothermal manifestations, analysis of the hot waters and gases;
- direct borehole data (to 2504 m in depth in BO4): temperatures, zonation of the hydrothermal alteration, production zone, geological log, geochemical and isotopic composition of the fluids;
- indirect geophysical data, notably from the electrical profile to 700 m depth, and the offshore seismic profiles.

3.1 The Geothermal Fluid

The geothermal fluid of the Bouillante area, taken from the tapped reservoir or reconstituted from hot springs, is homogeneous in its composition. It corresponds to a sodium chloride (NaCl) brine with a salinity approaching 20 g/l and a pH of around 5.3 ± 0.3 at 250-260 °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 250-260 °C (Sanjuan *et al.*, 2001).

3. THE BOUILLANTE GEOTHERMAL SYSTEM

In view of the small number of geothermal wells (7) and the difficulty of outcrop observation (tropical climate), we have limited amount of robust data available to build a conceptual model of the Bouillante geothermal system, i.e.:

One can reasonably infer that the meteoric water supply comes from the western side of the Pitons de Bouillante.

The measured temperature and pressure conditions in the wells indicate that the geothermal fluid is only in liquid form in the reservoir. The incondensable gases, primarily CO₂ (>90%), account for approximately 0.4% of the water vapour mass (Sanjuan et al., 2001). The ¹³C and ³He/⁴He isotopic signatures of these gases indicate a combined magmatic, marine and meteoric origin, recording a link between geothermal activity and magmatism.

3.2 The Bouillante Field at the Surface

Surficial expressions of the geothermal field are characterized by direct discharges of geothermal fluid along the coast (the lowest points acting as outlets) and offshore as hot springs and also gas emissions (e.g. CO₂, CH₄, He, Rn) preponderant at fumaroles and hot soil (Fig. 2). The density of occurrences culminates in Bouillante Bay, as ~120 °C submarine springs and gas emissions.

In addition, this bay was probably the seat of a phreatic explosion (Gadalia et al., 1988), as indicated by the many blocks of hydrothermal breccia collected near the Marsolle fault. Clasts and cement of the breccia are both characterized by a mineralogical assemblage with adularia, ordered illite-smectite mixed-layered clay and silica (± calcite and jarosite), indicators of high-temperature fluids (around 200 °C). The breccia would have resulted from the contact of very hot geothermal fluids (suboutcropping reservoir) with cold phreatic groundwater (Patrier et al., 2003). The K/Ar method on adularia gives the age of the breccia as 320,000 ± 20,000 years (N. Clauer, written comm.). This age would correspond to the phreatic explosion, i.e. the emplacement of the high-temperature fluid reservoir close to the surface, and thus marks the beginning of the active geothermal field approximately 320,000 years ago.

If one considers that the heat source is related to a magma chamber associated with the volcanism of the Bouillante Chain complex (see above), then there was a time lapse of approximately 200,000 years between the initial activity of the geothermal field (300,000 years) and the end of the volcanic activity (~500,000 years) close to Bouillante.

3.3 Zoned Hydrothermal Alteration Halos

At depth, the Bouillante geothermal field is characterized by a zoned distribution of the neutral-chloride -type hydrothermal alteration, classic in high-enthalpy geothermal systems within an island-arc context. This alteration develops pervasively in the rock to form zoned hydrothermal halos roughly parallel to the isotherms from the surface down (Mas et al., 2006; Guisseau et al., 2007, Fig. 3):

- a montmorillonite-type dioctahedral smectite zone (<100 °C) predominant in the subsurface and disassociated from the geothermal system, knowing that montmorillonite results from supergene processes related to shallow groundwater;
- a zone of beidellite-type dioctahedral smectite (110 to 163 °C), knowing that beidellite precipitates from geothermal fluids;
- an illite-smectite mixed-layer zone generally, which becomes progressively richer in illite with depth (180 to 250 °C). Epidote and wairakite (zeolite) appear together with temperatures above 200°C;
- a chlorite zone (with +- illite), well developed below 700 m depth, with stable temperatures of 250-260 °C (main reservoir).

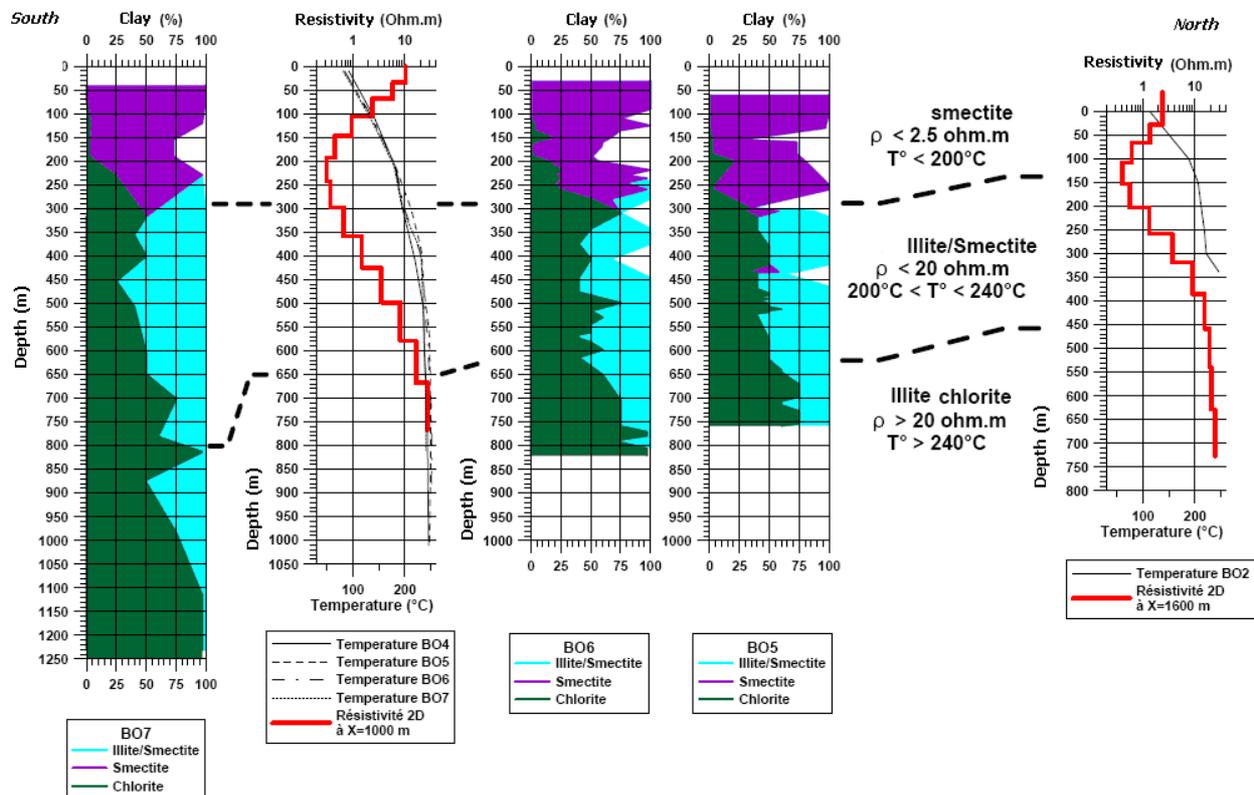


Figure 3: From south (B07) to north (B02), well data on hydrothermal alteration, temperatures and/or resistivities (modified from Bourgeois and Debeglia, 2008).

Even if chlorite is assimilated to a propylitic alteration earlier stage, the equilibrium between the high-temperature hydrothermal minerals, such as illite and chlorite, and the temperature conditions measured in the wells, indicates that the Bouillante geothermal field system is in a prograde phase (Mas *et al.*, 2006).

Broadly, the 8-km-long N-S trending resistivity profile (base of the Fig. 4) reveals, between 0 and 700 m depth, a subcontinuous conductive band (resistivity <2.5 ohm.m) interpreted, at the level of Bouillante, as a 'colder' argillaceous zone with predominant smectite (Fabriol *et al.*, 2005). This conductive band is 'mushroom head' shaped whose cap, may mark the top of the hydrothermal convection cells of the Bouillante system. In detail, well data on hydrothermal alteration and measured temperatures (Fig. 4) shows that the paths of the hydrothermal halos and associated isotherms rise towards the surface from the south (Descoudes fault) up to the north (Marsolle fault): an interval that represents the mini-graben of the Bouillante Bay (Figs. 3 and 4). The high density and temperature (up to 120 °C) of the submarine hot springs and evidence of hydrothermal explosion breccia at the level of the bay indicate that the uppermost part of the heat reservoir and the associated upflow zone is centred on the Marsolle fault below Bouillante Bay.

3.4 Geometrical Model of the Reservoir

The reservoir of the Bouillante field can be defined by two units: i) a heat reservoir corresponding to the total rock volume affected by intense pervasive hydrothermal alteration (mainly illite and chlorite zone) with a homogenized temperature of 250-260 °C; ii) a hydraulic network made up of permeable faults and porous aquifers along which the geothermal fluids circulate within the confines of the heat reservoir.

The pervasive alteration was concomitant with an intense ascending circulation of hot fluids along conduits, thus explaining the homogenization of the reservoir temperature around 250-260 °C and of the fluid's chemical composition.

The top of the heat reservoir, located at the base of the illite-smectite zone, deepens from north (~300 m) to south (~600

m) of the geothermal field, i.e. in moving away from the apical zone of the reservoir centred on Bouillante Bay.

Based on the well data, electrical resistivity tomography signature and the volcanic and structural mapping of the field, we consider that the most likely geometric hypothesis for the reservoir is as follows (this study).

In a N-S section (Fig. 4), the envelope of the heat reservoir is in the shape of a fist, about 2 km wide between Descoudes and Pointe Lézard, dependant on the geometry of the Bouillante Bay mini-graben controlling the fluid circulation. This envelope could be rooted at about 2500-3000 m depth in the Marsolle – Pointe Lézard corridor (i.e. a reservoir height equal of 2 km or more) if one accepts the hypothesis of a circulation of deep fluids controlled by the major tectono-magmatic corridor. The 240 °C isotherm roughly delimits the geothermal reservoir in this geometrical model. Its singular path below 1000m (toward the main fault), shows negative values of temperature gradient, as measured from 1000m to 1800m depth in Well BO-4. Such thermal signature is typical of the mixing zone of convective systems, and thus, could contribute to a more precise estimate of the reservoir geometry.

Along the E-W axis of the graben (Fig.5), the evidence of many geothermal discharges from the shallow reservoir in the Bouillante Bay confirms the extension of the reservoir offshore. The width of the reservoir could be of the order of 1 km onshore and 2 km offshore up to the major N160°E-striking fault.

In terms of permeability, the most productive conduits are the high-angle E-W faults and, to a lesser extent, certain lithological facies such as the discontinuous sandy layers, located at 400 m depth in two wells. The Cocagne fault is the zone of highest permeability intersected by two wells, providing a fracture zone several tens of metres wide (Fig. 2). The two same wells also intersect the Plateau fault which again shows good permeability, although less than that of the Cocagne fault. The Plateau fault's permeability is lower because the fault was intersected at a shallower depth than the Cocagne fault; being still in the illite-smectite zone it contains a higher proportion of argillaceous products.

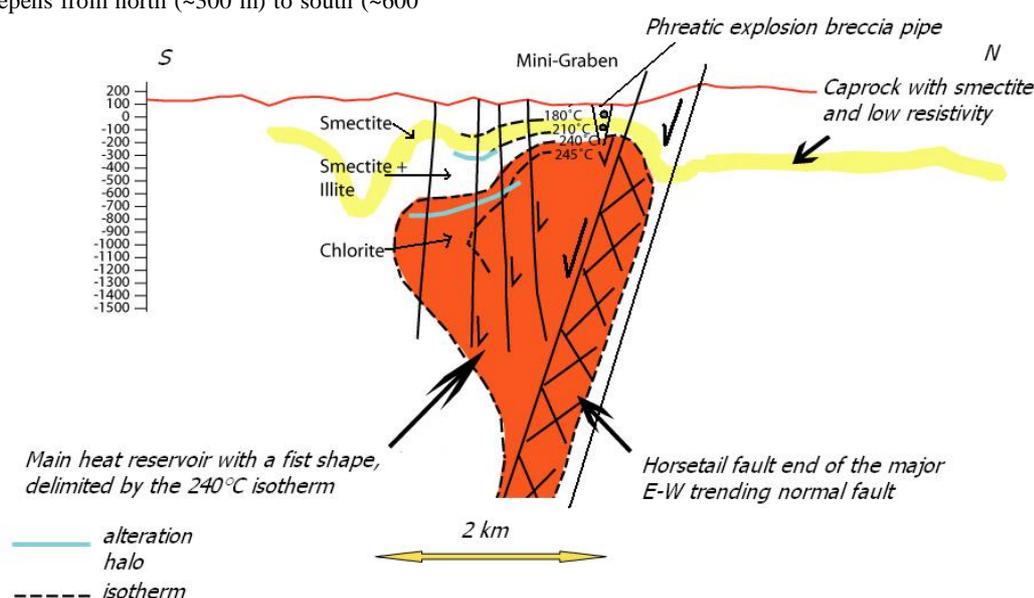


Figure 4: Preliminary conceptual model along a N-S section of the Bouillante geothermal system based on multidisciplinary borehole and surface data (see Fig. 2).

The presence of N-S faults remains to be demonstrated within the area of the tapped geothermal reservoir. However, the presence of the nearby offshore N160°E corridor tends to prove the existence of such fracturing which would increase in intensity as one approaches the corridor in question. Under this hypothesis, it is likely that the northerly-trending fracturing at the level of the tapped field would be a network of discrete N-S fractures likely to provide an interconnection between the E-W faults. Conversely, offshore, this northerly fracturing would certainly be better expressed, thus favouring large flows aided by the N-S connectivity.

3.5 Fluid Flow, Leakage and Recharge of the System

The fluid tracer test carried out in 2007 suggests a geothermal fluid flow direction from north to south. During the test, the average fluid circulation velocities were estimated at 0.3-0.4 m/h (Sanjuan *et al.*, 2008).

The geothermal reservoir, due to its impermeable smectite bearing cap rock, seems to have a very low leakage rate estimated in the region of 1 to 10 m³/h (Lachassagne *et al.*, in press). This leakage rate is reflected by the presence of hot springs mainly located in the littoral zone (topography-linked outlet) and offshore.

Excluding production, the leakage rate is compensated by a same rate of recharge with 42% being assured by the

infiltration of meteoric water immediately overlying the inland section of the aquifer and some 58% by the infiltration of seawater in the offshore section. The fresh water recharge rate of the geothermal reservoir (0.5 to 5 m³/h at the most) is only a very small fraction of that of the aquifers (mainly subsurface): a few millimeters per year at the most, for a total recharge assessed at 150 to 400 mm/year, depending on the watershed.

Based on ⁷Li isotopic arguments (Sanjuan *et al.*, 2008; Millot *et al.*, writ. comm), a probable meteoric water / seawater mixing zone occurs at the transition between the ocean floor and the overlying andesitic lavas. This interface, whose depth is estimated at >3 km (if not 5-6 km) beneath Basse-Terre Island is a preferential site for fluid circulation (Chan *et al.*, 2002). The deep mixing zone could be connected to the currently tapped reservoir via the regional Bouillante-Capesterre fault whose horizontal extension (>50 km) allows for a multi-kilometre vertical extension. On the other hand, given its orientation perpendicular to the N-S coast line (partly offshore, partly onshore) and its regional extension, the E-W to NW-SE Bouillante-Capesterre fault would be a major conduit hosting multi-kilometre E-W convective flowpaths. These paths would enable the descent of cold water to either side of the reservoir (58% marine, 42% meteoric), then the rise of hot fluids towards the Bouillante reservoir from a mixing zone located at more than 3 km depth.

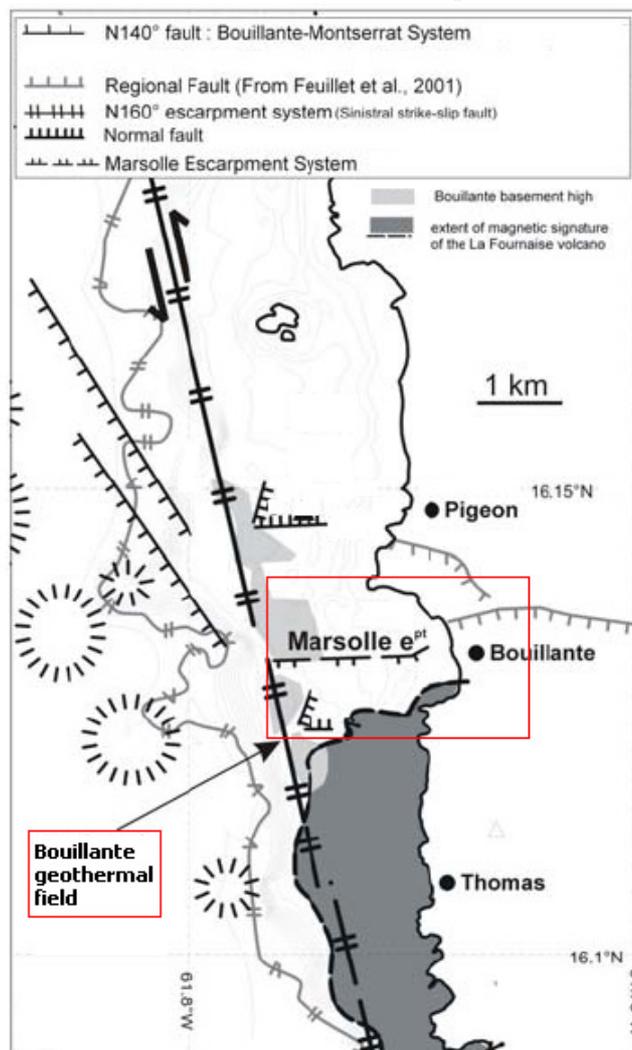


Figure 5: Offshore structures outlining the presumed area of the Bouillante geothermal field (modified from Thinon *et al.*, in press).

4. SPATIO-TEMPORAL SCENARIO FOR THE EVOLUTION OF THE BOUILLANTE FIELD

The synthesis of our knowledge described in the preceding sections enables us to consider a spatio-temporal scenario for the evolution of Bouillante, from early magmatic activity to development of the geothermal field.

Between 1.1 and 0.2 Ma, the Bouillante Chain complex developed both onshore and offshore along a northerly trending axis some 20 km long and controlled by the N160°E strike-slip fault (Montserrat-Bouillante-Les Saintes system, Fig. 1), whilst at Bouillante, on a local scale, the formation of the volcanic centres at about 0.5 Ma was controlled by the E-W-trending Marsolle-Machette corridor (Fig. 2). A common cooling magma reservoir located at depth beneath the Bouillante volcanic Chain complex would provide the heat source of the geothermal field.

The Bouillante geothermal system developed in this favourable structural context, and more precisely within a mini-graben located at the intersection between two major faults, no later than 200,000 years after the magmatic activity. The graben is made up of a network of E-W 'piano key' faults which, in view of their subvertical dip, would have favoured tension opening (strong component with respect to the shearing during the regional NNE-SSW extension) and thus the circulation of geothermal fluids. This network abuts against the regional corridor between Marsolle and Pointe Lézard.

The rise of hot fluids through the rock mass would preferentially be along this tectono-magmatic corridor. On arriving near the surface, their emergence would be blocked by the rather impermeable volcanic centres, occupying the upper part of the Marsolle-Pointe Lézard corridor. The fluids would thus leave the major fault at depth and concentrate in the Bouillante Bay mini-graben (with no recent volcanism). For this, the fluids would follow the network of subvertical normal faults, knowing that at depth these faults, mainly north dipping, are likely to be grafted onto the major south-dipping Marsolle fault zone.

With the arrival of the fluids, zoned alteration halos gradually developed at reservoir scale, centred beneath Bouillante Bay. This hot reservoir (250-260 °C) thus finds itself capped by a smectitic argillaceous cover which progressively blocks the hot ascending fluids. The reservoir is thus the centre of intense geothermal fluid circulation in a convection pattern along different possible conduits (E-W faults in priority, assumed N-S fracturing, sandy layers, etc.), homogenizing the reservoir temperature at about 260 °C.

Small amounts of fluid escape from the reservoir to reach the surface along faults (notably the Marsolle and Cocagne faults), even though these discontinuities are largely plugged by impermeable argillaceous products where they cut the smectite alteration zone. At about 320,000 years, when the system developed near the surface (apical part of the reservoir), the arrival of hot fluids via the Marsolle fault would have provoked a phreatic eruption to have given rise to an amagmatic maar-type crater in Bouillante Bay.

6. CONCLUSIONS

To conclude, our synthesis of recent work carried out on the Bouillante field has enabled us to propose an innovative conceptual model based on solid field data and on working hypotheses necessary for deeper thinking. Many scientific questions remain unanswered, and working hypotheses needs to be confirmed or invalidated, such as role of the

recent volcanism as heat source, hypothetical magmatic chamber, extension of the reservoir in depth, duration of the geothermal system.

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