__Fieldtrip__

Geology and geothermal activity of the Bouillante Volcanic Chain.

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1- Guadeloupe geodynamic setting

The Guadeloupe archipelago (Islands of Basse-Terre, Grande-Terre, les Saintes, Marie-Galante and Désirade) lies in the northern part of The Lesser Antilles Arc which spreads over 850 km long between the island of Saba in the North and Grenade in the South. Most of the magmatic products found in the island arc are related to the subduction of the North American Plate below the Carribean plate since at least 40 Ma (Bouysse et al., 1990).
Compared to other volcanic arcs, recent convergence rates are relatively slow (2 to 4 cm.y^{-1}) as is magma productivity (3 to 5 km^{3}.Ma^{-1}.km^{-1}) (Sigurdsson et al, 1980, McDonald et al., 2000). North of Dominique Island, two different arcs can be spatially distincted.

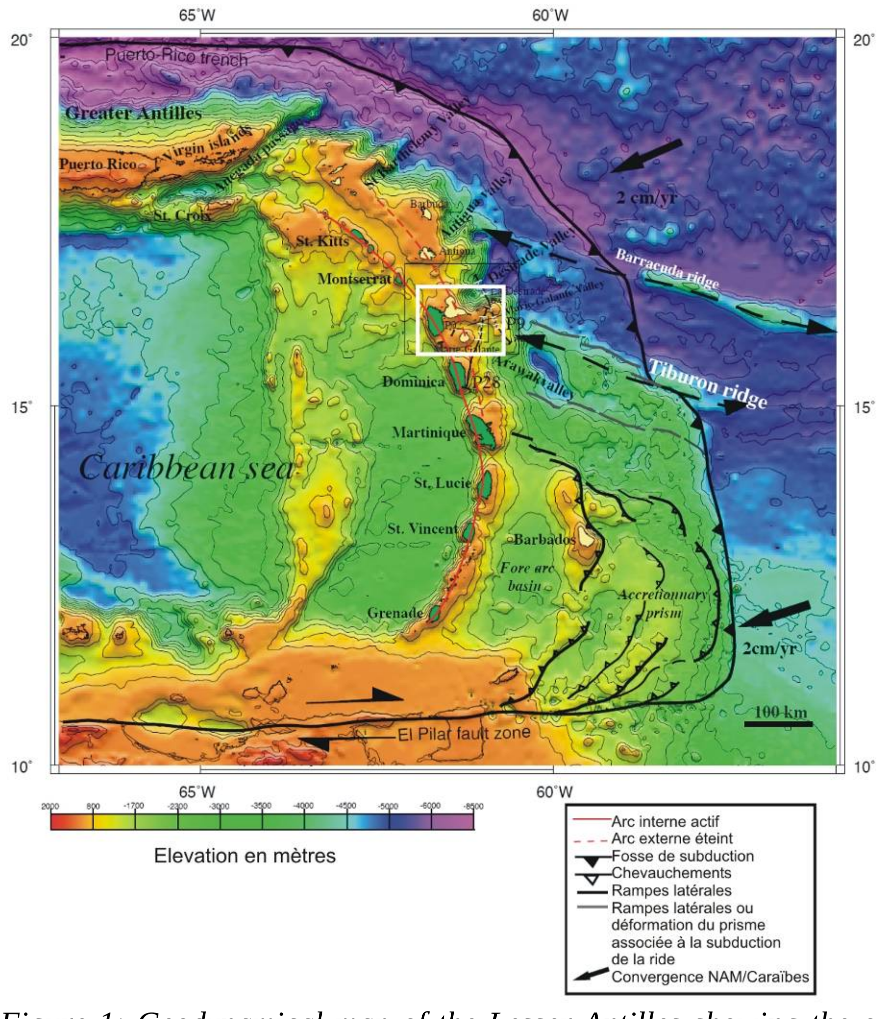

Figure 1: Geodynamical map of the Lesser Antilles showing the old extinct arc (dotted red line) and the recent active are (plain red line). Guadeloupe Archipelago is showed within the white box. (Slightly modified from Feuillet, 2000).

Around Mid-Miocene age, regional tectonic adjustments probably modified the dip of the northern part of the subducting slab, driving the migration of the volcanic front to the west and creating a new volcanic arc (Bouysse et al., 1990). In the southern part of the Lesser Antilles, both ancient and active arcs are surimposed. In the present active volcanic arc, magmatic activity is limited to the Pliocene and 12 volcanoes have been active in the last 10 000 years with a wide range of arc magma compositions and eruptive styles. The northeast part of the arc, now extinct, (also called Limestones Caribees) stretches from Anguilla to Guadeloupe and mainly consist of eroded volcanic edifices covered by sequences of limestones of Miocene to Quaternary ages. Locally (e.g. Saint-Martin and St Barthelemy) older sedimentary units from Paleocene to Ecocene age can be found). South of Dominique, most islands usually display Pliocene to quaternary volcanic deposits overlying Miocene or pre-Miocene volcanic and sedimentary units. The Lesser Antilles show strong along-arc petrological (tholeiitic to calc-alkaline) and geochemical variations that can be related to varying contributions of the subducted components to arc magma genesis (See McDonald et al., 2000 and Lindsay et al., 2005 for a review). For example, Pb isotopic composition of volcanic rocks show a strong increase in radiogenic Pb towards the south than can be attributed to increasing incorporation of sediments (bulk, or via melts) into the source of the magmas (e.g. White and Dupré, 1986, Carpentier et al., 2008).

2-Overview of the geology of Guadeloupe.

The Guadeloupe archipelago is a unique setting to review the history of the Lesser Antilles from early proto-arc formation to recent volcanic activity. Being part of the northern part of the arc, Guadeloupe displays both the recent active volcanic arc and the old extinct arc.

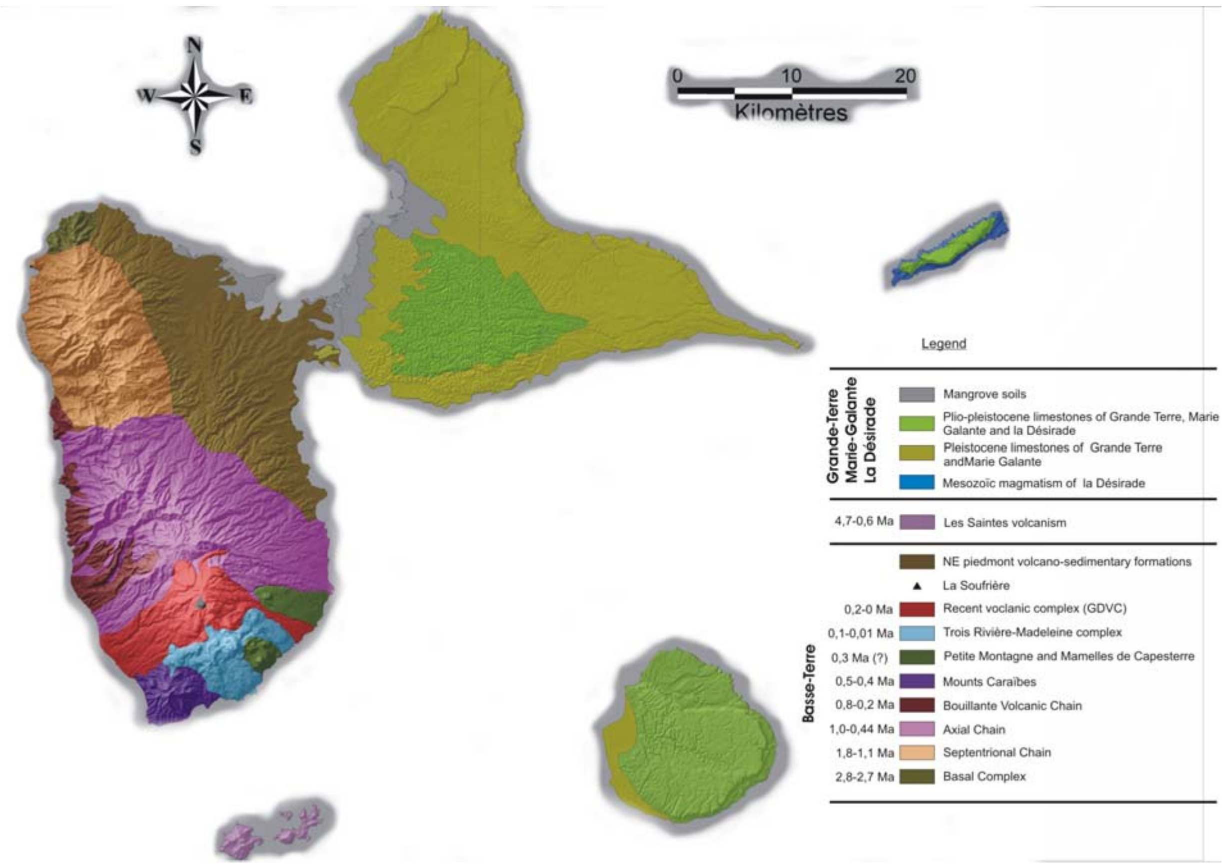

Figure 2: Geological sketch map of Guadeloupe

La Désirade

Lying to the east of the main islands, La Désirade Island displays a magmatic basement of mesozoic age, overlaid by a thick sequence of Pliocene to Quaternary limestones. The magmatic basement of la Désirade is constituted mainly by sub-aqueous effusive magmatic rocks (pillow lavas) and an intrusive sequence (trondjhemitic pluton and intermediate-felsic dykes crosscutting the entire magmatic complex). Radiolarians, of Pacific-origin, found in inter-lava flow cherts are upper Thitonian (ca. 150-145 Ma) to Late Kimmeridgian (153-150 Ma) age. (Montgomery et al., 1992; Mattinson et al., 2008; Cordey and Cornée, 2009). Zircons from the trondjhemitic pluton were date by U-Pb to 143.74+-0.33 Ma (Mattinson ett al., 2008). Despite a strong controversy over the origin of this volcanic complex (mid-ocean vs. subduction-related environment), there is a consensus towards the fact that La Désirade rocks were probably formed within a back-arc supra-subduction zone setting in the Colombian Marginal Seaway between the Americas, at a time of onset of the proto-carribean arc. This volcanic complex is the only example of Mesozoic volcanic and plutonic rocks in the Lesser Antilles. This complex is capped by a thick Neogene limestone series similar to Grande-Terre and Marie-Galante.

Grande-Terre and Marie-Galante

Both islands are part of the Limestone Carribees. Their basement (which, contrary to other islands of the Limestone Carribbees) has no visible outcrop, is probably composed of volcanic units of Eocene to Oligocene age (Andreieff et al., 1987). On Grande-Terre, the overlying carbonate platform is the thickest (120 m) and most complete Pliocene-Pleistocene sequence in the Lesser Antilles (Andreieff et al., 1987). It is massively cross-cut by normal faults related to regional stress regime in the carribean tectonic plate (Feuillet et al., 2002). From the base to the top, the carbonate platform has been divided in 4 distinct lithostratographic units. Unit P1 consits of a 60 m-thick yellowish rhodolitic limestone of Plio-Peistocene age. Unit P2 is a polygenic and heterometric volcano-sedimentary index-bed which thickness decreases from west (10 m) to east (few dm). Internal structures and composition (including foraminifera) indicate that this sequence was deposited in a shallow delta-like environment in lower Pleistocene time, with a source of volcanic material situated close to the present location of the Basal complex on Basse-Terre island (see below). Unit P3 or so called “Upper Limestones” is made of rhodolitic limestones of lower Pleistocene to upper Pleistocene age. Finally, the toping Unit P4 is composed of upper Pleistocene coral-reef limestones where foraminifera indicate a time of deposit between 0.78 to ca. 0.4 Ma. Within unit P4, a major erosional surface (S1) has been recently identified (Léticée et al., 2005) which separates an acropora-rich limestone formation above an agaricia-rich limestone formation. Right above the S1 erosion surface, a transgression series starting with sandy deposits can be identified. On top of Unit P4, the S2 erosional surface corresponds to the generalized emersion of the carbonate platform during the upper Pleistocene, the exact timing of which is still debated (Léticée et al., 2005).

Basse-Terre

The island of Basse-Terre, lying to the West of Grande-Terre, is part of the active volcanic arc of the Lesser Antilles where the oldest volcanic activity is of Pliocene age. Based on morphological evidences and a recent age re-evalutation (Samper et al., 2007), 6 main volcanic complexes have been have been identified. Since 2.89 Ma, the volcanism of Basse-Terre shows a temporal migration from North to south (except the southernmost volcanism of Monts Caraïbes, see below). Despite the fact that Basse-Terre and Grande-Terre are geographically separated by a narrow marine channel (la Rivière Salée), it is worthy to note that there is a complex relationship between the volcanic units of Basse-Terre and the carbonate platform of Grande-Terre which is presently hidden by the thick volcano-sedimentary piedmont occupying the northeastern part of Basse-Terre. For example, in the Jarry area, available data from deep wells indicates that the limestone identical to Grande-Terre caps volcanic units (Rançon et al., 1992). Around Destrelan and Petit-Bourg area, wells data also indicate that volcano-sedimentary units from the piedmont overlie a carbonate platform.

At the northern tip of Basse-Terre Island, the Basal Complex is mainly composed of fissural volcanism. Subaerial lava flows mark the coastline and deeply erodes edifices can be recognized inland (e.g. Piton de Sainte-Rose) or offshore (îlet à Kahouanne). This volcanic massif is rather small, the oldest of Basse-Terre and was emplaced between 2.79 and 2.68 Ma.

South of the Basal Complex, the Septentrional Chain occupies one-third of the island and was emplaced between 1.81 and 1.15 Ma. It is also dominated by fissural magmatism along a NNW-SSE line. Numerous thick SSW-NNE-directed lava flows can be related to several strongly eroded edifices (e.g. La Couronne). It is generally admitted that the Two Mamelles represent the last eruptive stage in the Chain around 1.

South of the Septentrional Chain, the axial Chain is characterized by imbricate composite volcanoes aligned along a NW-SE direction (e.g. Capesterre Volcano, Icaques Volcano or Grand Sans-Toucher volcano). Datations indicate that the eruptions took place between 1.01 and 0.435 Ma. The southern part of the massif was affected by at least two huge flank collapses at 640 ka and 550 ka. Magmatism started with extensive submarine volcanism followed by andesitic subaerial phase.

After the emplacement of the Axial Chain, the regular N-S migration of the volcanism was interrupted by a jump to the south with the eruption of the Mount Caraïbes around 500 ka which charaterized by an intense sub-aqueous activity of sursteyan type followed by sub-aerian volcanism (thin effusive lava flows intercalated with phreatomagmatic products) and the final extrusion of domes (e.g. Houëlmont). Magmatic compositions are dominated by basalts and basaltic andesites.

Finally, starting at 200 ka, the volcanism migrated to the north to create the recent Grande Découverte –Soufrière Massif where several magmatic stages can be recognized (e.g. Carmichaël, Grande Découverte, Trois Rivières complex, Madeleine Complex, etc…), although the volcanic activity is now strictly limited to the Soufrière Dome.

Within this volcanic time framework, the Bouillante chain occupies a specific place as it is characterized by the eruptions of small successive centers of hydromagmatic dynamism between 0.8 and 0.2 Ma along the carribean cost of Basse-Terre. Altough the Bouillante Chain can be both spatially and timely related to the Axial Chain, the specific geochemical signature of the erupted magmas (tholeitic vs. calc-alkaline for the rest of Basse-Terre volcanism) indicates a different origin.

3- The Bouillante Volcanic Chain

The Bouillante Volcanic Chain (Gadalia et al., 1988) is characterized by a succession of small monogenic edifices trending NNW-SSE which are partly imbricated in dominantly andesitic effusive volcanism of the Axial Chain. In the area of Bouillante, exploration boreholes indicate that the lithology of the Axial Chain (related the Pitons de Bouillante edifice) is constituted from bottom to top by: 1) a submarine volcanic unit, 2) a shallow submarine to coastal volcano-detritic unit, 3) a sub-aerial volcanic unit and 4) a subaerial volcano-detritic unit.

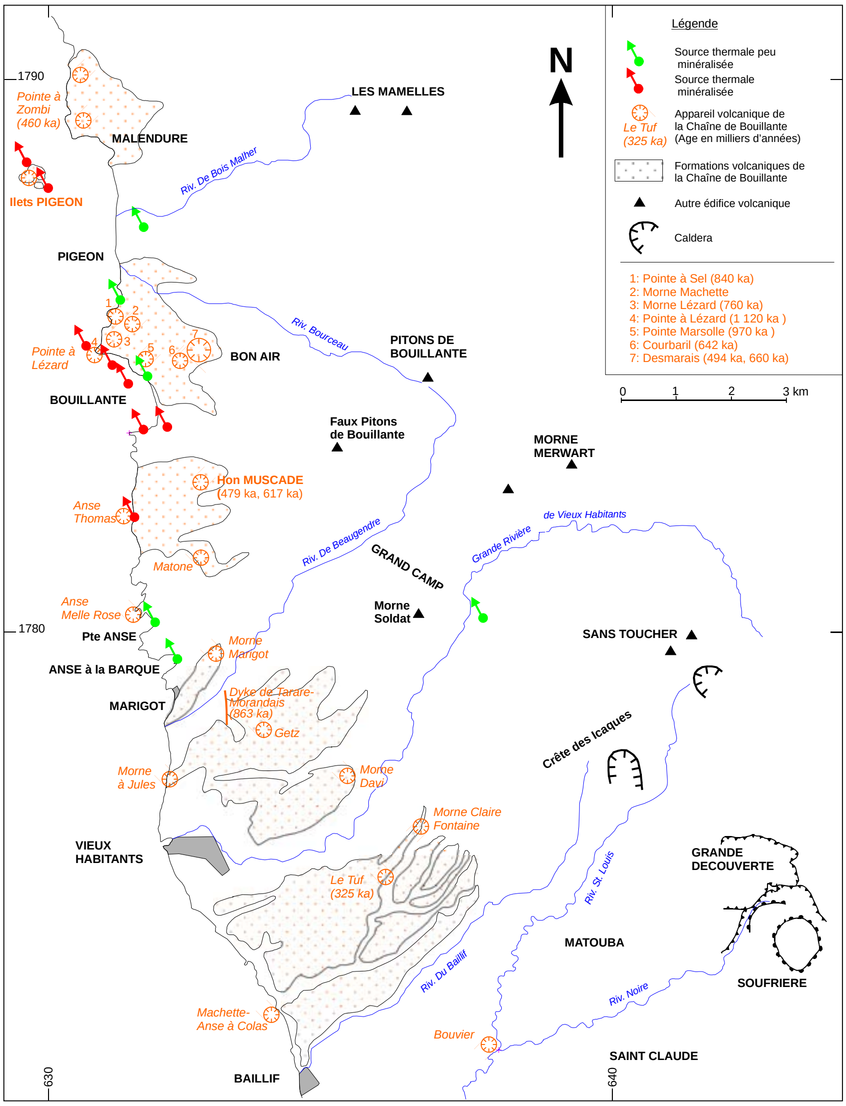

Figure 3: Geological sketch map of the Bouillante Volcanic Chain formations (modified from Gadalia et al., 1988)

Lying on this substratum, the Bouillante volcanic Chain defined by Gadalia *et al.* (1988) is constituted by several small edifices showing a wide range of volcanic style (with a strong hydromagmatic component): effusive, strombolian, maar, etc… which are clearly aligned on the offshore N160°-striking Montserrat-Bouillante system (cf. Thinon *et al.*, 2010) suggesting a major tectonic control on the emplacement of the BVC. Petrologic studies of BVC products indicate a tholeiitic trend contrasting with the low K calc-alkaline signature of the majority of volcanics of Basse-Terre. The BVC can be considered as a single series evolving through fractional crystallization with a geographical control: basalts and andesites seems to be predominantly present in the north, dacites and rhyolites in the south. Persistence of the volcanism in the limited area together with the NNW-SSE trending direction of the chain and a dominant control of fractional crystallization throughout the series displaying two level of f_{O2}, evidences of magma mixing, argue in favour of a two levels magmatic reservoir trending along the same alignment immediately below the volcanic chain.

4 - Geothermal fluids

Within the Bouillante area, the composition of the geothermal fluid (either taken directly in the reservoir, or “reconstructed” from the hot springs) is fairly constant. It is a slightly acidic (pH 5.3+-0.3) chlorine-rich fluid with a salinity close to 20g/l.

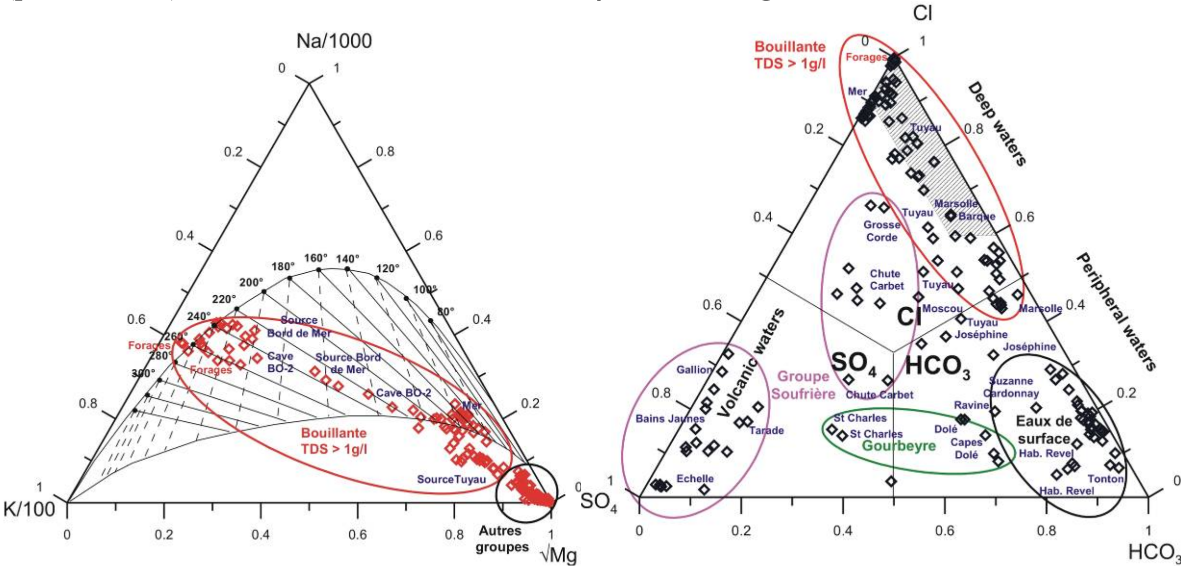

Figure 4: Na-K-Mag and Cl-SO4-HCO3 ternary diagrams (Giggenbach, 1988) applied to thermal waters from Bouillante and Basse-Terre.

The geochemical analyses indicate that the geothermal fluid results from a mix of seawater (58%) and freshwater (42%) reacting into the geothermal reservoir at a temperature around 260°C in equilibrium with illite. Compared to seawater diluted with freshwater, the geothermal fluid is enriched in K, Ca, Si, B, F, Sr, Li, Rb, Cs and most metals (Fe, Al, Mn, Cu, Ni, Pb, Zn, Co, Cd, etc…). The ^{13}C and $3He/^{4}He$ isotopic signature indicate a combined magmatic, marine and meteoric origin for the fluid. The process of mixing between seawater and meteoric water (probably infiltrated on the eastern slopes of the nearby Pitons de Bouillante forming the Axial Chain) is in good concordance with the regional W-E fault system extending both onshore and offshore (Bouillante – Capesterre fault system, see below). 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 CO_2 (>90%) account for approximatively 0.4% of the water vapour mass (Sanjuan et al., 2001).

5- Local and Regional tectonic control on the geothermal reservoir

The N-S trending Bouillante Volcanic Chain is probably controlled by the submarine NNW-SSE strike-slip fault which belongs to the regional, normal senestral Montserrat-Bouillante-Les Saintes system. The Bouillante geothermal field is located at the intersection between this major submarine transfer fault and the western horse-tail fault end of the Bouillante-Capesterre normal fault which is a major corridor of the E-W Marie-Galante graben system.

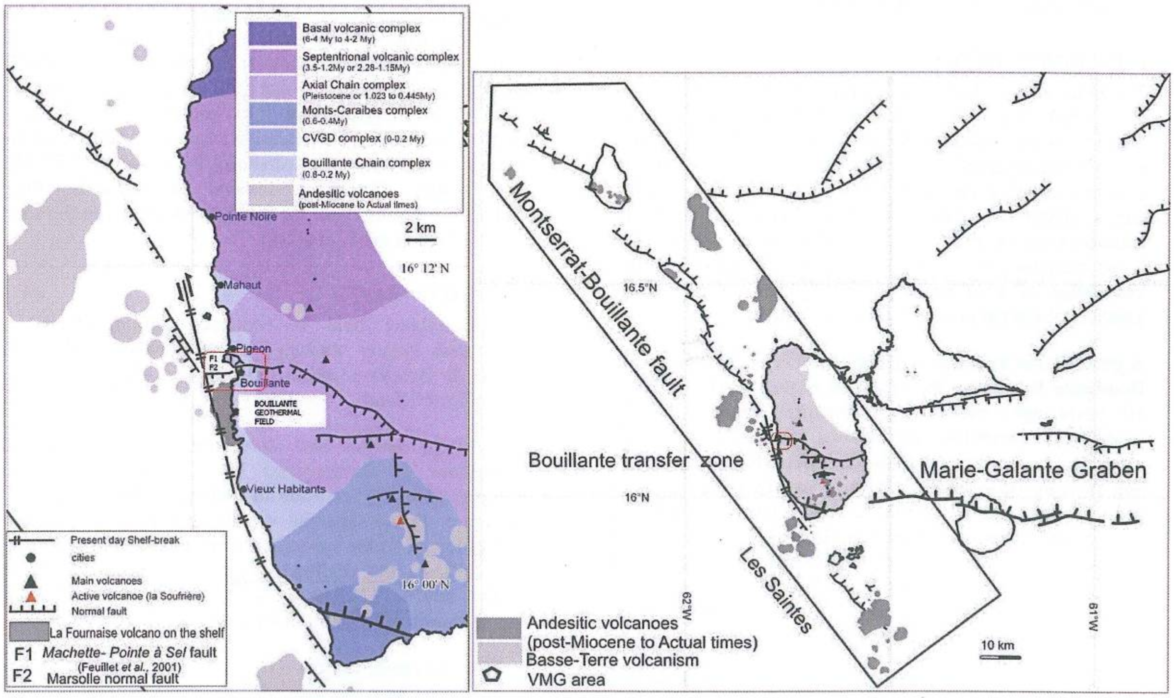

Figure 5: Regional and tectonic settings of the Bouillante field and associated volcanism. from Thinon et al. (2010)

In detail, the Bouillante geothermal field has developed within a small graben. Backing up against the major south-dipping Bouillante-Capesterre(-Marsolle) fault, this graben is made of a “piano-key” network of E-W antithetic faults which, considering their sub-vertical dip, favours tension opening subjected to NNE-SSW extension and the circulation of geothermal fluids. Locally, in the northern part of Bouillante bay, this fault-related extension is underlined by the E-W alignment of several small edifices of the BVC.

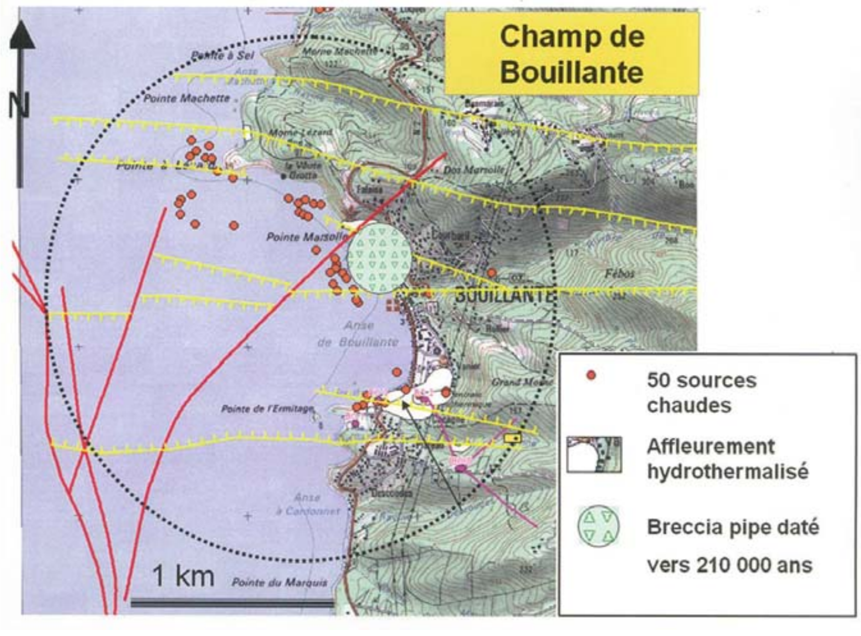

Figure 5: Structural pattern of the Bouillante geothermal field (From Bouchot et al., 2010). (Hydrothermal Breccia is now dated at 250 ka +-50 ka; Verati et al., 2011)

6 - Geometry of Bouillante geothermal Reservoir

The reservoir of Bouillante geothermal field can be defined by two units: 1) a heat reservoir corresponding to the total rock volume affected by intense pervasive hydrothermal alteration (mainly illite and chlorite zone) with a homogeneized temperature of 250-260°C, 2) a hydraulic network made up of permeable faults and porous aquifers in which the geothermal fluids circulate in the heat reservoir. The top of the reservoir located at the base of the illite-smectite zone deepens from north (ca. 300 m) to south (ca. 600 m) of the geothermal field, ie., moving away from the apical zone of the reservoir in Bouillante Bay.

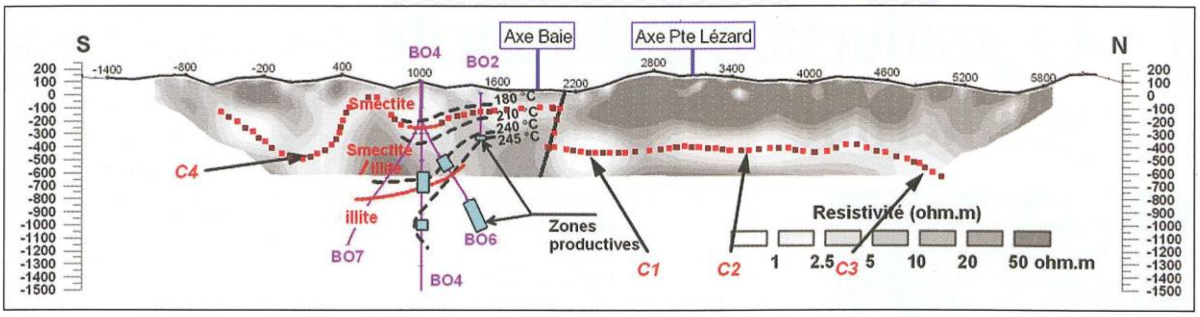

Figure 6: Isotherms and hydrothermal alterations horizons deduced from wells and the interpreted electrical profile across Bouillante Field (8 km N-S). (From Bouchot et al., 2010).

Based on the well data, electrical resistivity tomography signature and the volcanic and structural mapping of the field, it is considered that the most likely geometric hypothesis for the reservoir is as follow.

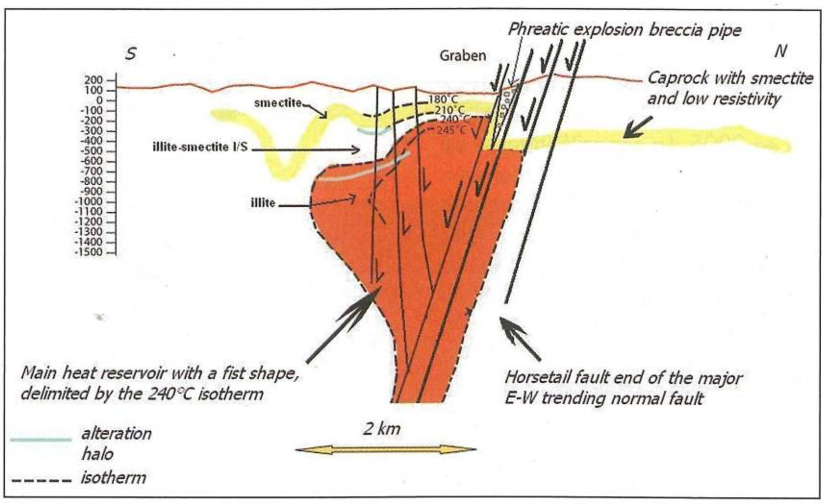

Figure 7: 2D conceptual model of Bouillante geothermal field (From Bouchot et al., 2010).

In a N-S Section, the envelope of the heat reservoir has a fist-like shape, about 2 km wide between Descoudes and Pointe à Lézards, 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 à Lézards corridor, if one accepts the hypothesis of a circulation of deep fluids controlled by the major tectono-magamtic corridor. The 240°C isotherm roughly delimits the geothermal reservoir in this geometrical model. Its singular path below 1000 m (toward the main fault) shows negative values of temperature gradient as measured from 1000 to 18000 depth in BO-4 well. 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, the evidence of many geothermal discharges from the reservoir in the Bouillante Bay confirms the extension of the the reservoir offshore, perhaps up to the major N160 E striking fault.

7 - A brief history of geothermal exploration and exploitation in the Bouillante Bay.

The first geothermal surveys in Guadeloupe were conducted in the 60's and the 70's under the leadership of the SPEDG (Société de Production et de Distribution de l'Electricité en Guadeloupe). Those surveys were focused directly on the Bouillante Bay area where a lot of surface signs pointing towards a geothermal reservoir at depth were found onshore: hot soils, hot springs and fumerolles. A geological survey was conducted including mapping of the local geology, hot springs water analyses and mapping of temperatures at 1 m depth. Following this survey, 3 exploration wells (BO-1, BO-2, BO-3) were drilled south of Bouillante village in 1969-1970. Theses wells, ranging in depth from 338 m to 850 m, confirmed the existence of a temperature anomaly around 240-250°C at less than 400 m depth. Unfortunately, only one well (BO-2) showed a significant productivity with 25-30 tons per hour of vapour at 6 bars pressure.

A new exploration phase started in 1970-1971 with the aim of finding clues of permeability at depth through electric resistivity and seismic (offshore) profiles. Following the survey, a new exploration vertical well (BO-4) was drilled during 1974-1977 in the vicinity of Bouillante village right above a major low resistivity anomaly (Plateau). Reaching 2500 m deep, it confirmed the thermal anomaly of 250°C but failed to crosscut a major hotwater drain and showed a very limited vapour productivity.

Following these two stages of exploration, the difficulty to highlight in the area a reservoir with a strong permeability led to the construction of a rather small electricity production unit with a maximum capacity of 5 MWe in 1986 (only fed by the vapour produced by the well BO-2). This production unit, known as B-1, is still in activity today, albeit it went through a major rehabilitation in 2009-2010.

In 1981-1984, a new geothermal exploration survey (geological mapping, soil gases, temperatures, hot water geochemical analyses, geophysics), started on a much larger area covering the coastal area between Pointe-Noire in the North to Basse-Terre in the south. The main result was the reconnaissance of the recent volcanism (0.8 to 0.2 Ma) of the Bouillante Volcanic Chain. It also concluded that the geothermal reservoir recognized right under the Bouillante bay had probably Northern (Malendure) and Southern (Thomas) extensions.

Starting in 1995, a new company, Géothermie Bouillante SA (a subsidiary of BRGM and EDF) was created for the exploitation of B-1 unit. In conjunction, a new geothermal survey was undertaken to further develop the geothermal field. A series of submarine hotsprings were discovered in the northern part of the Bouillante bay. New volcanic edifices related to the Bouillante Volcanic Chain were discovered and major faults having a strong control on the geothermal reservoir and underground fluids migration could be characterized. At the end of 2000, 3 new exploitation wells were drilled in the vicinity of BO-4. Drilling was done at 30° angle to maximize the chance to crosscut sub-vertical faults. Bo-5 and Bo-6 (both 1200 m deep) successfully went across the Cocagne and the Plateau faults and showed a good productivity. BO-7 (1400 m) went apparently through the Descoudes Fault but failed to be productive enough. The 3 new wells yielded geothermal fluids similar to the ones extracted at BO-2 and BO-4. In 2005, a new electricity production unit was exploited (know as B-2 unit) with a total gross power of 11 MWe.

When both in production, the two units deliver 6 to 8% of the total annual consumption of electricity of the island. Today, both units are fed by vapour extracted from BO-5 and BO-6. Other wells are used for in-situ observations and BO-2 has been specifically used for the reinjection of the extracted fluid into the geothermal reservoir since 2010.

Since 2003, ongoing scientific efforts with the financial support of Region Guadeloupe and ADEME (French Agency for Environment and Energy Saving) are undertaken to better constrain the geometry of the geothermal reservoir in the Bouillante area and to prepare the drilling of 2 or 3 exploration wells in the northern part of Bouillante Bay, between Pointe Marsolle and Machette Morne, that should take place during 2011.

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8 - Stops

Stop 1 - Anse Thomas

Cf. Overview of the Geology of Basse Terre and BVC

Anse Thomas is situated in the southern part of the BVC. The volcanic edifice associated to the pyroclastic deposits of Anse Thomas has not been identified and is probably situated off-shore in shallow waters. It could be a subaquatic maar. Anse Thomas hotspring is emerging within the hydromagmatic deposits overlying a massive lava flow formation also related to the BVC. In the same area, two edifices have been recognized: Muscade (a nearby lava was dated at 479+-17 ka and 617+-10 ka) and Matone (basic andesitic). The hot spring is associated to a sub-vertical N80°E striking fracture zone which is 20 cm large. Fault directions in the area are close to N80 to N100 in agreement with the direction of regional faulting in the Bouillante area. The flow has been estimated to 0.2 l/s. Water is slightly acidic and strongly mineralised (> 20 mSm/cm) with a temperature in excess of 50°C. Geochemical composition of the water indicate that it is a mix of sea water (64%), meteoric water (related to a shallow aquifer; 26%) and geothermal fluid (10%).

Stop 2 - Anse Marsolle

Cf. Local and regional tectonic control on the geothermal reservoir

In the area of Bouillante and Anse Marsolle, BVC magmatism has been date around 800 to 500 ka (e.g. Morne Lézard: 760 ka). Offshore, a major south-dipping E-W striking normal fault has been recognized (Bouillante Fault). It represents the northern limit of the Bouillante graben and is probably connected to the main structure of the regional Capesterre-Marie-Galante fault system described by Feuillet (2001). This northern part of the bay was probably the seat of a major phreatic explosion, as indicated by the many blocks of hydrothermal breccia collected around the Marsolle Anse. Clasts and cement of the breccia are both characterized by a mineralogical assemblage of adularia, illite-smectite and silica (+ - calcite and jarosite) indicating a high temperature fluid (around 300°C). The exact position of the breccia pipe is still to be found in the bay but recent Ar-Ar dating on the adularia crystals give an age around 250 ka±50 (Verati *et al.*, 2011).

Stop 3 - Visit of the geothermal plant - Geothermie Bouillante SA.

Cf: a brief history of geothermal exploration in the Bouillante area

Stop 4 - Pointe à Lézards/Anse Machette

Cf. Geometry of Bouillante Geothermal Reservoir

Anse Machette is characterized by the presence of several edifices of the BVC, and more particularly, a scoria cone (Pointe à sel) dated at 840 ka. It is capped by a thick sequence of plinian deposits probably originating from nearby younger edifices (Morne Machette or Morne Lezard). The brownish formation on top is made of slightly reworked pyroclastic deposits. The E-W south-dipping Machette Fault is a normal fault crosscutting the pyroclastic deposit with a total displacement of 20 to 30 m. Offshore seismic survey indicate a limited lateral extension of this fault (yet typical of the "piano-key" fault system of Bouillante graben)