Volcanological context of the Bouillante high temperature geothermal system, Guadeloupe, Lesser Antilles

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Abstract. The hydrothermal manifestations of Bouillante area (Guadeloupe, Lesser Antilles) motivated a geothermal survey in the sixties. Nevertheless, the heat source of the Bouillante hydrothermal system is still debated: (i) local magma body, (ii) magmatic source beneath the centre of the island or (iii) result from the deep circulation.

Several arguments support the first hypothesis and the definition of a specific volcanic series, the « Bouillante chain », according to the following characteristics:
- location: small monogenic volcanoes are scattered along the Caribbean coastline, on- and off-shore;
- structural control: volcanic centres have developed at the junction of two regional tectonic systems, the NNW-SSE trending Montserrat - Les Saintes fault and the sub-E-W trending Marie-Galante's grabens system;
- dynamics: their products often result from a magma - water interaction between, either in an external or internal hydromagmatism;
- petrology: specific magmatic trend reached an extreme (rhyolitic) level by crystal fractionation.

The links between the Bouillante chain and contemporary / neighbouring other Guadeloupe volcanic formations (Les Mamelles domes, Axial chain, Caraïbes mountains, Grande Découverte volcano) are discussed but partly remain to be specified.

1. Introduction

Among the characteristics of a high temperature geothermal system, the heat source sometimes remains unidentified after the exploration phase. This question remains a paramount one to guide the geothermal exploration. Moreover, while it is generally accepted that high-temperature geothermal sites generally coincide with recent or active volcanic areas, such as the Lesser Antilles arc, this relationship is by no means systematic. Bouillante geothermal system (Basse-Terre of Guadeloupe, Lesser Antilles) is an interesting example regarding both those aspects.

The objective of this article is therefore to characterize the heat source of the Bouillante geothermal system by taking into account (i) the works carried out for 30 years around the Bouillante field,
following the geothermal exploration and (ii) geoscientific studies dedicated to the definition of volcanic complexes and associated structures on the Basse-Terre island.

In Guadeloupe, geothermal exploration began in the early 1960s and continued through various campaigns (1982-85, 1997-2000, 2009-2013, 2016) while drilling was implemented (1977, 1999-2000) and two production units were commissioned (1985 and 2000). At the end of the 1980s exploration campaigns, a first synthesis was carried out on the Bouillante Chain [1] considered as the magmatic heat source of the Bouillante geothermal system.

Subsequently, multimodal geothermal exploration led by the BRGM and including university teams, made it possible to specify how operates the geothermal underground loop on the Bouillante site: tectonics (e.g. [2]), petrography of volcanism [3], mineralogy of magmatism (Moenne-Loccoz, 2012), hydrothermalism [4], geochronology [5], bathymetry [6], geochemistry of water and gas sources and boreholes as well as soil gases [7], gravimetry, aeromagnetism, electrical profiling, TEM, magneto-telluric, 3D seismic surveys [8]. A structural model of the Bouillante region [9] and a geological model of the geothermal system [10] have been proposed.

Numerous complementary geoscientific studies were performed on Basse-Terre island, particularly in tectonics (e.g. [11], [12]), in geochronology/geomorphology (e.g. [13], [14]), geochemistry (e.g. [15], [16]), petrology [17], volcanology [18].

Following these works, the options concerning the heat source of the Bouillante geothermal system can be summarized in three types: (i) local magma body (Bouillante volcanic chain), (ii) remote magmatic source beneath the center of the island (recent Axial Chain or La Soufrière active volcano) or (iii) result of the deep circulation without special magmatic contribution (Montserrat - Bouillante - Les Saintes fault system).

This paper will attempt to integrate the various new data to confront them to those hypotheses, in particular to the one involving the Bouillante Chain.

2. Geological context

2.1. Geodynamic and structural framework
The Lesser Antilles active island arc marks the eastern boundary of the Caribbean plate underthrust, in a subduction zone, by the oceanic crust of the Western Atlantic Ocean (Figure 1). Several features characterize it:

![Figure 1. Regional synthesis of the Guadeloupe archipelago [9]](image-url)
NB: in dark gray, on the right figure, the submarine volcanoes following the Montserrat accident - Les Saintes

- a relatively slow rate of North American plate subduction (2.1 to 2.2 cm/year [19]) leading to lower magmatic production than on other island arcs [20];
- a considerable crustal thickness of the Caribbean plate (35 km) possibly hindering the direct ascent of the magma produced at the mantle wedge of the subduction zone and favoring the stalling and differentiation of magmatic stocks (e.g. [21]);
- the presence of several aseismic ridges on the sinking plate, braking its subduction, the magmatic production and inducing deformations of the overriding crust (e.g. [22]);
- the existence of two arcs, separated in the northern half of the arc: the external one, active from the Eocene to the lower Miocene and the internal one, which is built, some ten million years later, further west, and remains active today. Bouysse and Westercamp [23] proposed to link this westward shift and the interruption of volcanic activity with the arrival, at the Upper Oligocene, of the Tiburon aseismic ridge at the level of the subduction zone (Figure 2). This would have had three consequences: (i) blocking the subduction of the Atlantic plate, (ii) stopping the magma production, (iii) at the Pliocene, bulging of the Désirade, Basse-Terre and Marie-Galante, (iv) straightening of the slab and (v) when it reaches 140 km depth, resumption of magma production but with a westward shift of the volcanic front more marked from the latitude of the Guadeloupe archipelago (see figure 2);

![Figure 2. Sketch of westward migration of Antillean volcanism following subduction of an aseismic ridge (from [23])]()
Basse-Terre island is in an intermediate position between the northern islands, from Saba to Montserrat, where the tholeiitic series predominate, and central islands from Basse-Terre itself to Saint-Lucia, dominated by andesites [24], [25]. The compositions of its lavas are logically straddling the calc-alkaline and tholeiitic domains [26]. Moreover, differentiated volcanic products, from andesites to rhyolites, are more significantly present on the northern and central islands. Finally, the central segment of the arc has a much higher eruption rate (0.4 km$^3$/ka) than in the northern and southern islands (0.015 km$^3$/ka) [20].

From a petrogenetic point of view, the authors converge on the hypothesis of magmas produced by an N-MORB type mantle source, modified by the addition of fluids from the subducted plate (crustal contamination, sediments, etc.), crustal or mantle dehydration. However, the respective components of this contribution is still debated. North of the arc, the isotopic composition is more homogeneous than in the south, where heterogeneity of the source mantle and variation of genesis processes are invoked.

The partial melting rate is approximately constant (10 to 15%) along the arc [27]. Seven volcanic series (Figure 3) have been identified on Basse-Terre [28], [29].

2.2.1. Basal Complex
Dated between 2.79 ± 0.04 and 2.68 ± 0.04 Ma [13], those formations consist of massive lava flows mostly andesitic, very eroded and some domes. The volcanic plumbing system would be driven by N-S to NNW-SSE faults and is contemporaneous of the progression of the Desirade graben toward Basse Terre. West of the Basse-Terre coasts, submarine volcanic seamounts are attributed to this episode: the Directeur volcano, dated between 2.5 and 2 Ma and that of Vieux-Fort between 3.7 and 3.4 Ma [22].

2.2.2. Northern Chain
The age of these composite and eroded volcanoes ranges from 1.81 ± 0.03 to 1.15 ± 0.02 Ma [13]. No clear trend of migration emerges during its activity (only 650 ka), but it starts rather at the North and ends at the South with the two domes of Les Mamelles. A recent zircon U/Th dating (1.05 ± 0.06 Ma, Lach, 2018) slightly extends the age spectrum of this volcanic province. Its NNW-SSE general striking links it to the extensional fault system of the Eperon de Bertrand-Falmouth [30]. It is an essentially effusive volcanism (flows and domes) whose products belong to a calc-alkaline series, enriched in K$_2$O compared to the other Basse-Terre series [26]; the differentiation reaches rhyolitic magmas.

2.2.3. Axial Chain
After a likely submarine stage, producing large units of hyaloclastites, a fissural volcanism occurs controlled by the Montserrat - Les Saintes accident through a normal faults system [13]. Nested composite edifices are then built in four stages: (i) Pitons de Bouillante from 906 ± 13 ka to 712 ± 12 ka, to the North, (ii) Moustique - Matéline - Capesterre complex from 681 ± 12 ka to 509 ± 10 ka and finally (iii) Sans-Toucher volcano from 451 ± 13 ka to 412 ± 8 ka [14]. Due to severe erosion, only a quarter of the volcanoes remain [14]. The lavas evolve from basalts to dacites but basaltic andesites and andesites dominate. Their composition is depleted to moderately enriched in potassium, from calc-alkaline to tholeiitic lavas. The nature of two depressions within this chain is still debated: after being interpreted as caldeiras [31], some authors attributed them to flank collapses (e.g. [32]) when others see them as the effect of erosion in intensely faulted areas [1],[14] (see § 3.3.).

2.2.4. Bouillante Chain
This string of small edifices, all eccentric toward the Caribbean coast, forms a particularity in the Basse-Terre volcanism. The individualization of this series is, moreover, still in debate. Some authors see it as Axial Chain adventive cones [13], [14]. For others [1], the following characteristics justify considering it as a specific series that has operated parallel, in space and time, to the Axial Chain: - volcanic activity distributed from 1.07 to 0.24 Ma, partly synchronous with that of the Monts Caraîbes, the Axial Chain, or even the beginning of the Grande Découverte volcano;
- NNW-SSE alignment of generally monogenic volcanoes superimposed on the Montserrat-Bouillante-Les Saintes accident, along the Caribbean coast, onland and off shore;
- predominantly hydromagmatic activity;
- very broad petrological spectrum from basalts to rhyolites displaying marked differentiation;
- evolution of a tholeiitic magma, weakly potassic, with frequent magma mixing.

To these peculiarities is added the development of a still active hydrothermalism (thermal springs connected or not to a geothermal reservoir, hydrothermal alterations, ...) occurring in many formations of the Bouillante Chain.

Gstalter [33] favoured the hypothesis of several small, shallow magmatic reservoirs periodically fed from deeper magma storage levels.

2.2.5. Monts Caraïbes

They form the southernmost volcanic set of Basse-Terre and are dated from 555 ± 26 to 472 ± 16 ka [34], in agreement with the magnetic polarity. Their activity has thus been contemporaneous of the southern Axial Chain (Sans-Toucher) and of the Bouillante Chain.

They were mainly built around three emission centers (Houelmont, Grande Voute and Grand Ajoupa) [17] aligned according to the regional NNW-SSE direction, probably in connection with the Montserrat-Les Saintes fault system.

Their magmatic production differs from other Guadeloupean series by the importance of basaltic products and the diversity of cumulate rocks [17]. It has been split in three series: (i) series I, an aluminous paragenesis, of calc-alkaline affinity, (ii) series II with a more marked tholeiitic character and (iii) a more differentiated series depleted in LIL and REE. According to Bissainte [17], the Monts Caraïbes do not result from a single cogenetic series ranging from basalts to dacites, but from several packages of magma, of small size, having evolved separately, at different depths, in an open system, with, however, mechanical mixing phenomena between basic and differentiated terms.

2.2.6. Grande Découverte – Soufrière Volcanic Complex (GDS)

The construction of this volcanic complex, whose activity is still ongoing, has been split into three phases:

(i) Grande Découverte phase: initially constrained between 200 and 42 ka (e.g. [32]), the beginning of its activity was extended at 445 ka [29]. The edifice consists of alternating andesitic lava flows; explosive episodes resulting in the formation of three calderas are accompanied by some highly differentiated pumice emissions [33]; at least three flank collapses have marked this episode [35].

(ii) Carmichael phase (42 - 11.5 ka): it was characterized by the growth of a composite volcano in the heart of the Grande Découverte caldeira with emission of lava flows and especially dome extrusions generating important pyroclastic flows as well as pumice events (e.g. [26], [32]) plus, at least, two flank collapses [35].

(iii) La Soufrière phase (11.5 ka to present): successive dome extrusions interposed between periods of explosive phreatic activity producing thick layers of ash fall; numerous flank collapses occur as well likely facilitated by intense summit hydrothermal activity.

The GDS complex belongs to the calc-alkaline domain with dominant basaltic andesites and andesites [29]. Magma mixing is observed from the first phases to the last eruptions where rhyolite glasses have been analyzed in crystal inclusions as in the matrix of some rocks (e.g. [36]). Gstalter [33] emphasizes that the Grande Découverte pumices remain in the tholeiitic domain. The preferred petrogenetic hypothesis (e.g. [37]) is that of a single zoned magma chamber.
Figure 3. Geological sketch of Basse-Terre (modified after [39])
2.2.7. *Trois Rivières – Madeleine Field (TRMF)*

Between the GDS volcanic complex and the Monts Caraïbes, begins, at least 100 ka ago, a mainly effusive episode (Palmiste flow and Madeleine domes) but with some pyroclastic phases (surges and cinder cone of Gros Fougas). TRMF complex is considered as potentially active [29]. Several edifices of the South and SE of the Island have been associated with this complex in relation to the Marie-Galante graben [11], [29]. If the Morne Liquin (0 ± 20ka) and Morne Lenglet can match with this interval, the Morne Lafitte (314 ± 7ka) and the Petitel Montagne (261 ± 7ka) are significantly older. Petites Mamelles can also be included in this group that has been associated with the Monts Caraïbes to the Bouillante Chain [1]. Because of their geochemical similarity Samper *et al.* [29] propose to include the TRMF domain in the GDS complex.

3. *Bouillante Chain volcanism*

The following discussion aims at both integrating unpublished elements after the synthesis carried out on the Bouillante Chain [1] and reexamining some of its conclusions in the light of recent geoscientific works.

3.1. *Geographical extension*

Bathymetry surveys along the Caribbean coast of Basse-Terre [38], [6] confirm an alignment of reliefs displaying volcanic morphology (Pics de Bouillante) and except the Vieux-Fort seamount, all off the northern half of the Bouillante Chain and along the Montserrat – Les Saintes fault, including the Directeur volcano.

Despite some differences, likely due to their subaqueous character, the similarity with the Bouillante Chain remains remarkable: same dimension of the edifices, parallel distribution and morphological preservation suggesting relatively recent ages.

On shore, the small monogenic centres run on a strip, oriented NNW-SSE, less than 2 km wide and less than 20 km long, between Pointe à Zombi, in the North, and the city of Baillif to the South. The eastward shift of the Bouillante Range, south of the Beaugendre River, does not exceed 4 km and may be considered as homothetic of a similar shift towards the ESE, of about 5 km, of the Axial Chain (between Pitons de Bouillante and the Moustique - Matéline - Capesterre complex).

3.2. *Structural framework and control*

The Bouillante Chain follows the NNW-SSE striking of the "Montserrat - Bouillante - Les Saintes" regional fault system. The volcanic edifices are, in second order, controlled by a fracturing around the EW direction corresponding to the mildly opening tectonics, prolonging the Marie Galante grabens system [11], [9].

The distribution of volcanoes can be broken down into three groups according to their geographical distribution, tectonic control and age (Figure 3):

1) Malendure-Ilet Pigeon, to the North, where the tectonic control is rather NW-SE and the ages between 1100 and 790 ka;
2) Pigeon-Bouillante-Morne à Jules, in the centre, where the E-W direction dominates until the Petite Anse Duché and SW-NE in the South, with ages between 770 and 460 ka;
3) Laurichesse-Vanibel, to the South, with an eastward drift, a SW-NE striking and ages from 330 to 230 ka.

3.3. *Characteristics of volcanism*

Short geological exploration campaigns were carried out by the BRGM in 2009, 2010, 2011, 2012, 2016 and 2018. The observations carried out, essentially confirm, those of the years 1982 to 1985 [1] with some new elements.
From North to South, the Bouillante Chain, despite the dispersion and small size of its centres, has an exceptional variety of dynamism and volcanic facies, often combined in a single unit. This diversity is due to (i) their location on a littoral shallow waters zone responsible of various types of hydrovolcanism) and (ii) the wide compositional spectrum of volcanic rocks. Without establishing an exhaustive list, we can thus find:
- lava flows, often fissure-driven and of limited extension (dike-flow or even dome-flow at Ilet Pigeon), and locally forming swarms (Trois Tortues, Pointe Dibuque);
- Strombolian scoria fall deposits, “cauliflower” or “bread crust” bombs (Anse Feuillard, Pointe à Sel);
- ubiquitous hyaloclastites with palagonitized cement;
- pumice falls of various compositions, including “mixed” or “banded” ones, mainly as Plinian deposits but, locally a pumice flow is described; quartz crystal-lapilli deposits may accompany them;
- frequent maar coarse breccia, often initiating an eruptive sequence;
- surge deposits in waves with hydroplinian deposits where are often observed accretionary lapilli, some enclaves of cumulate (plagioclase or pyroxenes) or microgranites.

The distribution of volcanic centers can also be split in three groups: (i) in the North of the chain, they form local small clusters, (ii) from the South coast of Bouillante, they will be more distributed according to various feeding fissures of limited extent and (iii) in the SE part of the chain the andesitic lava flows disappear and pyro-(or hyalo-) clastic deposits will predominate.

The Morne à Jules formations, at the junction of (ii) and (ii) part, (Figure 2) have been interpreted in various ways. They would result from:
- either a debris avalanche from the flanks of the Beaugendre River basin ([12], [18], [32]). Nevertheless, new dating and paleomagnetism do not show any lava displacement after their emission. No sector collapse scar, neither topography in hummocks, nor jig-saw cracks in the deposits were found. Eventually, the relatively narrow Beaugendre Depression outlet diverges from the typical horseshoe morphology of such event. Thus, this hypothesis was questioned [14].
- or the explosive activity of Pitons de Bouillante [14].

According to our observations [13], Morne à Jules volcano followed a sequence typical of the Bouillante Chain dynamism according to the following four steps:
(i) initial ultra-vulcanian phreatomagmatic explosion mobilizing various blocks, some more or less hydrothermalized, coarse grained fragments, possibly geothermal system cap rock fragments in a hyaloclastic matrix;
(ii) intrusive - effusive phase in a NE-SW-oriented dike-flow, likely forming the framework of the relief;
(iii) plinian phase with dacitic pumice and ash deposits;
(iv) final phreatomagmatic phase with more or less hydrothermalized blocks, quenched blocks, scoriaceous elements and pumice of the previous episode remobilized and banded pumice fragments; the latter displaying a magma mixing interpreted as the result of a more basic magma pulse arriving in the already differentiated magma chamber and triggering this latter eruption.

The existence of such hydrothermalized elements can also be found in Malendure maar deposits, North of the chain. They may represent fragments of geothermal cap rock expelled in the eruption. This type of event may have altered possible hydrothermal circulation systems in these areas. This is not the case of the Bouillante sector where, despite various hydromagmatic or phreatic events, the geothermal system was preserved.

3.4. Time distribution

3.4.1. Methodological issue
Obtaining reliable ages, particularly by the K/Ar method on the Bouillante Chain, in particular, has been a methodological challenge for several reasons:
- frequent magma mixing phenomena;
- submarine eruptions;
- abundance of pyroclasts (ash and pumice), more sensitive to alteration;
- lavas and minerals depleted in potassium.

Most of the K/Ar results obtained by the 1980s were of uncertain reliability until the development of a dating method on the groundmass [34] which was then generalized (e.g. [40]).

The K/Ar ages on samples attributable to the Bouillante Chain are between 1.1 and 0.2 Ma (Figures 3 and 4; Table 3) and can be split, as indicated above, in three groups based on geographical, structural and temporal criteria. We notice, in the light of the most recent datings, that the Bouillante Chain operated
- to the North, contemporaneously along with the terminal phase of the Northern Chain (extrusion of Les Mamelles domes) and the initial phase of the Axial Chain (Pitons de Bouillante);
- in its central part at the same time as the construction of the Moustique-Matéline-Capesterre and Sans Toucher volcanoes (Axial chain) as well as the Monts Caraïbes;
- in the South, synchronously to the installation of Morne Lafitte and Petite Montagne, or even the first phase of activity of the Grande Découverte volcano.

The hydrothermal breccia dated at Bouillante Bay (Marsolle) dated at 248.2 ± 50.2 ka, matching with the illites of the geothermal drilling BO-6 at 285 ± 26 ka, would mark the beginning of the geothermal system [41]. Although the age of this breccia is coeval with the most recent volcanic events of the Bouillante Range, the hypothesis favored by the authors is that of a purely phreatic explosion. Anyway, this radiometric dating shows that the duration of the Bouillante geothermal activity, as other geothermal system, is not negligible regarding the lifetime of its associated heat source [40].
3.4.2. *South- and west-ward migrations*

The volcanic complexes of Basse-Terre evolve roughly at younger ages as one move from North to South. This led Samper *et al.*, 2007, to propose a southward migration process of the volcanism. Nevertheless, the ages obtained on the Monts Caraïbes, the TRMF and the Bouillante Chain, or even within the different groups are not always consistent with this hypothesis. If volcanism migrates, it is not in a continuous way.

Following the hypothesis of Bouysse *et al.* [23], Gadalia *et al.* [1] proposed to explain the volcanism shift of the Bouillante Chain towards the SE by the progression of the subducted Tiburon ridge below the Basse-Terre island (see § 2.1.). However, (i) the synchronism of the activity of the Bouillante Chain with the Axial Chain, as well as (ii) the trend to a southward migration of the Axial Chain volcanism, both points confirmed by the recent dating [13], [14], require modifying this hypothesis.

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**Figure 4.** Bouillante Chain ages of volcanic and hydrothermal activity (see Table 3) among the Basse-Terre volcanic series (1: Pitons de Bouillante; 2: Moustique-Matéliane-Capesterre; 3: Sans-Toucher; 4: Anse Feuillard; 5: Ilet Pigeon; 6: Petite Anse Duché; 7: Courbaril; 8: Habitation Muscade-1; 9: Anse de Mademoiselle Rose; 10: Desmarais; 11: Habitation Muscade-2; 12: Le Tuf; 13: Danoy; 14: BO6 borehole, 655m, illites; 15: Anse Marsolle, adularia; 16: Grande Découverte; 17: Carmichaël; 18: Soufrière.)
Several authors’ considerations may, nevertheless, remain valid: (i) motion of the subducted plate and, therefore, of the ridge, toward the WSW, (ii) subducted ridge subject to ripples, interruptions and offsets, (iii) the determining role of the partial melting of subducted sediments, at constant depth, in the genesis of volcanism.

Once the magma production zone has reached the Basse-Terre, following the resumption of ridge subduction (Figure 4 and 2), the volcanic activity begins with the Basal Complex, North of the island. The ridge goes on progressing towards the WSW, obliquely with respect to the N-S direction of the arc at the level of Basse-Terre. Let us consider a flexure of the slab induced by the ridge. As the motion can be broken down into two components (i) southward and (ii) westward. The volcanic front would thus move globally towards the SSE (Labeau, 2018, pers. comm.) under the effect of this southern component of the flexure.

Figure 5. Proposed evolution sketch for the progression of the Tiburon ridge subduction and the southward migration of Basse-Terre volcanism

Legend a): Oligocene ≈ 28 Ma - arrival of the ridge below La Désirade; b): 4 - 3 Ma: volcanism of the Basal Complex (B.C.) and Directeur Volcano (D.V.); c): 1 - 0.5 Ma: volcanism of the Northern Chain (N.C.) then of the North of the Axial Chain (A.C.) parallel to that of the beginning of the Bouillante Chain (B.C.) and of the Pics de Bouillante (B.P.); d) 0.5 - 0.2 Ma: volcanism of the Southern Axial Chain (A.C.), of the Caribbean Mountains (C.M.) then of the Grande Découverte volcano (G.D.) parallel to that of the end of the Bouillante Chain (B.C.)

The western component of the flexure, in turn, would induce the development of volcanism westward, at the level of the Bouillante Chain simultaneously and parallel to the major volcanic axis of the island (North Range, Axial Range, Caribbean Mountains, GDS) but with a significantly lower magmatic output.

The recent ages (Ilet Pigeon and especially Anse Feuillard) extend the domain of the Bouillante Chain towards older ages, even contemporary ones of the South of the Northern Chain and support a relative permanence of the westward shift.

The alignment of submarine volcanoes (Pics de Bouillante), shifted offshore a little further North-West, but still parallel to the northern part of the Bouillante Chain, could also account for a westward shift. It would anyway be interesting to date again the Directeur Volcano: its age (between 2.5 and 2
Ma) would probably be rejuvenated by an updated K/Ar method, as it was the case for most rocks recently dated anew (e.g. [13]).

Montserrat island, NNW of Basse-Terre, is possibly also on the way of the Tiburon ridge. It is one of the rare islands of the active arc whose volcanism displays a southward migration of its ages. Thus Harford et al., [42], can calculate both components of the migration speed of Montserrat volcanism: 6 km/Ma from North to South and 2 km / Ma from East to West. Samper et al. [13] obtain a value of 18 km/Ma only for the southern component for the “axial” volcanism the shift of Basse-Terre.

The progression of the ridge is also consistent with:
- the sinistral motion of the Montserrat - Les Saintes fault system and with the Marie-Galante horsts and grabens system;
- the various recent eustatic movements recorded on the Caribbean littoral, notably those which would explain the extension in altitude of the hyaloclastites deposits, of the Bouillante Chain;
- the small size of the Bouillante Chain units (and parallel submarine volcanoes) and their scattering that could be due to the unequal distribution of sediments near the subducted ridge causing hiatuses in the process of partial melting.

3.5. Mineralogical approach

This part re-examines analyzes carried out at the BRGM microprobe as part of
- module B of the ADEME-BRGM project Ghemod “Understanding the hydrothermal system” of Bouillante, Guadeloupe [43]
- Master's report by J. Moenne-Loccoz [44], co-supervised by Pr. M. Pichavant from the University of Orléans (ISTO) and A Gadalia from the BRGM.

The results complement those of Blanc [34] and Gstalter [33] who focused on the southernmost pumice episodes of the Bouillante Chain (and, moreover, on the earliest of the Grande Découverte complex).

3.5.1. Plagioclase

This crystal phase largely dominates most of the observed rocks. It is the major factor in the magmatic evolution of the Bouillante Chain. This role is confirmed by the presence of xenocrysts in aggregates, or even plagioclase cumulates [45].

As Blanc [34] and Gstalter [33] have shown, the plagioclase compositional spectrum is wide and continuous. More basic minerals (at 75-85% anorthite, typical of basalts) evolve in acidic andesites to
dacites. Contrasting zonation of the crystals reflects the greater sensitivity of plagioclase to pressure and temperature conditions as well as to the magma mixing [46]. Inverse zonation (a heart more differentiated than the rims) can reveal such mixing phenomena which can be either "external", such as more basic magma injections into a differentiated magma reservoir, or “internal” due to convective motions bringing differentiated crystals to deeper, more primitive media.

The Bouillante Chain plagioclases are characterized by a final potassium enrichment (Figure 6) with a proportion of orthoclase exceeding 6% (Figure), reflecting the evolution of the magmatic fluid at the end of differentiation.

3.5.2. Pyroxene

The pyroxenes of the Bouillante Chain are distinguished by their late (and pronounced for the orthopyroxenes) enrichment in iron (Figure 7). This evolution, dominated by the calcium decrease, results from the massive fractionation of plagioclases depleting magmatic liquid in calcium. This evolution is classical among the arc tholeiite series. The occasional existence of pigeonite strengthens this trend. Pyroxenes of basic primitive composition (enriched in aluminum, for instance) are rarer.

Orthopyroxenes coexist most often with clinopyroxenes; the zonation is less visible than on the plagioclase but sometimes can result in the evolution of an orthopyroxene into a clinopyroxene from the heart to the rims of the crystal.

The pyroxenes of a pyroxene cumulate in a hydromagmatic deposit, shows that its mineral phases do not display any primitive signature. The presence of primary sulfides (pyrrhotite) can be emphasized. The absence of amphibole and the predominance of clinopyroxenes distinguish it from the Monts Caraïbes cumulates [17]. Nor does it display any mineral bedding, unlike some enclaves of St. Vincent and Grenada [65]. This cumulate could indicate intermediate magmatic segregation.

Figure 7. Ternary representation of the pyroxene composition in the Bouillante Chain, Soufrière and Montagne Pelée magmas (legend for orthopyroxenes on the left, legend for clinopyroxenes on the right)
3.5.3. Olivine
Olivine is rare and often destabilized (in iddingsite). The analyzed compositions range from Mg-rich minerals (Fo83-74), even in dacitic pumice falls as proxies of magma mixing, up to an iron-enriched composition (Fo10) [33], with intermediate compositions (Fo52). Fayalitic olivine is found in dacites of Monts Caraïbes [17] and in rhyolites of Saint Lucia [47]. Its coexistence with quartz and magnetite is an indicator of the temperature and oxygen fugacity conditions (Quartz-Fayalite-Magnetite, QFM buffer). This paragenesis is common in spreading zones, as in Afar (e.g. [48]) but rare in the lavas of the subduction zones.

3.5.4. Quartz
Quartz is present either in phenocrysts in the ultimate terms of differentiation (numerous pumice deposits from North to South of the chain, Vanibel obsidian, crystal lapilli deposits), or in xenocrysts in less differentiated matrices. Quartz episodes are relatively common in the Bouillante Chain but are also found in the Northern Chain and in the GDS complex.

3.5.5. Amphibole
This phase grows in some of the most differentiated products, associated with quartz. It does not display, in general, any alteration nor zonation, highlighting a late crystallization. The available analyzes [34], [33], [44], despite different denominations, respectively ferro- or magnesio-hornblends, hornblende-ferro-edenitic [49] or even edenites [50], correspond to calcium, slightly potassic amphiboles. Two deductions can be made:
- a relative similarity of the physico-chemical conditions of crystallization despite their late occurrence and the dispersion of the volcanic emission centers in the Bouillante Chain;
- a consistency with the final enrichment in potassium of magmas and plagioclases.

The Bouillante Chain amphiboles are similar to those of the Grande Découverte early phase pumices on the Caribbean side of this volcanic complex but differ from those outcropping on the Atlantic side (Trois Rivières pumice flow with a marked magma mixing) [34].

The various amphiboles of the Monts Caraïbes are also calcic ones but are all distinguished from the Bouillante Chain amphiboles by a marked depletion in Si and Fe and enrichment in Al [17].

3.5.6. Fe-Ti Oxides
These minerals are mainly expressed as titanomagnetite (UsP_{26-38}) or exceptionally ilmenite Hem_{5-12} according to a range of variation classical in the Lesser Antilles, especially in the formations near the GDS [33]. Sometimes their composition is quite contrasted in the same rock in relation to magma mixing phenomena. The smaller range of variation, notably the lower Ti-enrichment, the absence of primary phases such as pleonaste or chromite, distinguish the Bouillantes Chain oxides from those of the Monts Caraïbes [17].

3.5.7. Glass and fluid inclusions
The study of intra-crystalline glasses and associated fluids [33] has shown that the trapped magmas had contrasting fluid saturation levels between basic and rhyodacitic magmatic liquids. In the first case the crystal growth occurred in a water-saturated medium, while in the second the magma was undersaturated with respect to the fluid phase.

In summary, five points can emerge from the mineralogical approach:
- the behavior of the different mineral phases evolves according to a tholeiitic trend.
- variations in the composition of the mineral phases of the Bouillante Chain formations does not depend on the geographical locations;
- extreme variations can affect the minerals of the same rock;
- thermodynamic conditions control the magmatic evolution can be distributed into two levels;
- several points distinguish the Bouillante Chain minerals from the three series of the Monts Caraïbes, but, at this stage, no clear distinction can be established with the GDS initial phase pumices.

3.6. Geochemical approach
The above-mentioned difficulties to obtain reliable radiometric K/Ar dating on the samples of the Bouillante Chain will be found again in the geochemical investigation.

3.6.1. Major species
The mineralogical approach has provided (i) bases for building a model of magmatic evolution of the Bouillante Chain and (ii) elements of comparison with some series of the Basse-Terre. The different volcanic complexes of the island having been analyzed [34], [33], [45], [51], [51], [29], [53], [54], [55], [56], [57], [17], [58], [66], geochemistry should complete the characterization of the Bouillante Chain regarding the other series. In order to represent the compiled data, binary diagrams using the concentration of each species as a function of SiO2 content were used.

Petrographic observations, mineralogical analyzes and the geochemistry of major species correlate according to the following characteristics:
- the determining role of plagioclase in the chemical evolution of magmas illustrated by a quasi-continuous decrease of CaO and Al2O3, with a steeper decrease in andesites;
- evolution in two stages of Na2O whose growth, pronounced at the beginning of differentiation, clearly attenuates from the dacites due to the fractionation of a more sodic plagioclase;
- reduction of the Na2O/K2O ratio from the andesites, after a growth in the basic terms, but stabilization at the level of the rhyolites in agreement with the more potassic plagioclase fractionation additionally to the amphibole growth;
- MgO decrease corresponding to the disappearance of olivine and the significant fractionation of pyroxene; at the end of the differentiation, as mafic crystals are rarer, this process attenuates;
- late fractionation of Fe-Ti oxides, resulting in TiO2 growth up to andesites, and mitigation of the decrease in rhyolites where there is a relatively low fO2 limiting this fractionation.

Differentiation, therefore, remains essentially controlled by a fractional crystallization process. The major elements of the Bouillante Chain position it astride the calc-alkaline and tholeiitic domains limit, for instance in the diagram. K2O vs. SiO2 (Figure 8), as the mineralogical approach emphasized its tholeiitic properties. Nevertheless, the Bouillante Chain remains relatively low in potassium and, on the Basse-Terre island, only the Monts Caraïbes have lower K2O content. The example of the Martinique volcanic formations [59] shows, as well, that a series can be classified as tholeiitic from a mineralogical point of view and geochemically calc-alkaline.

The binary diagrams allow distinguishing the domain of different series and to examine that of the Bouillante Chain with regard to them.
3.6.2. Trace elements
The analysis of trace elements provides complementary information to characterize the magmatic series and their evolution. This method has already allowed Vatin-Pérignon et al. [37] and Gstalter [33] to distinguish the pumice series of the Bouillante Chain from those of the Grande Découverte. We will also use an element such as Thorium because (i) its strong hygromagmaphile properties (tendency to concentrate in the liquid phase of the magma), (ii) its high enrichment along the differentiation and (iii) its low sensitivity to secondary processes [60]. Some examples among hygromagmaphile and transition elements will be selected for their discriminant properties. Binary diagrams constructed with this reference show, for couples of hygromagmaphile elements, correlation lines crossing the origin. A slight deviation from this alignment is observed, for these elements, within the rhyolite domain. The authors (e.g. [61]) attribute to amphibole and orthopyroxene the ability to incorporate hygromagmaphile elements (La, Ta, ...). Zircon can also incorporate Zr and other elements that can lose their hygromagmaphile character. For the Bouillante Chain, La deviates strongly from linearity and Zr, Ce, Hf, Ta to a lesser extent. This deviation is, nevertheless, a peculiarity of the Bouillante Chain and is much smaller for other Basse-Terre series, reaching this differentiation level (GDS pumices or Mamelle dome in the Northern Chain). The transition elements (Co, Ti, ...) deplete rapidly (according to hyperbolas) because of their incorporation in olivines, pyroxenes and Fe-Ti oxides. The drop in Co concentrations clearly distinguishes the Bouillante Chain from the GDS series.

3.6.3. Comparative study with other volcanic series of Basse-Terre
It should be first emphasized that Bouillante Chain geochemical behavior as a series is, at least, as coherent as other series of the island.
Monts Caraïbes

The Bissainte' study (1995) includes the geological (field), petrographic (microscope), mineralogical and geochemical aspects of a complete volcanic ensemble, clearly identified. Several points in common between the Monts Caraïbes and the Bouillante Chain had led Gadalia et al. [1] to join them:

- wide range of composition from basalts to dacites and at the limit of the tholeiitic and calc-alkaline domains;
- low concentration in K₂O (≤ 1%) and clear enrichment in K₂O at the end of differentiation;
- plagioclase predominance and basicity of their heart, indices of high P H₂O in andesitic magmas [62];
- frequent magma mixing.

However, other points decidedly distinguish the Monts Caraïbes from the Bouillante Chain:

- basic products constituting 80% of the emissions;
- presence of an aluminous paragenesis;
- amphiboles are present from basalts to dacites, including cumulates and are distinct from those of the Bouillante Chain;
- cumulates are abundant, diversified and different from those of the Bouillante Chain.

The latest compilations of analysis and the resulting diagrams confirm these differences and separate the Monts Caraïbes, all series included, from the Bouillante Chain.

Small edifices at the South and South East of the GDS (Morne Liquin and Morne Lafitte, Petite Montagne, Petites Mamelles)

As for the Monts Caraïbes, they were proposed as southern extensions of the Bouillante Chain. The binary diagrams of major species show that the above-mentioned small edifices belong to the TRMF group that is closely related to the GDS complex. Those small edifices of the SE Basse Terre are, thus, distinguishable from the Bouillante Chain.

Initial Grande Découverte pumiceous events

The pumice flows and falls of the South of the Bouillante Chain, on the one hand, and of the Grande Découverte first phase [34], [33], [37], on the other hand, provide a partial view of both series. These products have, however, been chosen because they result from the same dynamism, they were emitted at close times and in neighboring areas. Their mineralogy, including the composition of intra-crystalline glasses, is similar and the belonging of these pumice to a series or another has long been debated. The studies of Blanc, [34], Vatin-Pérignon et al. [37] and Gstalter [33] led to separate both lineages according several criteria:

- the contrast between the chemical composition of the dark (basic) terms of the “banded” pumice and clear (acidic) terms, showing a magma mixing, is more pronounced for the pumice fragments of the Bouillante Chain. Vatin-Pérignon et al. [37] relate this to the small size of the edifices and, therefore, to the corresponding magma reservoirs of this Chain, compared to the Grande Découverte composite volcano, which exceeds them in size by an order of magnitude;
- alkaline contents and K / Na ratios higher for the glasses of the Grande Découverte;
- the ratios between different trace elements (Zr, Ta, La, Hf, Ce, Co, Sc) or major species (MgO, FeO, Fe₂O₃, TiO₂, CaO, K₂O, Na₂O, SiO₂) and Th, also chosen as a reference element.

The magmas would have a different mantle origin, but the authors could not determine if these series have (i) the same source with different degrees of partial melting or (ii) a heterogeneous source. In the first case, the magmatic series "Bouillante Chain" results from a higher partial melting rate than that of the "Grande Découverte" series.

The mechanism of evolution of magmas, then, combines, in both cases, differentiation by fractional crystallization and magma mixing in two levels (see below).

The distinction between both series support the hypothesis of different magmatic reservoirs scattered below the Bouillante Chain.
Axial Chain
The activity of the Bouillante Chain and that of the Axial Chain have been largely synchronous, their tectonic control is assumed to be similar, and petrographic examination also indicates a major role of plagioclase along the Axial Chain magmatic evolution [51]. Nevertheless, the Axial Chain differs from the Bouillante Chain by the location, the dimensions and the dynamism of volcanic edifices and by a smaller spectrum of differentiation (SiO$_2$ <65% and Th <1.8).

For the major species the relatively dispersed clouds of both sets do not make it possible to distinguish both groups with the exception of Na$_2$O vs. SiO$_2$. The Bouillante Chain is globally depleted in Na at the level of the basic terms (basalts and basaltic andesites) with respect to the Axial Chain. This distinction is found in the diagrams TAS (sum of alkalis/SiO$_2$) and Na$_2$O/K$_2$O vs. SiO$_2$.

Although little is still known about its mineralogy, we infer from the available results that the Bouillante Chain owns enough peculiarities to be distinguished from the Axial Chain and does not constitute its western outgrowth. This point is not without consequence on the positioning of the magma reservoirs and, therefore, of the heat source in the Bouillante geothermal system.

![Figure 9. Evolution of Ce versus Th for the Basse-Terre magmatic series](image)

To conclude this comparative study, we agree with Ricci [51] that “the Basse-Terre volcanic complexes have a large geochemical homogeneity on the island scale”. The behavior of the hygromagmaphile elements (Zr, Hf, Ta, La, Ce) vs. Th confirms Ricci’s remark [51] that the Basse-Terre series are divided into two groups according to the Th/Nb and Th/Yb ratios. Axial Chain, Basal Complex and Bouillante Chain form the highest ratios group. Within this group, however, and in an interval where there is a relatively correct linear correlation between hygromagmaphile elements, the Bouillante Chain systematically displays a lower trend than both the other series and this trend is well discriminated for La and Ce (Figure 9).
The variations in the hygromagmaphile elements ratios for the Basse-Terre volcanism show (i) that the partial melting rate has varied over time or (ii) that the partial melting has involved a heterogeneous mantle without it being possible to decide this question. The hypothesis of the subduction of Tiburon's aseismic ridge, with the heterogeneities of sedimentary contribution that it is likely to generate, may help to explain these geochemical variations.

4. Petrogenetic model and heat source of the Bouillante geothermal system

The study of the various characteristics of the Bouillante Chain leads us to specify the conditions of its magmatic evolution before addressing the question of the Bouillante geothermal system heat source.

4.1. Petrogenetic model

The study of the Bouillante Chain mineral phases (olivines, plagioclases, pyroxenes, Fe-Ti oxides and amphiboles) allowed specifying the thermodynamic conditions of their formation thanks to the geothermo-barometer calculation and the study of intracrystalline glasses. The results (Table 1), summing up the conditions of evolution of the magma, are quite convergent.

|                | Temperature (°C) | Pressure (MPa) | fO2          |
|----------------|------------------|----------------|--------------|
| Magma reservoir 1: Andesites to dacites | 1000 < T < 1150 |                | > Ni-NiO     |
| Magma reservoir 2: dacites to rhyolites | 810 < T < 950   |                | ≈ QFM (10^{-14} - 10^{-13}) |
| Plagioclase Glass Inclusion | 900 < T < 1120  | 300 < P_{H2O} < 400 |              |
| Quartz Glass Inclusion | > 810           | 180 < P_{H2O} < 250 |              |
| Fe-Ti Oxides     | 680 < T < 880    |                | = Ni-NiO (10^{-16.8} - 10^{-12.3}) |
| Amphiboles       | 760 < T < 820    | 170 < P_{H2O} < 330 (5 - 10 km depth) | > Ni-NiO (10^{-14.5} - 10^{-13}) |

Table 1. Temperature and pressure conditions of the magmatic evolution of the Bouillante Chain

These results are similar to those obtained on the Grande Découverte [33] and on the Monts Caraïbes [17] showing the plausible formation of intra-crustal magmatic reservoirs within a thickened lithosphere (Lardeau, 2011) as the one over which the Lesser Antilles are developed. They highlight two media of magmatic evolution:
- up to the level of the dacites, a system of higher temperature and P_{H2O}, where the fO2 would be higher than the Ni-NiO buffer
- from the dacites to the rhyolites, a system of lower temperature and P_{H2O} where the fO2 are closer to the QFM buffer.

Gstalter [33] dismisses the hypothesis of a single stratified magma chamber for the Bouillante Chain, due to
- the low dispersion and low volume of products suggesting small volume reservoirs (less than ten km³ for the Bouillante Chain);
- the existence of a fluid-saturated basic magma underlying a fluid-undersaturated differentiated magma chamber incompatible with a fractional crystallization process in a single reservoir;
- the absence of ferromagnesian minerals that could have crystallized on the walls of the magma chamber.

The hypothesis of two levels of magma chambers seems to better match the magmas evolution of the Bouillante Chain. It remains, however, to specify whether the same diversity characterizes these two levels or if, for instance, the deep level would be common to all and if diversification would occur only in the upper levels. This separation into two levels of magmatic reservoirs is in line with a series
of magma stocks more or less developed and whose rise was favored by the NNW-SSE accident Montserrat-Bouillante-Les Saintes (syntectonic set up).

4.2. Discussion on the Bouillante geothermal system model

The quantification obtained by the petrological approach remains rather broad: magmatic reservoirs whose roofs would be between 5 and 10 km, at a temperature of more than 800 °C when the magma was stored. This result converges, however, with the thermal simulation [5], starting from the thermal conditions of the Bouillante geothermal reservoir (250 °C), and inferring that there is a deep heat source of 400 to 500 °C at about 7 km deep under Bouillante, cooling for about 500 000 years.

More generally, our results contribute to the debate on the Bouillante geothermal field model. Some prefer, for this geothermal system, an external heat source connected to a distant geothermal "outflow" up to the Bouillante Bay (and its geothermal expressions). Here are two versions:

- Ricci (2014) suggests the Bouillante Pitons (Axial Chain) as the thermal engine of the Bouillante geothermal system, considering the Bouillante chain as series of adventive cones of the Axial Chain. We show that this volcanic ensemble has at least as many structural, volcanological, petrographic, geochemical and mineralogical characteristics as the volcanic complexes of the axial zone of the island. This conclusion also applies to the Monts Caraïbes [17] forming series separated from the Bouillante Chain and from the Axial Chain. On the opposite, unless some mineralogical data contradicts it, the Trois Rivières-Madeleine series have no discriminating geochemical character of the same level. The Guadeloupean series are geochemically close enough and it is not irrelevant to envisage common magmatic sources in the mantle wedge above the slab [16] … but with different intra-crustal magma stocks.

- Verati et al. [41], from the age determination of a hydrothermal breccia in Bouillante Bay (248 ± 50 ka, Figure 3), correlate this result with (i) the assumed age (but discussed by Samper et al., 2009) of the beginning of GDS activity (200 ka), (ii) with the E-W accidents considered as the most recent tectonic system of Basse-Terre and (iii) E-W striking of the faults in which the Bouillante geothermal fluid circulates. They consider “the initiation of hydrothermalism within the E-W oriented Bouillante normal faults … as a “precursor” of the volcanic activity of the GDS system rather than related to “the ultimate magmatic activity of the Bouillante Chain”.

In our opinion, the E-W mini-graben that controls the Bouillante system is closely associated to the sinistral, NNW-SSE striking Montserrat-Les Saintes fault system [10]. This accident remains very active (see bulletin IPGP following the earthquake of 21/11/2004). The NS extension of the geothermal circulation system (from Thomas to Marsolle according to Owens et al., [63] or to Ilet Pigeon, according to Sanjuan et al., [7]) is also in agreement with a combined tectonic system controlling the geothermal system and the Bouillante volcanic chain.

The petrological approach and volcanological examination of the Bouillante Chain followed in this work, converge toward considering the Bouillante geothermal system as generated from a local heat source [10], i.e. an “upflow” type of geothermal system:

- ages less than 500 ka (Desmarais, Habitation Muscade),
- consistency of the E-W striking of the geothermal circulation faults (from Marsolle to Descoudes) and of the volcanic structures of the Bouillante Chain (from Pointe à Sel to Thomas),
- geochemical convergence of the most differentiated magmas and minerals (enrichment in SiO₂ and K₂O) with the first hydrothermal mineralizations (adularia, illites) and with the current geothermal fluid [7].

Recent magneto-telluric survey [63] shows an ascent of the conductive layer from East to West consistently with cold water supply from the East and a heat source towards the coast.
The geothermal system model still needs to be clarified for its N-S, E-W and deep extensions. The strictly tectonic hypothesis of heat source may consist in a deep circulation, interaction with a deep gas phase through a network of lithospheric faults. It can complete the local magmatic heat source if not by the arrival of juvenile magma, at least by the reactivation of circuits allowing combining the deep circulation of the geothermal fluids and the rise of magmatic gases.

Our approach has also reinforced the hypothesis of occurrence of intra-crustal cooling magma stocks, of varying sizes, distributed below the different recent volcanic series of Basse-Terre. These magmatic reservoirs can be considered as potential sources of heat to which possible geothermal circulation systems remain to be highlighted.

5. Conclusions
New, so far unpublished, works made it possible to specify the characteristics of a volcanic ensemble at the southwest side of Basse-Terre, Guadeloupe, Lesser Antilles, the Bouillante Chain. The monogenic, fissural volcanic edifices, largely characterized by hydromagmatism, are aligned on a NNW-SSE striking onland and off shore. They are located at the junction of two regional fault systems: that of the Montserrat - Les Saintes strike-slip sinistral fault zone, and the one extending the Marie-Galante graben, around an E-W striking. The volcanic activity of this chain has taken place simultaneously with that of other ensembles on the island and could be associated with the subduction of the Tiburon Ridge.

The mineralogical approach of the Bouillante Chain characterizes it as a marked differentiation, arc tholeiite series. It leads to a two-level petrogenetic model: (i) deep storage (s) where basaltic to dacitic magmas are differentiated and (ii) superficial reservoirs where dacitic to rhyolitic liquids continue to evolve. The geochemical representations allowed distinguishing this series from other volcanic groups of Guadeloupe.

Taking into account these different characteristics leads to discuss the Bouillante geothermal system models and to favor a local heat source accompanied by an “upflow” circulation.

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### Supplementary data

| Volcanic series | Method | Sample       | Age BP                        | Location                | Formation                        | Authors                                      |
|-----------------|--------|--------------|-------------------------------|-------------------------|----------------------------------|----------------------------------------------|
| **Northern Chain** |        |              |                               |                         |                                  |                                              |
|                 | U/Th (zircons) | Mamelle      | 1.05±0.06 Ma (1.11 ≤ t ≤ 0.99 Ma) | Mamelle de Petit-Bourg | Perlitic base of pumice flow     | Ph. Lach, BRGM, 2018                        |
|                 | K/Ar   | GG-363       | 1.358±0.021 Ma (1.337 ≤ t ≤ 1.379 Ma) | Pointe à Zombi         | Lava flow                        | H. Guillou, CEA-CNRS, 2013                   |
|                 | K/Ar   | GG-600       | 1.067±0.025 Ma (1.042 ≤ t ≤ 1.092 Ma) | Anse Feuillard          | Clast from hydromagmatic explosion | H. Guillou, CEA-CNRS, 2013                   |
|                 | K/Ar   | 00GU43       | 0.853±0.065 Ma (0.788 ≤ t ≤ 0.918 Ma) | Ilet Pigeon             | Lava-Dome                        | Ricci, CNRS-Univ.Orsay, 2014                |
|                 | K/Ar   | BO17R        | 0.642±0.016 Ma (0.626 ≤ t ≤ 0.658 Ma) | Courbaril               | Lava flow                        | H. Guillou, CEA-CNRS, 2007                   |
|                 | K/Ar   |              | 0.617±0.019 Ma (0.598 ≤ t ≤ 0.636 Ma) | Road to Habitation Muscade | Scoriaceous lava block         | H. Guillou, CEA-CNRS, 2007                   |
|                 | K/Ar   | GG-301       | 0.592±0.011 Ma (0.581 ≤ t ≤ 0.603 Ma) | Anse de Mademoiselle Rose | Clast from hydromagmatic explosion | H. Guillou, CEA-CNRS, 2013                   |
|                 | K/Ar   | BO17P        | 0.494±0.02 Ma (0.474 ≤ t ≤ 0.514 Ma) | Desmarais               | Block from glowing avalanche     | H. Guillou, CEA-CNRS, 2007                   |
|                 | K/Ar   | BO20J        | 0.479±0.016 Ma (0.463 ≤ t ≤ 0.495 Ma) | Road to Habitation Muscade | Lava block                       | H. Guillou, CEA-CNRS, 2007                   |
|                 | K/Ar   | 30A          | 0.325±0.008 Ma (0.317 ≤ t ≤ 0.333 Ma) | Le Tuf                  | Rhyolitic Dyke                   | F. Blanc, P.Y. Gillot, C.E.A., 1983          |

**Bouillante Chain**

| Volcanic series | Method | Sample       | Age BP                        | Location                | Formation                        | Authors                                      |
|-----------------|--------|--------------|-------------------------------|-------------------------|----------------------------------|----------------------------------------------|
|                 | K/Ar   |              | 0.325±0.008 Ma (0.317 ≤ t ≤ 0.333 Ma) | Le Tuf                  | Rhyolitic Dyke                   | F. Blanc, P.Y. Gillot, C.E.A., 1983          |
|                | Thermoluminescence | F. 802.gl | 0.244±0.018 Ma (0.226 ≤ t ≤ 0.262 Ma) | Danov | Dacitic Pumice (satiny) | F. Blanc, G. Valladas, C.F.R., 1983 |
|----------------|--------------------|-----------|-------------------------------------|-------|------------------------|----------------------------------|
| Bouillante     | K/Ar               | BO6-655 m | 0.285 ±0.026 Ma 0.259 ≤ t ≤ 0.311 Ma | BO-6 drill hole at 655 m depth | Hydrothermal illites | H. Guillou, CEA-CNRS, 20 |
| Hydrothermalism| K/Ar               | 215A      | 0.230 ±0.026 Ma 0.204 ≤ t ≤ 0.256 Ma | Anse Marsolle | Adularia from hydrothermali sed breccia | H. Guillou, CEA-CNRS, 20 |
|                | Ar/Ar              |           | 0.198 ≤ t ≤ 0.298 Ma 0.248 ±0.05 Ma |       |                        | C. Verati Université Nice |

**Table 2.** Ages from the Bouillante Chain; Unpublished ages are in bold, including for the Northern Range.
Table 3a. Major species of Bouillante Chain samples and unpublished analyses from other Basse-Terre volcanic series. Unpublished analyses are in bold
| SAMPLE NAME | CITATION | LOCATION | SERIES | SiO₂ (wt %) | TiO₂ (wt %) | Al₂O₃ (wt %) | Fe₂O₃T (wt %) | Fe₂O₃ (wt %) | FeO (wt %) | MnO (wt %) | MgO (wt %) | CaO (wt %) | Na₂O (wt %) | K₂O (wt %) | P₂O₅ (wt %) | H₂O⁺ (wt %) | H₂O⁻ (wt %) | LOI (wt %) | Total |
|-------------|----------|----------|--------|-------------|-------------|-------------|---------------|-------------|-----------|-----------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|--------|
| GG11E       | Gadalia (1985) | Bouillante Chain | 1900 | 3.60 | 3.30 | 0.16 | 2.10 | 8.60 | 2.80 | 0.74 | 0.14 | 0.25 | 0.09 | 100.15 |
| H1702       | Blanc (1983) | Bouillante Chain | 1857 | 8.14 | 0.18 | 2.13 | 8.39 | 3.21 | 0.57 | 0.27 | 1.03 | 99.78 |
| D1401b      | Blanc (1983) | Bouillante Chain | 1653 | 7.70 | 0.18 | 2.33 | 6.43 | 2.32 | 0.95 | 0.12 | 1.74 | 100.30 |
| D1401a      | Blanc (1983) | Bouillante Chain | 1643 | 9.10 | 0.20 | 3.03 | 6.49 | 3.16 | 0.79 | 0.11 | 0.92 | 100.26 |
| 3A          | Blanc (1983) | Bouillante Chain | 1285 | 2.82 | 0.07 | 0.29 | 1.98 | 4.55 | 1.89 | 0.01 | 1.18 | 100.77 |
| F802g       | Blanc (1983) | Bouillante Chain | 1795 | 8.27 | 0.16 | 3.64 | 7.88 | 2.43 | 0.71 | 0.09 | 0.54 | 99.98 |
| E1103a      | Blanc (1983) | Bouillante Chain | 1808 | 7.65 | 0.15 | 2.15 | 6.96 | 2.71 | 0.81 | 0.17 | 1.78 | 100.18 |
| E1103c      | Blanc (1983) | Bouillante Chain | 1973 | 9.89 | 0.17 | 4.80 | 10.16 | 0.93 | 0.45 | 0.22 | 2.66 | 100.15 |
| E1103d      | Blanc (1983) | Bouillante Chain | 1799 | 7.70 | 0.24 | 2.55 | 7.05 | 2.15 | 0.68 | 0.16 | 2.28 | 99.12 |
| H901b       | Blanc (1983) | Bouillante Chain | 1713 | 7.59 | 0.19 | 2.92 | 6.90 | 2.99 | 0.95 | 0.18 | 1.61 | 100.07 |
| H901a       | Blanc (1983) | Bouillante Chain | 1710 | 7.70 | 0.17 | 2.97 | 6.75 | 2.58 | 1.11 | 0.20 | 1.51 | 100.23 |
| D1204       | Blanc (1983) | Bouillante Chain | 1677 | 7.82 | 0.17 | 3.27 | 6.45 | 1.91 | 0.80 | 0.17 | 2.01 | 100.82 |
| GG7y1       | Gstalter (1986) | Bouillante Chain | 1704 | 7.32 | 2.55 | 5.97 | 1.37 | 3.03 | 7.43 | 2.32 | 0.58 | 0.27 | 1.06 | 0.39 | 99.16 |
| GG7y2       | Gstalter (1986) | Bouillante Chain | 1835 | 2.87 | 4.16 | 0.19 | 2.12 | 7.09 | 2.92 | 0.91 | 0.28 | 1.22 | 0.48 | 101.29 |
| GG7y3       | Gstalter (1986) | Bouillante Chain | 1649 | 2.96 | 3.99 | 0.13 | 1.46 | 5.72 | 3.33 | 0.13 | 1.50 | 0.93 | 99.62 |
| GG7y4       | Gstalter (1986) | Bouillante Chain | 1831 | 3.16 | 3.98 | 0.16 | 1.62 | 6.91 | 3.07 | 0.88 | 0.11 | 2.13 | 0.64 | 100.10 |
| GG7t        | Gstalter (1986) | Bouillante Chain | 1868 | 2.29 | 5.17 | 0.17 | 2.50 | 7.26 | 3.35 | 0.80 | 0.17 | 1.27 | 0.40 | 101.03 |
| GG7x        | Gstalter (1986) | Bouillante Chain | 1539 | 1.25 | 3.37 | 0.18 | 1.12 | 4.10 | 3.57 | 1.37 | 0.17 | 2.29 | 0.99 | 99.85 |
| GG9u        | Gstalter (1986) | Bouillante Chain | 1408 | 0.08 | 2.69 | 0.15 | 0.10 | 3.28 | 3.79 | 1.43 | 0.15 | 3.33 | 1.03 | 100.04 |
| GG7ws       | Gstalter (1986) | Bouillante Chain | 1810 | 0.32 | 3.32 | 0.11 | 1.89 | 6.70 | 2.87 | 0.93 | 0.07 | 2.03 | 0.69 | 100.62 |
| GG7wc       | Gstalter (1986) | Bouillante Chain | 1602 | 0.95 | 2.24 | 0.14 | 0.45 | 3.97 | 3.62 | 1.45 | 0.08 | 2.02 | 0.69 | 100.03 |
| GG4t        | Gstalter (1986) | Bouillante Chain | 1288 | 0.22 | 1.78 | 0.13 | 0.14 | 1.77 | 4.21 | 1.87 | 0.09 | 2.50 | 0.60 | 100.00 |
| GG4w        | Gstalter (1986) | Bouillante Chain | 1739 | 0.33 | 1.76 | 0.15 | 0.44 | 1.67 | 4.52 | 1.93 | 0.07 | 0.95 | 0.23 | 100.79 |
| GG9pc       | Gstalter (1986) | Bouillante Chain | 1625 | 1.91 | 2.21 | 0.11 | 0.78 | 3.48 | 3.37 | 1.69 | 0.09 | 2.90 | 1.10 | 102.40 |
| F902a       | Blanco (1983) | Bouillante Chain | 1724 | 8.87 | 0.20 | 3.17 | 7.42 | 2.73 | 0.65 | 0.13 | 1.04 | 100.50 |
| F902a       | Blanco (1983) | Bouillante Chain | 1716 | 9.46 | 0.19 | 3.06 | 7.60 | 2.93 | 0.68 | 0.14 | 0.64 | 100.95 |
| GG9i        | Gadalia (1984) | Rivière Grande Anse | 1775 | 2.75 | 5.90 | 0.19 | 3.40 | 7.50 | 3.08 | 0.76 | 0.14 | 0.60 | 0.12 | 99.09 |

Table 3a. (following): Major species of Bouillante Chain samples and unpublished analyses from other Basse-Terre volcanic series. Unpublished analyses are in bold.
| SAMPLE NAME | CITATION | LOCATION | SERIES | U (ppm) | Th (ppm) | Zr (ppm) | Hf (ppm) | Ta (ppm) | Ba (ppm) | Sr (ppm) | Cs (ppm) | Rb (ppm) | Cs (ppm) | Ni (ppm) | Sc (ppm) | La (ppm) | Ce (ppm) | Sm (ppm) | Eu (ppm) | Tb (ppm) | Yb (ppm) |
|-------------|----------|----------|--------|--------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| VB156B      | Gstalter (2012) | Plagne Malendure | Bouillante Chain | 0.64 | 187 | 12.6 | 3.8 | 0.25 | 105 | 154 | 0.85 | 23 | 0.14 | 9 | 4 | 9.4 | 9.6 | 26.2 | 1.2 | 0.86 |
| Hs702       | Blanc (1983) | Morne à l'Isle | Bouillante Chain | 0.59 | 179 | 102 | 2.8 | 0.19 | 140 | 194 | 0.69 | 28 | 0.09 | 6 | 13 | 0.6 | 184 | 7.7 | 17.3 | 0.91 | 0.56 |
| D1401b      | Blanc (1983) | Le Bouc h | Bouillante Chain | 0.57 | 193 | 102 | 2.8 | 0.19 | 134 | 190 | 0.71 | 21 | 0.08 | 13 | 18.2 | 7.2 | 17.7 | 0.97 | 0.56 |
| 30A         | Blanc (1983) | le Tuf Vanbet | Bouillante Chain | 0.88 | 2.85 | 153 | 4.2 | 0.31 | 234 | 177 | 1.83 | 30 | 0.1 | 4 | 4 | 9 | 11.4 | 25.8 | 1.16 | 0.78 |
| F002g       | Blanc (1983) | Dany | Bouillante Chain | 0.44 | 146 | 92 | 2.5 | 0.18 | 196 | 198 | 0.55 | 17 | 0.07 | 11 | 20 | 5 | 20.7 | 6.4 | 11 | 0.99 | 0.56 |
| Hs00b       | Blanc (1983) | Riviere des Rance | Bouillante Chain | 0.63 | 223 | 95 | 2.5 | 0.2 | 144 | 207 | 0.7 | 21 | 0.09 | 18 | 6 | 213 | 7.2 | 16.9 | 1.01 | 0.51 |
| Hs01a       | Blanc (1983) | Riviere des Rance | Bouillante Chain | 0.31 | 105 | 74 | 2.2 | 0.16 | 104 | 212 | 0.43 | 12.9 | 0.08 | 19.9 | 3.5 | 271 | 5.9 | 10.7 | 2.3 | 0.86 | 0.55 | 3.3 |
| G007a       | Gstalter (1986) | Blandet | Bouillante Chain | 0.42 | 137 | 100 | 2.5 | 0.19 | 133 | 226 | 0.56 | 15.8 | 0.12 | 12.5 | 0.7 | 22.4 | 6.9 | 10.6 | 2.7 | 1.04 | 0.64 | 4 |
| G007b       | Gstalter (1986) | Blandet | Bouillante Chain | 0.48 | 162 | 94 | 3.1 | 0.25 | 154 | 206 | 0.58 | 17.5 | 0.12 | 10.8 | 1.1 | 23 | 10.2 | 16.8 | 4.2 | 1.41 | 0.93 | 5 |
| G007c       | Gstalter (1986) | Blandet | Bouillante Chain | 0.4 | 133 | 100 | 2.6 | 0.19 | 127 | 200 | 0.56 | 15.8 | 0.14 | 12 | 0.5 | 22 | 6.9 | 13.6 | 2.7 | 1.04 | 0.63 | 4 |
| G007d       | Gstalter (1986) | Blandet | Bouillante Chain | 0.39 | 133 | 98 | 2.6 | 0.17 | 127 | 222 | 0.57 | 16.5 | 3.99 | 14 | 1.6 | 24 | 6.4 | 13 | 2.7 | 1.06 | 0.64 | 3.9 |
| G007e       | Gstalter (1986) | Blandet | Bouillante Chain | 0.8 | 256 | 129 | 3.7 | 0.28 | 230 | 159 | 0.98 | 29.6 | 0.12 | 6 | 15.8 | 11.6 | 24.2 | 4.2 | 1.21 | 0.94 | 5.6 |
| G009a       | Gstalter (1996) | Riviere des Sirens | Bouillante Chain | 0.69 | 2.17 | 142 | 3.9 | 0.28 | 189 | 149 | 0.93 | 26.8 | 0.1 | 2.9 | 8.8 | 9.6 | 24.1 | 4.2 | 1.19 | 0.92 | 4.5 |
| G009b       | Gstalter (1996) | Dany | Bouillante Chain | 0.57 | 1.9 | 111 | 3 | 0.26 | 154 | 201 | 0.68 | 20 | 0.8 | 12.7 | 2.9 | 18.2 | 8.3 | 17.6 | 3.1 | 1 | 0.65 | 3 |
| G009c       | Gstalter (1996) | Dany | Bouillante Chain | 0.04 | 3 | 162 | 4.4 | 0.3 | 227 | 177 | 1.05 | 30.3 | 0.22 | 4 | 5 | 8.2 | 11.5 | 25.1 | 3.7 | 1.1 | 0.78 | 5.2 |
| G010a       | Gstalter (1996) | Dany | Bouillante Chain | 1.2 | 3.9 | 184 | 5.2 | 0.35 | 277 | 93 | 1.39 | 40.6 | 0.12 | 1.2 | 7 | 12.9 | 29.2 | 4 | 0.93 | 0.84 | 4.1 |
| G010b       | Gstalter (1996) | le Tuf Vanbet | Bouillante Chain | 1.24 | 4.3 | 211 | 5.8 | 0.37 | 291 | 103 | 1.54 | 44.1 | 0.16 | 1.2 | 7.3 | 13.7 | 30.3 | 4 | 0.96 | 0.89 | 6.2 |
| G010c       | Gstalter (1996) | Morne à l'Isle | Bouillante Chain | 1.24 | 4.6 | 109 | 3.7 | 0.37 | 290 | 132 | 1.4 | 40 | 0.19 | 5.8 | 1 | 102 | 12.1 | 28.3 | 3 | 0.88 | 0.54 | 2.9 |
| F002d       | Blanc (1983) | Dany | Bouillante Chain | 0.41 | 147 | 93 | 2.4 | 0.19 | 103 | 210 | 0.45 | 13 | 0.05 | 14 | 7 | 22.4 | 6.7 | 19.4 | 1.1 | 0.58 |
| F002e       | Blanc (1983) | Dany | Bouillante Chain | 0.42 | 138 | 95 | 2.4 | 0.19 | 123 | 220 | 0.48 | 14 | 0.05 | 14 | 18 | 3 | 23 | 6.7 | 15.8 | 1.12 | 0.59 |
| L10044      | RCSC (1987) | Het Pigeon | Bouillante Chain | 0.33 | 0.92 | 90.02 | 2.46 | 0.18 | 118.9 | 319.1 | 0.31 | 10.48 | 0.78 | 5.7 | 15.29 | 7.15 | 17.08 | 3.82 | 1.26 | 0.68 | 2.94 |

Table 3b. Trace Elements of Bouillante Chain samples and unpublished analyses from other Basse-Terre volcanic series. Unpublished analysis is in bold.
(Na₂O/K₂O) vs SiO₂

AXIAL CHAIN
BOUILLANTE CHAIN
BASAL COMPLEX
MONTS CARAIBES
GRANDE DECOUVERTE - SOUFRIÈRE
NORTHERN CHAIN
TROIS RIVIERES - MADELEINE

SiO₂ (wt%) vs TiO₂

TiO₂ / SiO₂

AXIAL CHAIN
BOUILLANTE CHAIN
BASAL COMPLEX
MONTS CARAIBES
GRANDE DECOUVERTE - SOUFRIÈRE
NORTHERN CHAIN
TROIS RIVIERES - MADELEINE

SiO₂ (wt%) vs Al₂O₃

Al₂O₃ / SiO₂

AXIAL CHAIN
BOUILLANTE CHAIN
BASAL COMPLEX
MONTS CARAIBES
GRANDE DECOUVERTE - SOUFRIÈRE
NORTHERN CHAIN
TROIS RIVIERES - MADELEINE

SiO₂ (wt%) vs MgO

MgO / SiO₂

AXIAL CHAIN
BOUILLANTE CHAIN
BASAL COMPLEX
MONTS CARAIBES
GRANDE DECOUVERTE - SOUFRIÈRE
NORTHERN CHAIN
TROIS RIVIERES - MADELEINE
Figure 10. Binary diagrams displaying major and trace elements as a function of SiO$_2$ and Th for Guadeloupean volcanic series.