
Hydrogeological model of a high-energy geothermal field (Bouillante area, Guadeloupe, French West Indies)

P. Lachassagne · J. C. Marechal · B. Sanjuan

Abstract The Bouillante geothermal field provides about 8% of the annual electricity needs of the French West Indies island of Guadeloupe. It has been the subject of several studies covering various disciplines. A hydrogeological conceptual model of the field is proposed. The reservoir consists of two perpendicular sets of fractures and faults, related to major regional tectonic structures, which have been clogged near surface by self sealing. The heat exchanges of the reservoir with the outside are reduced, through thermal and hydraulic blanketing, to conductive transfers. Convection cells are active within the reservoir, ensuring its thermal and geochemical homogeneity. Heat exchange with the magmatic chamber is only conductive. The Na–Cl geothermal fluid in the reservoir is composed of 60% seawater and 40% freshwater and has reached a chemical equilibrium with a mineralogical assemblage at 250–260°C. Many arguments (equilibrium state, absence of tritium, low in/out fluxes, large reservoir volume) suggest a long residence time (>100years) of the geothermal fluid. Three factors explain the existence and location of the geothermal field: a heat source (cooling hypovolcanic intrusion), a network of permeable fractures at the origin of the geothermal aquifer, and an impermeable surface cover, limiting the loss of energy and ensuring the durability of the field.

Keywords Conceptual model · Geothermal field · Groundwater hydraulics · Guadeloupe · French West Indies

Received: 2 June 2008 / Accepted: 18 May 2009
Published online: 5 June 2009

© Springer-Verlag 2009

P. Lachassagne (✉) · J. C. Marechal
BRGM, Water Division,
Hard Rock Aquifers Unit,
1039, rue de Pinville, 34000, Montpellier, France
e-mail: patrick.lachassagne@danone.com
Fax: +33-4-67157975

B. Sanjuan
BRGM, Department of Geothermal Energy,
3 Av. Claude Guillemin, 45060 Orléans Cedex 2, France

Present Address:
P. Lachassagne,
Danone Eaux France - BP 87, 74503 Evian Cedex, France

Introduction

The Bouillante geothermal field is located on the volcanic island of Basse Terre which, together with the adjoining island of Grande Terre, forms Guadeloupe. Both islands are part of the French West Indies (Fig. 1) that lie on the Lesser Antilles island arc (Andrieuff et al. 1989). The Bouillante site is located on the west coast of Basse Terre Island, half way between the north and south ends of the island (Fig. 2). With a water temperature of about 260°C, no vapor in the aquifer and an enthalpy of about 1,100 kJ/kg, the Bouillante geothermal field is considered as a high energy, high temperature, medium-to-low enthalpy geothermal field (Zarrouk et al. 2006).

This area has been long known for its terrestrial hydrothermal surface expressions (hot springs, mud pools, steaming grounds and fumaroles) and consequently the village has been named ‘Bouillante’ which means ‘boiling’ or ‘off the boil’ in French. The development of the Bouillante geothermal field follows several key periods which will be presented later. Today, the Bouillante power plant consists of two units (GB1 and GB2), with a total installed power output close to 15 megawatt electrical (MWe), supplied by three geothermal wells (BO-4, BO-5 and BO-6). It covers about 8% of the annual electricity consumption of Guadeloupe (450,000 inhabitants). The plant contributes significantly to a secure electricity supply for the island as well as to a decrease in its production cost (in Guadeloupe most non-geothermal electricity is generated by burning fossil fuels), and to a concomitant reduction in greenhouse gas emissions.

Data from multidisciplinary studies acquired on the Bouillante site over the past years, cover geology, geophysics, hydrodynamics, hydrogeochemistry, geothermometry, etc., and range from the regional scale of Guadeloupe to that of a well or an outcrop. Combining and cross-correlating these various data has led to significant progress in the understanding of the geothermal field and to proposing a complete hydrogeological conceptual model that is described in this paper. As, in geothermics, most of (natural or man induced) heat transfers rely on water fluxes (either liquid or vapour), this model is largely oriented towards the hydrodynamics of this area.

Such a hydrogeological model is indispensable from an operational viewpoint, in particular in view of ongoing projects on site, which include increasing the actual power production through development projects for the geother-

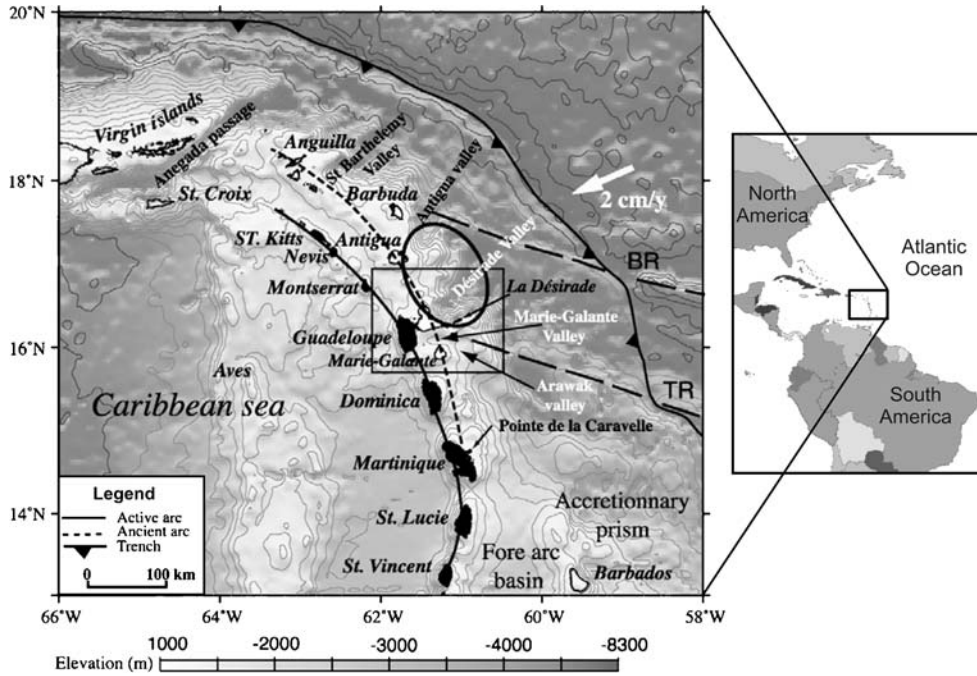


Fig. 1 Bathymetric map of the Lesser Antilles arc. Bathymetry from Smith and Sandwell (1997), contour interval 500 m. *Continuous black line*: recent volcanic arc; *dotted black line*: ancient arc from Bouysse et al. (1988). Volcanic islands (on recent arc) *in black*; coral-reef islands (on ancient arc) *in white*. *Black dashed lines* mark the Barracuda (BR) and Tiburon ridges (TR). *White labels* mark undersea main bathymetric features in the Guadeloupe island vicinity and the motion vector (2 cm/y) of the Atlantic oceanic plate. *Black rectangular box*: frame for Fig. 2. *Black oval box*: no meaning in the present paper (from the original figure of Feuillet et al. (2001), with permission from Elsevier)

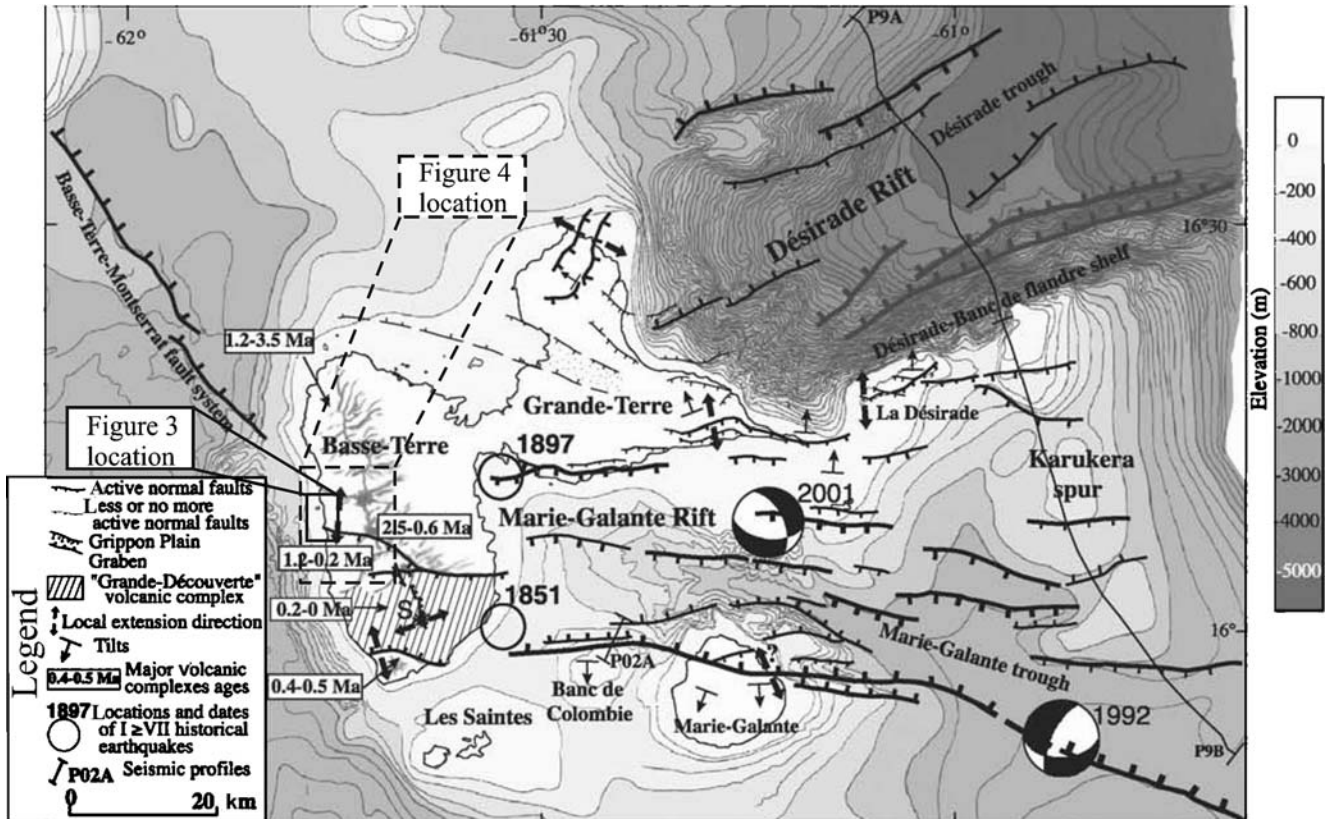


Fig. 2 Bathymetric and tectonic map of the Guadeloupe archipelago; modified after Feuillet et al. (2002), with permission of American Geophysical Union. *Hatched area* is the recent volcanism (<0.2 Ma); *S* Soufrière; *double black arrows* indicate local extension direction estimated from microtectonic measurements and fault geometry. *I>= VII historical earthquakes*: macroseismical intensities $\geq VII$. *Circles with black/white segments* (2001, 1992): location of major recent earthquakes with date

mal field (feasibility studies for a third stage started in 2004), and production improvements such as a reinjection project. Such a model is also the first stage of mathematical modelling of the field.

Several conceptual models of high-energy geothermal fields have been published. For an understanding of andesitic type volcanism (or for shallow granitic intrusions) see, for instance, Westercamp and Traineau 1987; Akasako et al. 2002; Arellano et al. 2003; Batini et al. 2003, 2006; Tamanyu and Wood 2003; Dilsiz 2006. For basaltic type volcanism, see Bodvarsson et al. 1984a, b, c; Gandino et al. 1985; Ingebritsen and Scholl 1993; Violette et al. 1997; Hulen and Anderson 1998.

Most of these conceptual models present, with varying degrees of precision and exclusively in two-dimensions (cross section), the geological and geophysical structure of the subsurface. Some also identify the source of deep heat, in general a magma chamber (Bodvarsson et al. 1984a, b, c) or an intrusion (Batini et al. 2003; Tamanyu and Wood 2003; Bertini et al. 2006). The modes of heat transfer to the surface remain generally imprecise. The respective roles of different types of 'fluid' (water, gas, steam; Akasako et al. 2002; Arellano et al. 2003; Tamanyu and Wood 2003) or of water at different temperatures, and the different means of thermal energy transfer (conduction, convection, advection) are in some cases distinguished (Tamanyu and Wood 2003). The effects of thermal blanketing and interaction with subsurface hydrosystems (cold aquifers) are mentioned for certain sites (Gandino et al. 1985; Westercamp and Traineau 1987; Clemente and Villadolid-Abrigo 1993; Ingebritsen and Scholl 1993; Violette et al. 1997; Akasako et al. 2002; Tamanyu and Wood 2003), but always with a low degree of precision concerning the definition of the concerned aquifer structure and flow directions (the latter mostly as schematic arrows, and generally without individualizing the concerned aquifers), and, in most cases, without a precise quantification of the water fluxes between the geothermal aquifer and the surface (cold aquifers and/or surface waters). In several papers, the proposed diagrams suggest (through arrows for instance) the existence of significant fluxes (recharge, discharge) between the geothermal aquifer and the surface—see for instance (Gandino et al. 1985; Ingebritsen and Scholl 1993)—but these important fluxes or, conversely, the absence of significant fluxes, are rarely demonstrated. The quantification of such fluxes has only been performed for shallow low-energy geothermal areas—see for instance (Dim et al. 2002; Kühn and Stöfen 2005; Flores-Márquez et al. 2006).

On active hot spot volcanoes such as the Fournaise volcano, Réunion Island (Indian Ocean; Violette et al. 1997) or Kilauea volcano, Hawaii (Pacific Ocean; Ingebritsen and Scholl 1993), the hydrogeological characterization is more advanced. Quantitative hydrogeological modelling of the upper permeable part of the edifice has been carried out, which indirectly helps to reconstitute some of the characteristics of the underlying geothermal system, in particular the fact that infiltrating water is kept away from the magma chamber by a thick impervious

shell surrounding the chamber (Violette et al. 1997), and that substantial variations in permeability and the presence of magmatic heat sources influence the structure and position of the freshwater/saltwater interface (Ingebritsen and Scholl 1993). On this basis, Ingebritsen and Scholl (1993) proposed a general conceptual model of the Hawaiian volcanoes.

The present paper proposes a hydrogeological model of the Bouillante geothermal field, based on all available data at different scales. This synthesis is meant to improve understanding of high-energy geothermal fields, in particular those in an active andesitic type volcanic setting. Few publications present the structure and functioning of a high-energy geothermal field in an integrated manner, from the heat source until the subsurface exchanges, whether natural (leaks through conduction, advection and convection) or manmade (through boreholes), combining the characterization of the different energy transfer types within the various compartments of the subsurface with their structural and hydrodynamic (lithology, type of permeability, etc.) properties.

Summary of the main works carried out in the Bouillante area

The first exploration studies of the Bouillante geothermal field, financially supported by SPDEG (Société de Production d'Electricité de la Guadeloupe), were carried out by BRGM between 1963 and 1964 (Cormy et al. 1970; Demians d'Archimbaud and Munier-Jolain 1976; Demians d'Archimbaud and Surcin 1976). These studies mainly included geology and temperature gradient surveys in shallow drill holes. The thermal flow in the hottest area was close to 6.3 W/m^2 , which represents a hundred times the normal geothermal flow (Demians d'Archimbaud and Surcin 1976). These encouraging results enabled the companies SPDEG and EURAFREP to carry on the exploration.

In 1970, following a geochemical study on the fluids of the thermal springs, three wells (BO-1, BO-2 and BO-3; Fig. 3, with respective depths of 800, 338 and 850 m) were drilled by EURAFREP. Among these wells, only BO-2 showed a capacity of large production of geothermal fluid (240°C). In 1971 and 1974, during two long-term production tests, this well discharged a mixture of about 30 t/h (t/h) (8 kg/s) of steam and 120 t/h (33 kg/s) of water after separation of these phases at 5 bars. In 1974, on the basis of geophysical surveys performed in 1972 and 1973, the well BO-4 (Fig. 3) was drilled at a depth of 1,200 m. Even after its deepening down to 2,500 m in 1977, the low steam output of this well was not considered economical. In 1974, a seismic reflection profile was also shot at sea along the whole western coast of Guadeloupe.

In 1980, EDF (Electricité de France) decided to build a pilot geothermal plant with a 4.5 MWe turbine (GB1) only feed by the BO-2 well. This experimental plant operated from 1986 to 1992 and was then stopped. Between 1980 and 1984, several geological, geophysical and geochemical

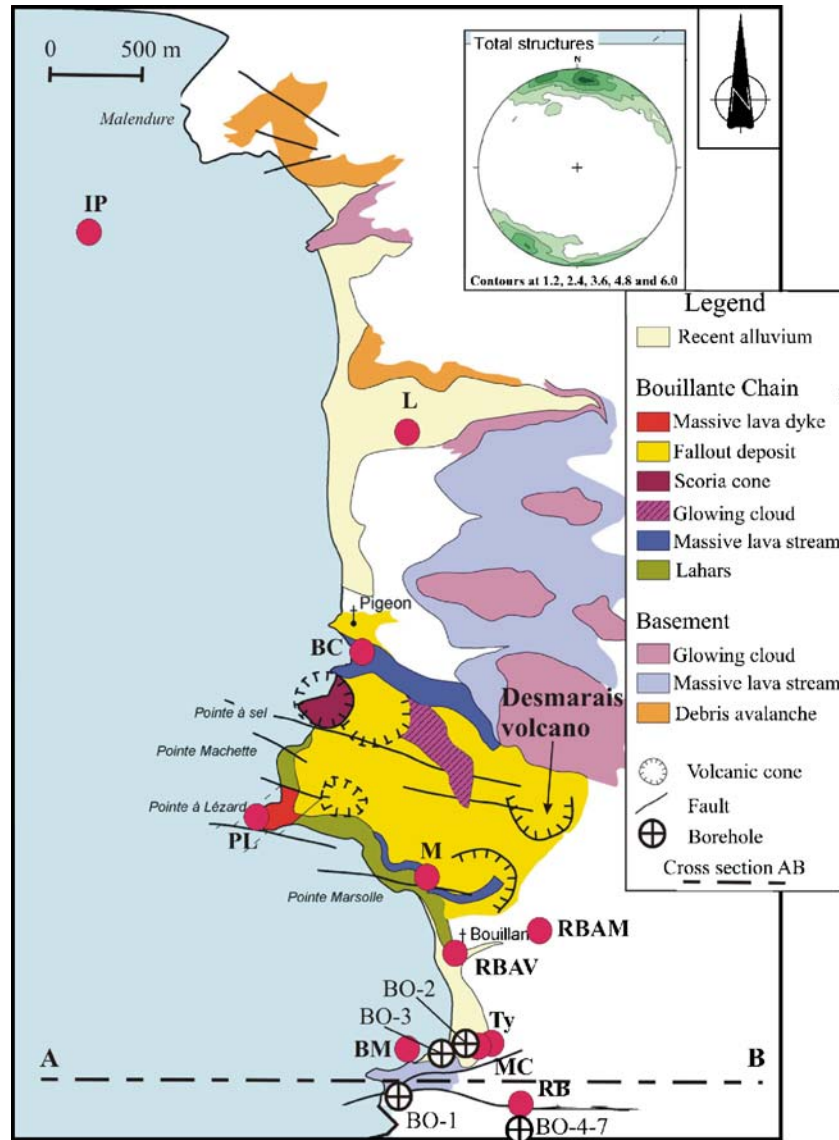


Fig. 3 Geological map of the Bouillante site, after Sanjuan et al. (2005) (main hot springs are red circles; see Fig. 4 for the location of all the springs cited in Table 1; for cross section see Fig. 6). *Top right figure*: polar projection diagram of tectonic discontinuities (joints, faults, etc.) from all surface field observations (density representation)

exploration studies were carried out by BRGM (Barthes and Mennechet 1984; Gadiola and Westercamp 1984; Fabriol and Ouzounian 1985; Fabriol 2001; Sanjuan 2001).

In 1996, the Géothermie Bouillante company, created by CFG Services (60%) and CHART (40%), respective subsidiaries of the BRGM (the French Geological Survey) and EDF Groups, totally rehabilitated and brought back in service the GB1 plant for industrial production of electricity. In 1998, the GB1 unit supplied 23 GWh to EDF, which represented 2% of the annual electricity needs in Guadeloupe.

Between 1995 and 1999, BRGM and CFG Services undertook several research studies with the financial support of Géothermie Bouillante, European Union, Guadeloupe Regional Council and ADEME (French Agency for the Environment and Energy Resources) in order to identify favourable areas for drilling new wells.

Geological and geochemical studies showed that the main indices of geothermal activity were concentrated in and around Bouillante Bay (Traineau et al. 1997). They also allowed for identification of the main faults. Submarine hydrothermal springs and gas escapes were discovered and mapped in the north of Bouillante Bay (Sanjuan and Brach 1997; Sanjuan 2001; Sanjuan et al. 2001). A relatively recent local volcanic activity event was also discovered (<650,000 years). In 1998, an experimental stimulation program of well BO-4 by thermal cracking induced through cold seawater injection increased its permeability and productivity (Correia et al. 2000; Sanjuan et al. 2000).

After these studies, Géothermie Bouillante launched the Bouillante 2 project. In 2000 and 2001, three deviated wells (BO-5, BO-6 and BO-7; Fig. 3) were drilled at depths close to 1,000–1,200 m. BO-5 and BO-6 dis-

charged a geothermal fluid whose temperature was close to 250–260°C and whose chemical composition was similar to that analysed in the wells BO-2 and BO-4 (Sanjuan et al. 2001). BO-7 was not productive and BO-2 was disconnected from GB1 in 2002. After several production tests, the wells BO-5 and BO-6 were alternatively connected to the GB1 unit between 2002 and 2004 (Sanjuan et al. 2005). During the second half of 2004, the wells BO-4, BO-5 and BO-6 were connected to GB1 (4.5 MWe) and GB2; the new GB2 unit (11 MWe) was brought into continuous service at the beginning of 2005.

The Bouillante power plant, a double flash plant without reinjection, is the sole geothermal plant on the French territory. After phase separation in the high pressure (HP) separator, the HP steam is distributed between the GB2 turbine and the HP level of the GB1 turbine. About a quarter of the separated water is vaporized in order to produce low pressure (LP) steam which feeds the LP level of the GB1 turbine. All the residual water is cooled below 40°C by mixing with

seawater in a tank before being discharged to the sea. In 2004, in the framework of the development of the Bouillante geothermal field (Bouillante 3 project), additional exploration studies, financially supported by Géothermie Bouillante, were carried out by BRGM and CFG Services with the future objective to drill new exploration wells in the north of Bouillante Bay (Fabriol et al. 2005; Sanjuan et al. 2005).

Geographical and geological setting

Location of the geothermal field: surface morphology

The Bouillante site is located on the Caribbean coast of Basse Terre Island (Figs. 1, 2, 4 and 5). The main active geothermal surface manifestations (hot springs, mud pools, steaming grounds and fumaroles), are located south of Bouillante Bay, around the geothermal power plant. Several submarine hot springs exist as well, especially north of Bouillante Bay in the Pointe à Lézard/Anse

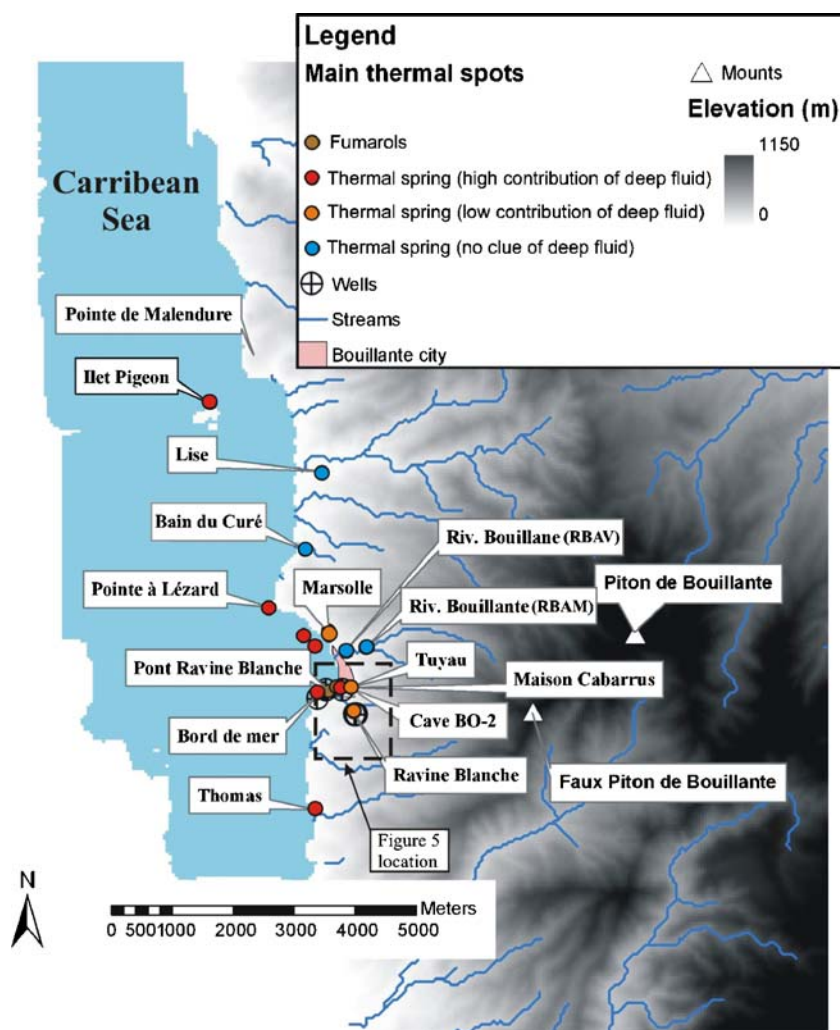


Fig. 4 Location of Bouillante on the western coast of Basse Terre Island showing the location of the main thermal spots. The thermal power plant is located in Bouillante town, close to the Tuyau hot spring. The two points “Ravine Renoir” cited in Table 1 are outside of this map

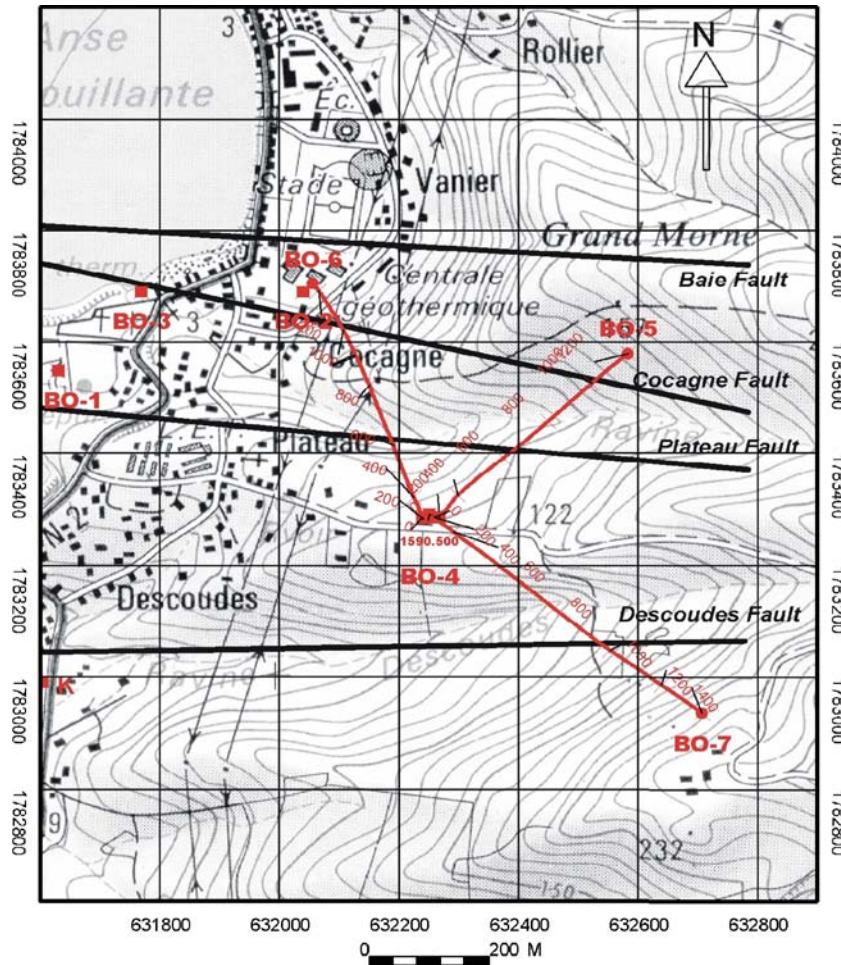


Fig. 5 Location map of wells (BO-1 to BO-7) and the main faults. The projections of the non-vertical wells on a horizontal plane are given as *red lines*, with depths (m)

Marsolle area and have been extensively mapped, both on and offshore (Sanjuan 2001; Sanjuan et al. 2001). Generally speaking, the surface thermal manifestations associated with the Bouillante geothermal system extend over approx. 12 km along the coast and offshore, from Pointe de Malendure in the north to Anse Thomas in the south (Fig. 4).

The west coast of this part of Basse Terre Island shows a relatively steep slope of around 30%. Over a distance of about 3 km, between the Faux Piton de Bouillante and the coast, elevations go from 900 m to sea level. This slope continues offshore (Figs. 1, 4, 6 and 7), with a depth of over 2,000 m being reached only a few kilometres from the coast (Thinon et al. 2004).

Volcanism

The Basse Terre volcanic island belongs to the recent Lesser Antilles volcanic arc (Andreieff et al. 1989). This arc, located on the northeastern edge of the oceanic Caribbean Plate (Fig. 1), is the expression of Atlantic lithosphere subduction in a NE-SW direction, with a velocity of about 2 cm/year. The northern part of this arc is well known for its active volcanoes of Soufrière Hills in

Montserrat, Soufrière in Guadeloupe, Montagne Pelée in Martinique, etc.

Basse Terre island, consisting exclusively of volcanic and volcanosedimentary rocks, was progressively built from the northeast to the southwest over roughly the past 5 million years. It comprises six main geological units (Boudon et al. 1982):

1. The “basal complex”, emplaced over 3.5 million years ago (-3.5 Ma), is exposed at the northern tip of the island. It consists mainly of submarine volcanic and volcanosedimentary formations.
2. The “Northern massif” comprises submarine volcanic products and then subaerial formations that mark the emergence of the island. The extrusion of the Dôme des Mamelles (-1 Ma), northeast of the Bouillante site, signifies the end of this phase of volcanic activity.
3. The volcanism of the “Axial Chain”, first submarine (hyaloclastites) and then mostly subaerial as shown by the massive superposed andesite flows of the Bouillante peaks, continued that of the Northern massif southward. It formed the central volcanoes of the island that constitute the geological substratum of the Bouillante area. These rocks were mostly emplaced around -1.5 and -1.25 Ma,

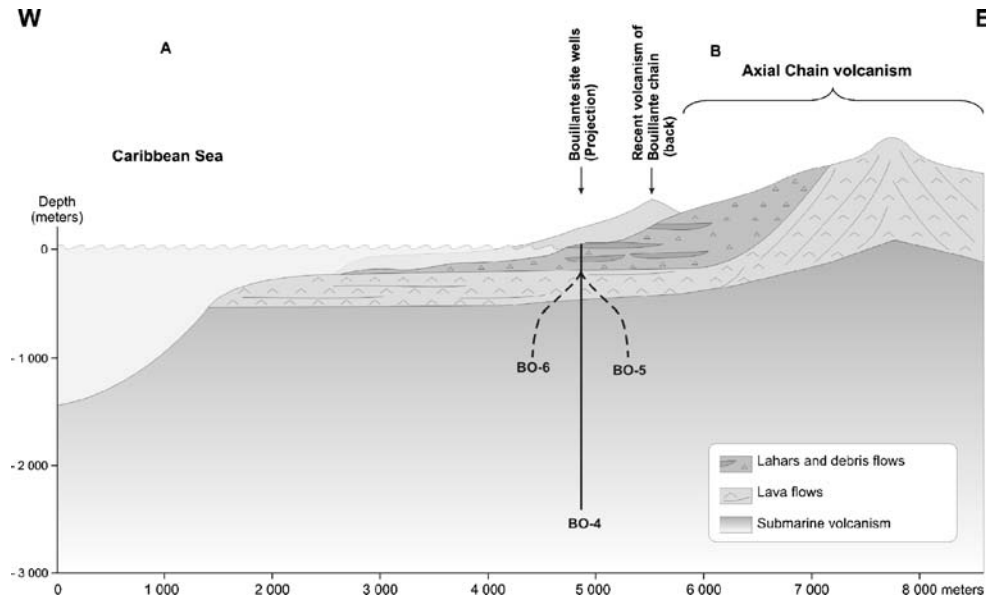


Fig. 6 Schematic geological cross section oriented W–E (for location, see Fig. 3; drawing: B. Aunay)

but activity continued until about -0.5 Ma when the activity of the composite Sans Toucher volcano came to an end.

4. Erection of the “Monts Caraïbes” created the southern tip of the island. Activity started with submarine basaltic volcanism of the Surtsey type, and finished around -0.5 Ma with explosive hydromagmatic activity and the subaerial effusion of domes and lava flows intercalated in phreatomagmatic products.
5. The “Bouillante Chain” is composed of a whole series of volcanic vents emplaced on the southwest (Caribbean) flank of the Axial Chain, from Baillif to north of Bouillante where the most continuous exposures are found, even though a few such vents also occur on the Atlantic side of the island. Their eruptive dynamics being mostly hydromagmatic, the vents emitted only small amounts of volcanic products. Their lava covers a wide range of chemical and petrographic compositions, from olivine basalt to dacite and quartz rhyolite. The chain was emplaced between about -0.8 and -0.6 Ma and continued up until the start of the erection of the Soufrière massif (-0.25 to -0.14 Ma).
6. The last unit is that of the “Soufrière”, the presently active volcano of Basse Terre Island in Guadeloupe.

The subsurface of the Bouillante area is thus almost entirely composed of the volcanic formations of the Axial Chain, locally covered by vents belonging to the Bouillante Chain. Volcanic activity can be considered as having been almost continuous at the scale of geological time, since emplacement of the Bouillante Chain until the present day activity of the Soufrière volcano, whose main emission point is less than 15 km from the Bouillante site, the superficial magmatic chamber feeding this volcano being estimated at a 6 km depth below the summit of the volcano (Bernard et al. 2006).

Geological data from surface observations

Geological surface observations at Bouillante (Sanjuan et al. 2005) showed the extent in this area of the recent formations attributed to the eruptive products of the Bouillante Chain. They cover an area of 2 to 3 km², mainly to the north of Bouillante Bay (Fig. 3).

The vents mainly ejected andesitic pyroclastic products resulting from explosive activity: ash and lapilli falls and surges, and pumice flows and glowing cloud deposits, locally reworked into lahars. Two Strombolian cones and rare lava flows were identified as well. These recent formations are at most a few dozen metres thick and overlie with a normal contact the substratum composed of massive lava, pyroclastic deposits and eroded formations attributed to emissions of the Pitons de Bouillante stratovolcano (Axial Chain volcanism).

The Desmarais volcano (Fig. 3) appears to be the most important of the Bouillante Chain. It had polyphase activity and varied dynamics (Plinian eruptions, glowing clouds, and lava flows). It also was the seat of the last known magmatic activity in the area, and it is thus tempting to propose the existence of a presently cooling magmatic intrusion below this volcano, which might be at the origin of the Bouillante geothermal anomaly.

Geological data from wells

At depth, the lithology of the volcanic formations is mostly known from data obtained in exploration and exploitation wells (Figs. 5, 6, 7; Cormy et al. 1970; CFG 2001; Traineau 2001). Figure 7 illustrates the main type of geological data obtained from the boreholes. Three main units are identified, from bottom to top (Traineau 2001):

- The first stage of submarine activity in the Axial Chain, from 500–600 m depth to at least 2,500 m (at the

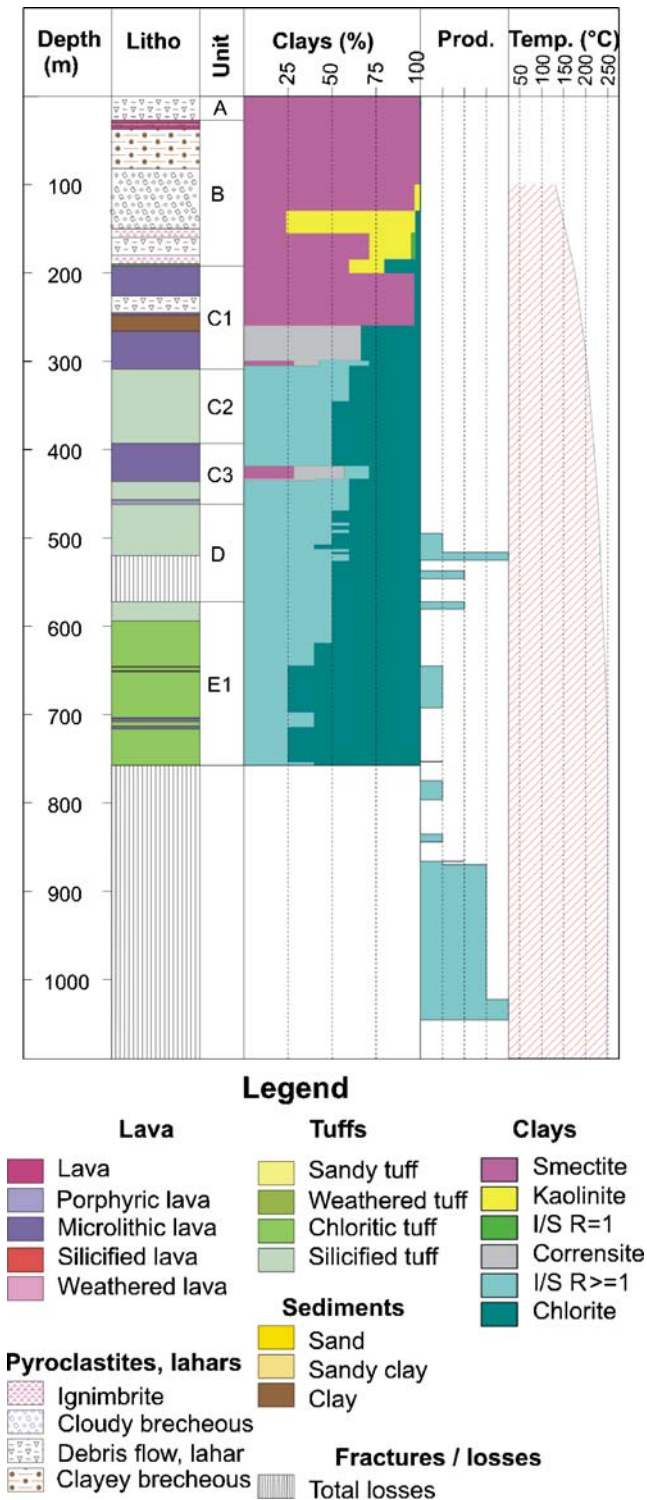


Fig. 7 Example of the main data obtained from well BO-5 (from Sanjuan et al. 2004). The productivity (*Prod.*) scale is relative, based on mud losses observed during drilling (*left*: no mud loss; *right*: total mud loss; *in between*: partial mud losses). *I/S R=1*: R1-ordered interstratified Illite/Smectite with 50 to 70% Illite. *I/S R>=1*: R2 or R3-ordered interstratified illite/smectite with 80% or more of illite

bottom of the deepest hole BO-4), consists of hyaloclastites intruded by rare subvertical dykes or submarine flows

- A transition unit between submarine and subaerial volcanism, 200–350 m thick, mostly consists of brecciated formations (tuff, lahars, conglomerates, sandy horizons, shelly limestone) corresponding to shallow water deposits or coastal volcanism, alternating with lava that witnesses a more or less subaerial effusive activity
- Finally, over the first 250–300 m below surface, subaerial volcanic formations comprise successively (from the bottom up): a unit of 4–5 lava flows, each 20–100 m thick, intercalated with lahar levels each 10–30 m thick, overlain by lahars and conglomerates 30–130 m thick, depending on the borehole. The last unit was the result of rapid erosion of the Pitons de Bouillante volcano in the Axial Chain, associated with huge collapse events.

No precise element is available for dating the various formations of the wells, but all available geological data point at them being part of the Axial Chain volcanism. The fact that the transition from submarine to subaerial volcanism is located at least 450 m below present day sea level, suggests that the region was subjected to significant negative vertical movement since the emplacement of these formations. This agrees with the graben structure proposed by Feuillet et al. (2002) and described hereafter.

Structural setting

At a regional scale (Feuillet et al. 2001, 2002), the structure of the Bouillante area is marked by (Fig. 2):

- E–W oriented graben type faults, extending from the south of Basse Terre until beyond Marie Galante, with a generally steep southerly dip
- The Basse Terre/Montserrat normal fault system, NNW–SSE oriented

Field observations around Bouillante (Sanjuan et al. 2005) have confirmed this general scheme. The recent formations and outcrops of the older substratum (Figs. 3 and 5) show almost exclusively open E–W structures (normal faults, and traction cracks lacking indicators of significant movement, subvertical, and dipping mainly southward), associated or not with present day or past traces of hydrothermal circulation. Only one large (E–W) fracture corridor is seen at outcrop (the Cocagne fault); this is probably because either others exist but are masked by recent volcanic formations, or this is the only fault that is regularly reactivated (due to tectonic or hydraulic influence) and thus receives sufficient fluid circulation (although low in absolute value) to reach the surface.

Rare N120–N160°E fractures are only found in the oldest formations of the Axial Chain. This roughly

northwest direction, quite common offshore (Thinon et al. 2004) and close to the orientation of the regional Monserrat/Basse Terre fault, seems to witness an older, or less active, fracturing episode, essentially affecting the old formations of the Axial Chain that are exposed on the sea floor and masked by the recent Bouillante chain products.

Hydrodynamic properties: groundwater flow

Roles of fractures in the hydrodynamic properties of the geological formations

The hydrodynamic properties, in particular permeability, are mostly known from observations during drilling (Fig. 7). These cover the location and quantification of levels with partial or total mud loss (Cormy et al. 1970; CFG 2001; Sanjuan et al. 2004). These observations were confirmed in certain wells by thermometric profiles run after injection of cold water within the aquifer (the cooled areas after water injection allowing for the location of the permeable zones of each well).

These data show that:

- All the wells except BO-7 intersected permeable intervals
- Except in well BO-2, the only one to intersect a shallow aquifer consisting of marine sand, all permeable intervals appear below at least 400 m depth below sea level
- Some of the permeable intervals intersected in wells are isolated (over only a few metres thickness). However, in all productive wells, there are at least several tens of metres and even a few hundred metres thick permeable intervals; in wells BO-4 and BO-5, the cumulated length of these permeable intervals exceeds 300 m. These permeable intervals show a heterogeneous distribution of the local permeabilities, as alternating highly permeable and less permeable levels
- No obvious relationship was found between the original lithology of the rocks and their permeability. The larger permeable intervals can consist of several rock types. Fracturing appears to have a similar effect, from a hydrodynamic standpoint, within the different types of geological formation intersected by the wells: for example, the fractures developed within competent rocks (e.g. lava) present permeability characteristics that are similar to those affecting rocks that are theoretically less favourable, for example due to a higher clay content (e.g. lahars)
- Most permeable intervals intersected in boreholes could be correlated with faults observed at the surface

Compilation and synthesis of these data provide the following main results (Fig. 8):

1. The geological formations that may have had a significant original permeability (in particular lava that, at the surface, has well-developed fissuring with flow

and cooling figures (Lachassagne and Maréchal 2004; Lachassagne et al. 2006) occur exclusively in the first few hundred metres below the surface. However, this original permeability has been completely obliterated. Exhaustive analysis of clay minerals from wells BO-5 (Fig. 7), BO-6 and BO-7 (Mas et al. 2006; Guisseau et al. 2007) and from surface samples (Patrier et al. 2003) shows that this obliteration can be explained by self-sealing processes related to the alteration by circulation of hydrothermal fluids (smectite type clays down to about 250 m depth, partially replaced by kaolinite from 150 m down and, lower down, interbedded illite smectite). As the geological formations that had significant original permeability are at shallow depth within this particularly clogged zone, the geothermal system no longer comprises formations with a significant matrix or fissure permeability. This point is indirectly confirmed by surface geophysical measurements: deep electrical resistivity tomography profiles show very low resistivity areas in the first hundred meters below the surface (Fabriol et al. 2005).

2. The wells are thus only characterized by a fracture permeability. The hydrodynamic interpretation of interference between the wells confirms this point: flow dimensions close to 1, as deduced with the method developed by Barker (1988), confirm the existence of one or more major planar structures, i.e. of the fracture type, within which most of the flow occurs (Lachassagne and Maréchal 2004).
3. The fracture permeability itself is subject to obliteration through self sealing. Hydraulically speaking, it only becomes efficient 400–500 m below sea level downward, which explains the low flow rate of hydrothermal fluid leaks observed at the surface (see the following).
4. The fractures are of tectonic origin. Hydraulic fracturing processes, partly related to pressure buildup associated with the self-sealing phenomena already described, probably exist; surface indications such as anastomosing structures with a variable geometry, have been seen in outcrops (Sanjuan et al. 2005). Certain fractures intersected in wells could be correlated with the E–W faults identified at the surface (Figs. 3 and 5; Genter and Traineau 2004; Sanjuan et al. 2004). For instance, Cocagne Fault (Fig. 5), which coincides with the area where the strongest hydrothermal surface features of the entire Bouillante site occur, is intersected by wells BO-5 and BO-6. The permeable zone is extensive and its vertical projection confers it a width of around 100 m, which means that the fracture zone must be at least several tens of metres wide. Wells BO-5 and BO-6 also intersected Plateau Fault, which has a lower permeability (sealed zone) because the wells intersected it at a shallower depth than for Cocagne Fault.
5. The downward extension of these permeable fractures is unknown, but they must extend to at least 1,100 m below sea level (the deepest permeable zone identified in a borehole), which is most likely a default estimate that is far removed from reality.

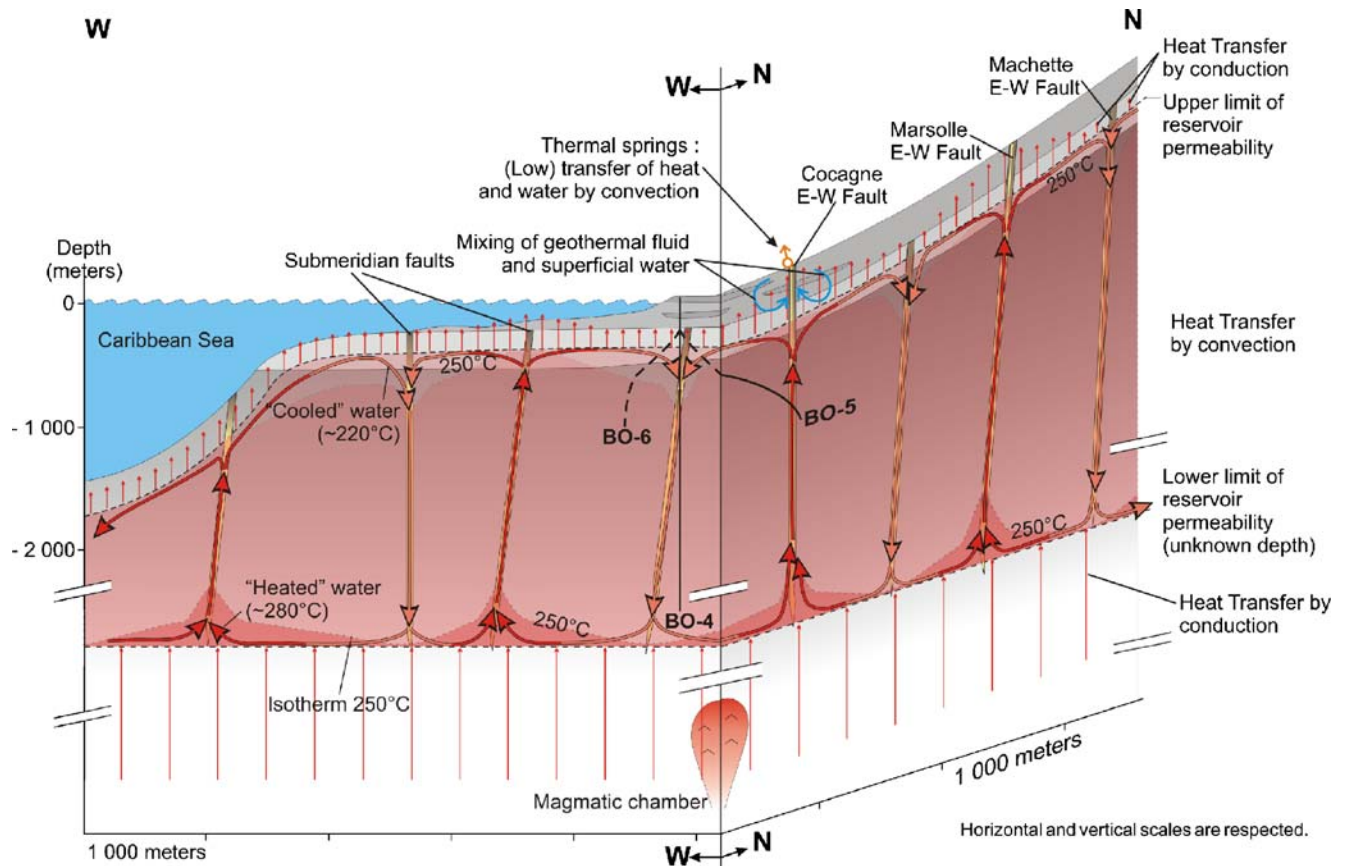


Fig. 8 Conceptual model of thermal and water-flow exchanges in the Bouillante geothermal field (note that the size of the magmatic chamber is not at scale; it should probably be enlarged; drawing: B. Aunay)

6. Such fractures are relatively numerous as they are intersected by most wells.
7. Hydrodynamic interpretation of the interference between production wells (Lachassagne and Maréchal 2004; Sanjuan et al. 2004), in particular between BO-4, BO-5 and BO-6, requires consideration, not only with respect to the E–W fracturing, but also with respect to the existence of almost perpendicular, thus roughly N–S fractures; the interference is similar between two wells located on the same east–west fracture and two wells located on two different E–W fractures. The second fracture network identified in the Bouillante region (the Montserrat/Basse Terre fault system) thus probably has, at depth, similar permeability properties to those of the east–west fault system. The results obtained from two long-term production tests carried out in 1971 and 1974 (6 months each) on well BO-2, showing that the major drain of this well (the Cocagne fracture) also communicated with “a relatively high capacity reservoir” (Demians d’Archimbaud and Munier-Jolain 1976), are consistent with this hypothesis.
8. These two relatively dense fracture networks form a geothermal aquifer with good hydrodynamic properties (high flow rates from the wells, low amplitude interference measured in the observation wells located at a distance of 300–400 m), which extends from

around 500 m below sea level to a depth of several kilometres. The equivalent transmissivity (for pure water at 25°C) of the aquifer tapped by wells BO-5 and BO-6 is evaluated to be 2.10^{-3} to 4.10^{-3} m²/s, from hydrodynamic interpretation of the interference between production wells.

Hydrogeological functioning of the geothermal aquifer

Composition and origin of the geothermal fluid

Geochemical characterization work provided the following main information:

1. The waters collected from hot springs, which are NaCl fluids and whose salinity is higher than 1 g/L (submarine springs and land-accessible springs: Thomas, Cave BO-2, Bord de Mer (and the neighbouring drillhole BO-BS drilled since 1999), Tuyau, Marsolle; Fig. 4), are a mixture in variable proportions of surface waters (freshwater and/or seawater) and the deep geothermal fluid (Sanjuan et al. 2001). The other thermal waters (Na–HCO₃ fluids with a salinity <1 g/L) such as those collected from the springs “Bain du Curé, Lise or River Bouillante” (Fig. 4), are only surface freshwaters heated by conduction (Mas et al. 2006).

2. The water flowing through the geothermal aquifer, whether sampled in wells or reconstituted from the geothermal contribution to hot springs waters, has a homogeneous composition at the scale of the Bouillante region (Sanjuan and Brach 1997; Traineau et al. 1997; Sanjuan 2001; Sanjuan et al. 2001, 2004), at least from Malendure in the north until Thomas in the south (Fig. 4). This NaCl fluid, with a salinity of about 20 g/L and a pH value of 5.3 ± 0.3 at 250–260°C, is the result of the mixing of about 60% seawater and 40% freshwater (Sanjuan 2001; Sanjuan et al. 2001, 2004). The amounts of noncondensable gases associated with this fluid are low (0.4% in mass in the wells). These gases essentially consist of CO₂ (>90% in volume). Their isotopic signatures (13-carbon and ³He/⁴He) indicate magmatic, marine and atmospheric origin. Geochemical and thermometric data show that, under the pressure and temperature conditions within the aquifer, the reservoir only contains water and, specifically, no steam.
3. At high temperatures, the geothermal fluid often shows an 18-oxygen enrichment caused by interaction with volcanic rocks. The absence of this enrichment in the Bouillante geothermal fluid and its residual marine $\delta^{34}\text{S}$ signature suggest a high water–rock ratio in the deep reservoir. The geothermal fluid reacts with the surrounding volcanic rocks reaching chemical equilibrium at about 250–260°C with respect to a mineral assemblage as shown by its composition and by saturation calculations (Sanjuan 2001; Sanjuan et al. 2001, 2004). Compared with a diluted seawater, the geothermal fluid is depleted in Mg, SO₄, HCO₃, Na and is enriched in K, Ca, Si, B, Li, Sr, Ba, Mn, Cs, Rb, As and trace metal ions. Its ⁸⁷Sr/⁸⁶Sr signature (close to 0.705) also characterises an equilibrium state with volcanic rocks (andesite or basalt). These results and the low tritium contents measured in the geothermal fluid suggest a relatively long residence time of the water in the geothermal aquifer (much greater than 100 years). The convergence of the geochemical and gas thermometer data toward a maximum equilibrium temperature of around 250–260°C and the geochemical homogeneity of the fluid indicates the existence of homogeneous processes at the scale of the field.
4. These results are in good agreement with inter well tracer studies that suggest a large interconnected reservoir volume (>30 million m³); (Sanjuan et al. 2004). The large reservoir volume is also supported by the temporal stability of the chemical and isotopic composition of the geothermal fluid discharged from the wells (Sanjuan et al. 2004); 5 million tons of fluid have been produced yearly since 2005, and a total of approx. 20 million tons have now been produced from the field.

Hydraulic heads in the geothermal aquifer

The hydraulic head prevailing within the geothermal aquifer is estimated at about 150 m above mean sea level

(of equivalent freshwater) from pressure measurements performed in wells BO-4, BO-5 and BO-6 after an eleven year period without production. As a consequence of the small number of wells reaching the aquifer, and the energy production constraints, no piezometric map is available. Nevertheless, a recent tracer test (2007) with injection at BO-2 and restitution observed (first in BO-6, then in BO-4) at two of the three discharging wells and no restitution at BO-5 (the third discharging well) shows that the artificial discharge from the aquifer significantly imprints the flow pattern inside it. Drawdowns (pressure drop) however remain quite low (less than 4–4.5 bars at the wells) in the aquifer.

The absence of tracer restitution at BO-5 is thought to be linked to several factors. First and most probably, it is a consequence of the dilution of the tracer (and thus also of the analytical threshold). Second, the fact that the tracer was mainly injected/restituted in the most superficial and less producing permeable level (300–350 m in BO-2 and 500–700 m in BO-6 and BO-4); thus, the tracer appears first at BO-6, with very low concentrations and then at BO-4 at higher concentrations. In fact, the BO-6 well is nearer BO-2 but is mainly fed by a deeper (800–1,000 m) producing level. Moreover, BO-6 produces 215 t/h (tonnes/hour) as BO-4 only produces 92 t/h. Third, BO-5 is also the most producing well (280 t/h) and it is also mostly fed by a quite deep level (800–1,000 m); thus the tracer arriving from the upper level, if any, is largely diluted.

Tentative water budget of the geothermal aquifer

In view of the large volume of the aquifer and the absence of significant natural fluctuations of its hydraulic head, it can be assumed that the geothermal aquifer was operating in a steady-state regime from a hydraulic viewpoint before its recent larger exploitation, i.e. the sum of geothermal fluid leakage balances the inflow of cold water (both continental fresh and marine water).

Because of the self-sealing processes in the top part of the aquifer and, very likely, around it at the edges of the hot area, and because of the absence of fluid (water or gases) exchanges with the underlying rocks, the outflow of the geothermal aquifer is concentrated in its roof. The flow of geothermal fluid from springs (leaks through fractures) thus provides a good estimator for this outflow.

Most of the hot springs of the Bouillante area emerge currently either close to the coastline or offshore, where they were extensively mapped (Sanjuan and Brach 1997; Sanjuan 2001; Sanjuan et al. 2001), and not inland. This location appears to be logical both from a structural standpoint (main faults) and from a hydrodynamical standpoint, the shore forming the present-day regional base level (Figs. 3 and 4). There, the emergence of fluids (from permeable structures that are not entirely clogged by self sealing and from cold superficial aquifers only partly influenced by thermal waters) requires the least energy (potential and thermal) to outflow. The location of hot springs near the coastline and offshore agrees with the fact

that the faults that are permeable near the surface, which are the locus of hot fluids that rise up to the surface, are mostly perpendicular to the coastline, i.e. E–W. In fact, structures with only a N–S direction would be at the origin of inland hot springs, located where these structures, parallel to the coast, intersect the valleys (ravines).

The flow rates of all springs with a thermal component are low (Table 1), from 1 to 10 L/min for those springs for which an estimate is available, or about 0.06 to 0.6 m³/h. The total known or estimated flow rate of such springs (Table 1) is around 4 m³/h. A grand total between 10 and 100 m³/h (20–200 times the flow rate of the Marsolle spring, the one with the highest recorded flow), can be assumed as a maximum for all hot springs combined, including submarine ones.

The contribution of geothermal fluid is quite small in most of the terrestrial springs (mostly below 10%, e.g. 2% for the Marsolle spring). For the submarine hydrothermal springs or the thermal spring “Cave BO-2”, this contribution is a bit higher. On the basis of a mean 10% contribution of the geothermal fluid to the springs, the leakage volumes from the geothermal aquifer can thus be estimated between 1 and 10 m³/h at most.

As the geothermal fluid is composed of 40% freshwater and 60% seawater, the contribution of meteoric origin to the aquifer must be 0.4–4 m³/h. Related to an infiltration area of 12 km² for the surface catchment area potentially supplying the aquifer on land—a rough hypothesis that reduces this surface area to a minimum since most recharge probably takes place at the edges of the geothermal reservoir where downward flows may occur—this represents a (thus overestimated) rainwater flux of between 0.4 and 4 mm/year.

This flux is extremely low when compared with the effective rainfall (rainfall minus real evapotranspiration) available for the hydrological basins of the area and compared to the great potential differences existing between the slopes and the coastal area. Note that on the west side of Basse Terre, the effective rainfall ranges from 1,000 mm/year in the near vicinity of the shore and increases very rapidly to reach 5,000 mm/year at 1,000 m elevation. This very low value for the recharge of deep hot

aquifers is coherent with subsurface hydraulic conductivity data and with the results of hydrological and hydrogeological modelling (global lumped model) of the catchments in the Bouillante area that do not require the existence of significant deep leaks nor inflows—modelled catchments are the Lostau and Beaugendre rivers, respectively at the hydrometric stations “Déversoir” at 60 m elevation, and “Cote 77” at 77 m elevation; Lachassagne and Maréchal 2004). This natural flux (0.4–4 m³/h) is quite low compared to the water abstraction for energy production (550 t/h of water as a mean). It implies both destorage within the aquifer and, as drawdown remains quite low, leakage from the semipervious neighbor geological formations.

Temperature distribution: conduction and convection processes

Figure 9 presents an example of equilibrium temperature profiles measured in the Bouillante wells (integrating the correction for well deviation) as well as one section through wells BO-2, BO-4, BO-6 and BO-7. As the reservoir has a fracture permeability, such profiles and cross sections only show an overview of the real temperature distribution.

The general aspect of all profiles is typical of that measured in most geothermal fields, with a high and stable gradient in the shallow part, followed by a regular decrease in the gradient, and finally a third zone where the temperature shows little variation over several hundreds of metres, or even kilometres. These elements suggest the presence of a deep convection system (zone with a null gradient), relayed by heat exchanges dominated by conduction at shallower depth (Guillou-Frottier 2003). Convection requires a significant permeability of the concerned horizon. Within this aquifer, hotter water rises whereas colder water descends; this process allows an efficient heat transfer between the top and the bottom of the horizon in question, water playing a role of heat exchange fluid.

Calculation of the Rayleigh number according to the equation of Combarous and Bories (1975), which

Table 1 Flow rates and contribution of geothermal fluid (BO-2 well type) of hot springs in the Bouillante area

Hot springs	Ref.	T °C	Approx. flow L/min	BO-2 fluid (%)	BO-2 fluid (L/min)
Bain Curé (BC)	9601	39.0	2	~0	~0
Lise (L)	9603	35.7	n.a. (~10)	~0	~0
Cave BO-2	9504	97.4	n.a. (~1)	82	~0.82
Maison Cabarrus (MC)	9617A	97.3	n.a. (~1)	~0	~0
Ravine Blanche (RB)	9618	29.2	very low	~0	~0
Tuyau (Ty)	9619	60.5	3.1	4.5	0.14
Thomas (Th)	9620	54.6	n.a. (~10)	10	~1
Ravine Renoir (downstream)	9621	36.9	n.a.	0	0
Ravine Renoir	9622	29.2	n.a.	0	0
Bord de Mer (BM)	9624A	81.0	n.a. (~1)	66	~0.66
River Bouillante (upstream) (RBAM)	9626	29.6	2.7	~0	~0
Marsolle (M)	9627	44.3	10	1.9	0.2
Pointe à Lézard (PL)	9628	92.0	n.a. (~10)	38	~3.8
Ilet Pigeon (IP)	9629	52.0	n.a. (~10)	7	~0.7
Total			(~60)		7.3

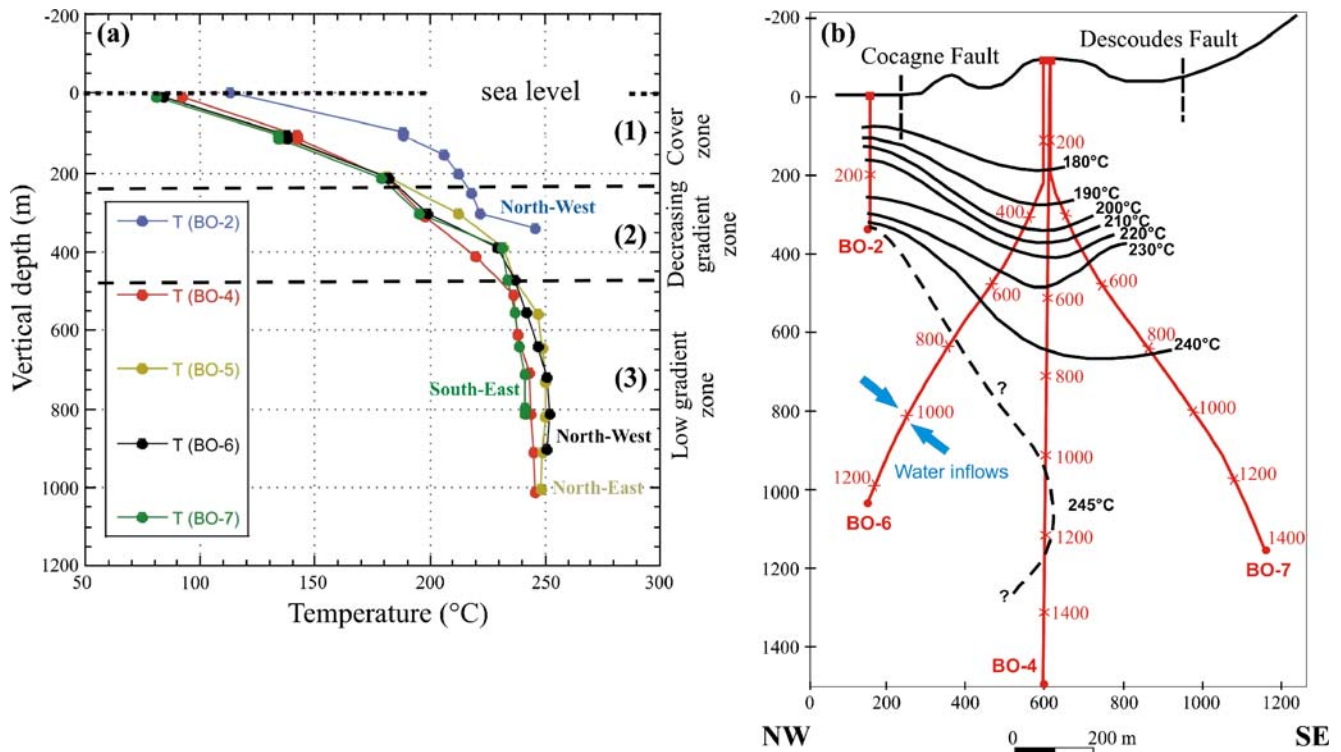


Fig. 9 a Equilibrium temperature-depth profiles in the main Bouillante boreholes, and b isotherms in a NW-SE plane (from Guillou-Frottier 2003)

assimilates as a first approximation the reservoir to an equivalent porous medium, and using the most probable hypotheses for the geometry of the system, suggests that the geothermal reservoir of Bouillante is favourable for the creation of convection cells. The Rayleigh number obtained is around 5,000, which is two orders of magnitude larger than the critical value of 40. Sensitivity analysis shows that Rayleigh numbers much higher than the convection threshold are obtained for all configurations than can be envisaged: low temperature difference (60°C) between top and bottom of the aquifer; relatively thin aquifer (1,000 m); relatively low intrinsic permeability (at constant transmissivity equal to that deduced from the interference tests); relatively wide permeable fractures. The thermal conductivity used is that of acid or basic rocks at 250°C (Vosteen and Schellschmidt 2003). The main factor explaining the appearance of convection is the fracture permeability.

This result forms an element of confirmation of the geological and hydrogeological hypotheses mentioned above. One can thus state that at Bouillante:

- Between the surface and the reservoir (above 400–500 m depth, where the fractures forming the geothermal aquifer deeper down are clogged):
- The rocks play a role of “thermal blanketing”, commonly assimilated with an effect of thermal insulation. These rocks are not strictly speaking

“insulating”, as their thermal conductivity is similar to that of the rocks of the underlying aquifer. Thus, there is an impermeable cover rather than a thermal blanket, heat transfer through conduction being much less efficient than transfer through convection. In other words, the hot deep fluids remain blocked under the “cover” thanks to permeability contrasts between the different formations. The accumulated heat within the reservoir diffuses toward the surface mainly through conduction, fluid losses being very low at the scale of the aquifer. This last phenomenon explains the shape of the geotherm curve in the intermediate zone, noted (2) on Fig. 9 (Guillou-Frottier 2003).

- Temperature distribution is locally influenced by the faults, among others by the major structure formed by Cocagne Fault. Their clogging being only partial, they are (low efficiency) water and thus heat vectors, by convection, toward the subsurface.
- Beyond 500 m below sea level, within the geothermal aquifer (see for instance Fig. 9b):
- The temperature is around 250–260°C within the reservoir (Guillou-Frottier 2003). The mixing of hotter and colder fluids through convection leads to good homogenization, which is shown by an almost null thermal gradient that locally can even be negative.
- The permeable zones (fractured areas intersected by the boreholes) host fluids with a relatively low

temperature (230°C) as well as hotter fluids (about 250–260°C), depending upon whether the wells intersect fractures driving ascending or descending branches of the convection cells.

- Below the footwall of the geothermal reservoir (not reached by the wells) lie rocks with low permeability, either without fractures or with fractures that are not very permeable, which ensure, through conduction, the heat transfer from the heat source to the geothermal reservoir. In fact, geochemistry has shown the absence of any contribution of fluids other than those of the aquifer and the gas transfers are also very low.

Discussion: hydrogeological model of the high-energy Bouillante geothermal field

After summarizing all the already-mentioned information, a hydrogeological conceptual model can be proposed that describes, according to current knowledge, the structure and hydrodynamic functioning of the Bouillante geothermal field.

Hydrodynamic properties and vertical extent of the geothermal aquifer

The geothermal aquifer presents exclusively fracture permeability (Fig. 8), with two main groups of fractures:

- E–W fractures affecting both the older formations at depth and the more recent overlying rocks. They belong to the northern slope of the Basse Terre/Marie Galante graben (Fig. 2) and are compatible with an overall N–S extensional component
- Sub N–S fractures (whose origin is related to the Montserrat/Basse Terre fracture system) and, possibly, to collapse due to the morphological asymmetry of the island)

The permeability of the E–W fractures is similar to that of the N–S fractures. Fracturing has a similar hydrodynamic effect within the different lithologies. At depth, the permeable zones correspond to fracture corridors several tens of metres thick. Due to self sealing, the top of the resulting geothermal aquifer lies at a depth of between some 400 and 500 m. The upper formations present a very low permeability, both primary (where any) and fracture permeability being quite completely clogged. The natural outflow of thermal water is thus localised (springs in the major fault corridors) and has a low discharge.

The lower boundary of the aquifer is assumed to lie at a depth of at least several thousand metres. Structural reconstructions and strain modelling (including fluid pressure), to be performed in the future, or even hydro-geochemistry will contribute to the evaluation of this depth.

Hydrogeological and geothermal functioning of the aquifer

The distribution of vertical permeability just described is responsible for the existence and the dynamics of the geothermal system (Fig. 8):

- The permeable aquifer zone contains hot waters with a relatively homogeneous temperature (about 250–260°C). Water circulation is controlled by convection. At least for the southern part of the geothermal reservoir (around the town of Bouillante), the E–W and N–S trending fracture networks are well connected and contribute to a ‘broad’ functioning of the reservoir, rather than a partitioning per individual fracture zone. The homogeneous nature of the geochemical data available at the scale of the entire Bouillante region suggests strongly that this ‘broad’ behaviour can be extended to the entire geothermal reservoir.
- This aquifer is separated from the surface (thermal blanketing) by the already-described low-permeability formations that restrict almost entirely any heat exchange with the surface to heat exchanges by the conduction process (and no heat exchange by advection or convection). The presence of this thermal blanket is the main factor explaining the durability, on a geological time scale, of the geothermal system. Along with convection within the geothermal aquifer, this also explains the relative homogeneous temperature of the fluids. Geothermal systems within which convection processes are active up until the topographic surface have consequently a short life span and are thus few on the Earth’s surface.
- The wall of the geothermal aquifer is in contact with low permeability formations that transfer heat from the heat source by conduction.
- It is tempting to position the heat source (a magmatic intrusion undergoing cooling, the initial temperature of which was some 900°C) beneath the Desmarais volcano (Fig. 3).

The geothermal aquifer, because of its low permeability ‘cover’, undergoes very little leakage, of the order of 1–10 m³/h at the most. This leakage is reflected by the presence of thermal springs, mainly located along the coast or offshore; this does not, however, constitute sufficient evidence to restrict the extent of the geothermal reservoir to the marine domain.

This leakage is compensated by a similar recharge volume composed of about 40% meteoric water infiltrated through the continental domain of the aquifer, and 60% seawater infiltrated through the marine domain. Recharge of the geothermal aquifer by freshwater (0.5–5 m³/h at the most) represents only a very small fraction of the supply of the aquifers (mainly subsurface aquifers): a few millimetres a year maximum, for a total recharge estimated at 150–400 mm/year depending on the catchment. Within any theoretical cross section in the geothermal aquifer, the groundwater flux associated with convection must be considerably greater than the leakage

flux of the aquifer towards the surface (and thus of the influx, or recharge, to the aquifer). The water stored within the permeable parts of the aquifer (several tens to hundreds of millions of m^3) is several orders of magnitude greater than the annual leakage flux (less than 10,000 to 100,000 m^3/year) which, under natural conditions (i.e. no exploitation), leads to an average renewal rate of the order of several hundred of years to several tens of thousands of years.

From the inferred distribution of hydraulic heads within the Bouillante area (this hydraulic head distribution resulting from the potential energy of water, the various flows and their associated head losses, but also from the input of thermal energy), a tentative conceptual scheme of the water flow lines, and thus of both the recharge (downflow) and discharge (upflow) areas, is proposed (Fig. 10) under natural conditions. Logically, the recharge of the geothermal aquifer occurs at the periphery of the heated area, whereas its discharge takes place at its top. This scheme is in accordance with the mixing of freshwater of inland origin and of seawater, without the need of a freshwater/saltwater wedge (classical sharp interface between fresh and marine groundwaters) within the geothermal aquifer.

Except for the impact of pumping by the geothermal power plant, the system operates in a steady-state hydraulic regime and is not significantly influenced by surface hydrological conditions, mainly because of the low permeability of the aquifer cover. If the heat source and/or fracturing are recent on a geologic time scale

(relative to the inertia of the system), then the system may not yet have reached thermal equilibrium (Maréchal et al. 1999). The flow and thermal numerical modelling of this scheme (Fig. 10) will later help in the parameterisation of the various processes, geometries and fluxes involved in the Bouillante geothermal field.

On the basis of a network of orthogonal permeable fractures, the convection cells within the aquifer may have a relatively regular spatial distribution. The thermometric data available for BO-4 (downward circulation via a probable N–S oriented fracture), BO-5 and BO-6 (upward circulation via an E–W trending fracture, Cocagne Fault) suggest that the fracture nodes could alternatively, spatially, be drainage sites with a vertical component that is respectively ascending and descending. The fractures located between each node would be associated with a convection cell and every half fracture would thus be the site of drainage with an alternating ascending and descending vertical component.

Considering the high hydraulic head throughout the aquifer, and especially the high temperature of the geothermal fluid whether this be within the ascending or descending branches, as well as the low volume of leakage towards the surface, it is unlikely that the spatial distribution of the surface thermal springs (or the thermal springs with a strong influence of deep fluids) respects this convection cell arrangement. At the scale of the Bouillante region, the perimeter delimiting the presence of surface thermal manifestations basically corresponds to that of the heated part of the geothermal reservoir. Recharge is

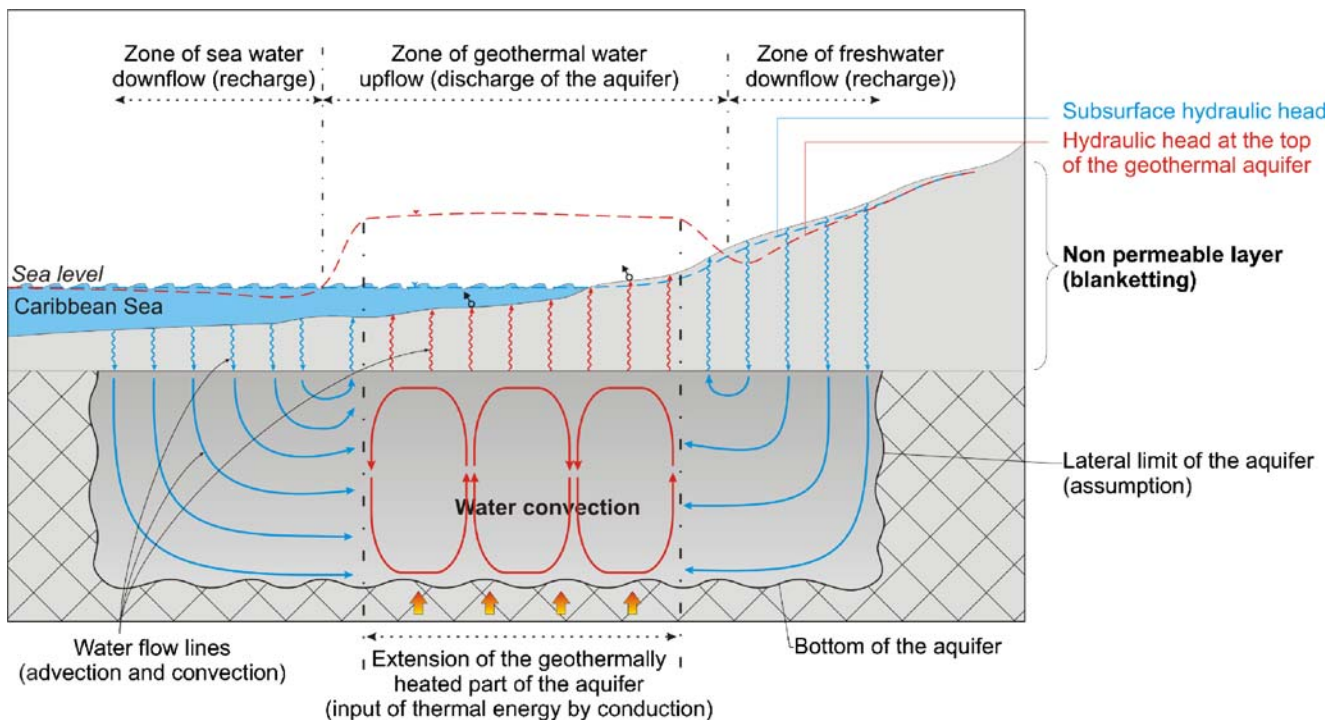


Fig. 10 Schematic distribution of the hydraulic heads, water flow lines, and main areas of discharge and recharge of the Bouillante geothermal aquifer (not to scale) in natural conditions (without artificial discharge). Red and blue arrows: hot and cold groundwater flow lines, respectively. Yellow arrows: input of thermal energy by conduction. Black circle with black arrow: onshore or offshore thermal spring (drawing: B. Aunay)

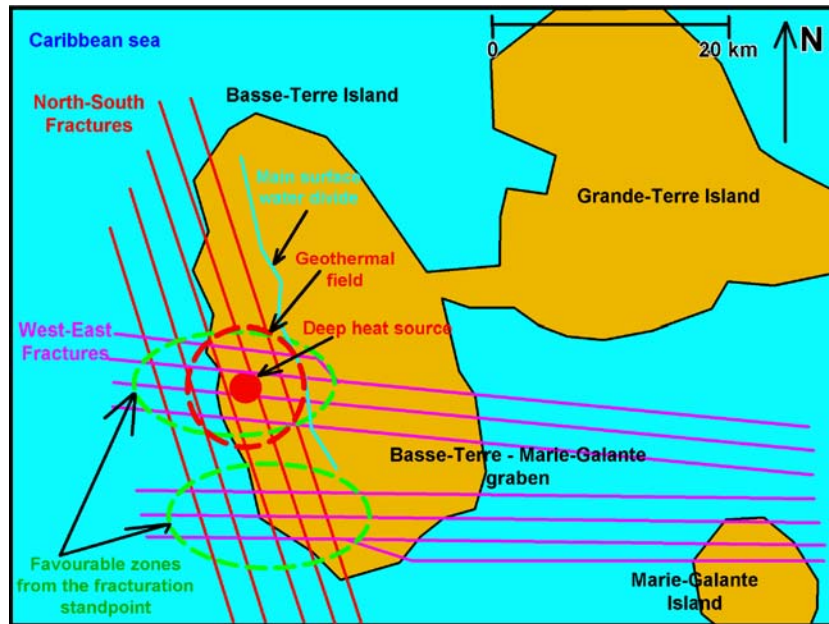


Fig. 11 Schematic conceptual model explaining, at the Basse-Terre island scale, the origin and location of the geothermal field (plan view). *Dark blue line*: Basse Terre Island coast; *light blue line*: main water divide of the Basse-Terre Island

mainly diffuse and along the edge where, due to a lower contribution of geothermal energy, the hydraulic head is lower within the geothermal aquifer enabling a downward vertical drainage from the overlying formations. The relative percentages of seawater and freshwater (about 60 and 40%, respectively) suggest that the maximum extension of the deep aquifer (both its heated part and the less heated one) is relatively balanced beneath the sea and the emerged part of Basse Terre, thus centered approximately along the coastline.

Origin and location of the geothermal field

On a smaller scale, two main factors, both essential, explain the existence and location of the Bouillante geothermal field (Fig. 11):

- The presence, location and volume of a heat source (magmatic intrusion)
- The presence of a network of permeable fractures at the origin of the aquifer (and that may also be at the origin of the magmatic intrusion)

Hydrogeological setting of the subsurface

In the subsurface, the hydrogeological characteristics of the Bouillante area are typical of an andesitic-type volcanic region composed of relatively recent formations, thus little affected by meteoric weathering, and subjected to a humid tropical climate. The aquifers are hosted by certain favourable geological formations from a lithological standpoint (lava flows, scoria cones, alluvium). These superficial aquifers often serve, but not exclusively, as a link with respect to the surface hydrothermal manifestations (thermal springs whose water is heated by convec-

tion and/or conduction). Note that cold springs without any geothermal influence and thermal springs not related to subsurface aquifers also exist. The hydraulic and thermal relationships between the geothermal aquifer and the superficial aquifers are limited, mainly because of the shallow nature of the surface aquifers and the low permeability cover that blankets the geothermal aquifer.

Conclusions

The multidisciplinary approach adopted in the present study, integrating several disciplines including geology, hydrogeology and hydrogeochemistry, and analysis of temperatures at depth, surface manifestations, and surface and subsurface data acquired at various scales, allows one to propose a hydrogeological model based on a physical and genetic description of the Bouillante geothermal field and the various processes governing it.

The study shows that the origin of this field, as with most high-energy geothermal fields, lies in the coexistence of three factors, all necessary and not sufficient individually, that have been identified for the Bouillante site:

1. The presence of a source of heat.
2. The existence of a fracture network near this heat source constituting an aquifer that is capable of storing a large volume of water and, consequently, heat, and transferring this from the deep subsurface upwards and making it accessible for geothermal exploitation.
3. An impermeable (and not really an insulating) surface cover, limiting the loss of energy to only conduction, and ensuring the durability of the field at the geological timescale. One important point to be stressed is the fact that the water fluxes exchanged between the geother-

mal aquifer and the subsurface appear to be very limited. This result should be kept in mind when dealing with most of the high-energy geothermal fields.

Nevertheless, even if this opens up numerous perspectives in operational terms (management of the existing set of wells, fluid reinjection, investigation for further development of the field, etc), this proposed conceptual model represents only the first step towards the understanding of how the geothermal field functions. It is the necessary stage prior to digital, hydraulic and thermal modelling of the field, which is expected to consist of two stages:

- Preliminary modelling intended to confirm and, if need be, modify or refine the present conceptual model. The aim in particular will be to clarify, by means of a sensitivity analysis: whether or not the system operates under a steady-state regime; the depth of the wall of the aquifer; the depth (and if possible the location and the characteristics) of the heat source; heat flux within the various horizons; the reservoir volume, etc.
- Operational modelling intended to optimize exploitation methods.

Indeed, mathematical models constitute not only management support tools, but also tools that can help further in understanding the physical processes. The lower boundary of the geothermal aquifer has not yet been clarified. Therefore, deep geophysical (magnetotelluric) surveys could also be very useful to investigate deeper areas of this aquifer and extend the data obtained by the electrical profile carried out in 2004.

Acknowledgements The authors thank ADEME (Agence de l'Environnement et de la Maîtrise de l'Énergie) and Geothermie Bouillante Ltd for supporting this research under various funding projects (particularly ADEME grants Nos. 02 05 035 and 02 05 036 Geothermie Bouillante grant RPI No. 141). The authors also thank Geothermie Bouillante Ltd and CFG Services for site facilities and technical and scientific support. Dr H. Traineau is particularly thanked for the fruitful discussions in the field and for his manuscript review. B. Aunay is thanked for his help for the drawing of some illustrations.

References

- Akasako H, Matsuda K, Tagomori K, Koseki T, Takahashi H, Dwipa S, Muraoka HC (2002) Conceptual models for geothermal systems in the Wolo Bobo, Nage and Mataloko fields, Bajawa area, central Flores, Indonesia: Indonesia-Japan geothermal exploration project in Flores Island. *Bull Geol Surv Jpn* 53(2–3):375–387
- Andreieff P, Bouysse P, Westercamp D (1989) Géologie de l'arc insulaire des petites Antilles et évolution géodynamique de l'Est-Caraïbe [Geology of the Lesser Antilles insular arc and Eastern Caribbean geodynamical evolution]. BRGM, Orléans, France
- Arellano VM, Garcia A, Barragan RM, Izquierdo G, Aragon A, Nieva D (2003) An updated conceptual model of the Los Humeros geothermal reservoir (Mexico). *J Volcanol Geoth Res* 124(1–2):67–88
- Barker JA (1988) A generalized radial flow model for hydraulic tests in fractured rock. *Water Resour Res* 24(10):1796–1804
- Barthes V, Mennechet C (1984) Prospection géothermique de la région de Bouillante–Vieux habitants (Guadeloupe). Etude gravimétrique [Geothermal survey of the Bouillante–Vieux habitants (Guadeloupe) area. Gravimetric study]. BRGM report no. 84 SGN 063 GTH, BRGM, Orléans, France
- Batini F, Brogi A, Lazzarotto A, Liotta D, Pandeli E (2003) Geological features of Larderello-Travale and Mt. Amiata geothermal areas (southern Tuscany, Italy): geology of Italy. *Episodes* 26(3):239–244
- Bernard M-L, Molinié J, Petit R-H, Beauducel F, Hammouya G, Marion G (2006) Remote and in situ plume measurements of acid gas release from La Soufrière volcano, Guadeloupe. *J Volcanol Geoth Res* 150(4):395
- Bertini G, Casini M, Gianelli G, Pandeli E (2006) Geological structure of a long-living geothermal system, Larderello, Italy. *Terra Nova* 18(3):163–169
- Bodvarsson GS, Benson SM, Sigurdsson O, Eliasson ET (1984a) The Krafla geothermal field, Iceland, 1. Analysis of well test data. *Water Resour Res* 20(11):1515–1530
- Bodvarsson GS, Pruess K, Stefansson V, Eliasson ET (1984b) The Krafla geothermal field, Iceland, 2. The natural state of the system. *Water Resour Res* 20(11):1531–1544
- Bodvarsson GS, Pruess K, Stefansson V, Eliasson ET (1984c) The Krafla geothermal field, Iceland, 3. The generating capacity of the field. *Water Resour Res* 20(11):1545–1559
- Boudon G, Dagain J, Semet M, Westercamp D (1982) Carte géologique du Massif volcanique de la Soufrière. Département de la Guadeloupe, Petites Antilles [Geological map of the Soufrière volcano. Guadeloupe Department, Lesser Antilles], BRGM, Orléans, France
- Bouysse P (1988) Opening of the Grenada back-arc basin and evolution of the Caribbean plate during the Mesozoic and early Paleogene. *Tectonophysics* 149:121–143
- CFG (2001) Champ géothermique de Bouillante. Synthèse lithologique des nouveaux puits BO-5, BO-6 et BO-7 et corrélation entre puits [Bouillante geothermal field. Lithological synthesis of the new wells BO-5, BO-6 and BO-7 and correlation between wells]. CFG report, CFG, Orléans
- Clemente WC, Villadolid-Abrigo FL (1993) The Bulalo geothermal field, Philippines: reservoir characteristics and response to production. *Geothermics* 22(5/6):381–394
- Combarnous MA, Bories SA (1975) Hydrothermal convection in saturated porous media. *Adv Hydrosci* 10:231–307
- Corny G, Demians d'Archimbaud J, Surcin J (1970) Prospection géothermique aux Antilles françaises, Guadeloupe et Martinique [Geothermal survey in French West Indies, Guadeloupe and Martinique]. *Geothermics (special issue)* 2:57–72
- Correia H, Sigurdsson O, Sanjuan B, Tulinius H, Lasne E (2000) Stimulation test of a high-enthalpy geothermal well by cold water injection. *Geotherm Resour Council Trans* 24:129–136
- Demians d'Archimbaud J, Munier-Jolain J-P (1976) Les progrès de l'exploration géothermique à Bouillante en Guadeloupe [The progress of geothermal exploration at Bouillante, Guadeloupe]. Eurafrep S.A., Proc. 25th Workshop on Geothermal Reservoir Eng., Stanford, CA, USA, 24–26 January 2000, pp 101–104
- Demians d'Archimbaud J, Surcin J (1976) Recherches d'énergie géothermiques en Guadeloupe [Study of geothermal energy on Guadeloupe]. *Bull BRGM* 4:365–373
- Dilsiz C (2006) Conceptual hydrodynamic model of the Pamukkale hydrothermal field, southwestern Turkey, based on hydrochemical and isotopic data. *Hydrogeol J* 14(4):562
- Dim JR, Sakura YS, Fukami HF, Miyakoshi AM (2002) Spatial characteristics of groundwater temperature in the Ishikari Lowland, Hokkaido, northern Japan: analytical and numerical applications. *Hydrogeol J* 10(2):296
- Fabriol H (2001) Champ géothermique de Bouillante : synthèse des études géophysiques [Bouillante geothermal field: synthesis of the geophysical studies]. BRGM report no. RP-50259-FR, BRGM, Orléans, France
- Fabriol H, Bitri A, Bourgeois B, Debeglia N, Genter A, Guennoc P, Jousset P, Miché J, Roig JY, Thion I, Traineau H, Sanjuan B, Truffert C (2005) Geophysical methods applied to the assess-

- ment of the Bouillante geothermal field (Guadeloupe, French West Indies). World Geothermal Congress, WGC 2005, Antalya, Turkey, April 2005
- Fabriol R, Ouzounian G (1985) Prospection géothermique des zones de Bouillante et de la Soufrière (Guadeloupe): modèle hydrogéochimique [Geothermal survey of the Bouillante and Soufrière areas (Guadeloupe): hydrogeochemical model]. BRGM report No. 85 SGN 433 GTH, BRGM, Orléans, France
- Feuillet N, Manighetti I, Taponnier P (2001) Extension active perpendiculaire à la subduction dans l'arc des petites Antilles (Guadeloupe, Antilles françaises) [Active extension perpendicular to the subduction in the lesser Antilles arc (Guadeloupe, French West Indies)]. CR Acad Sci Paris Earth Planet Sci 333(9):583–590
- Feuillet N, Manighetti I, Taponnier P (2002) Arc parallel extension and localization of volcanic complexes in Guadeloupe, Lesser Antilles. J Geophys Res 107(B12):2331–2359
- Flores-Márquez E, Jiménez-Suárez G, Martínez-Serrano R, Chávez R, Pérez D (2006) Study of geothermal water intrusion due to groundwater exploitation in the Puebla Valley aquifer system, Mexico. Hydrogeol J 14(7):1216
- Gadiala A, Westercamp D (1984) Prospection géothermique de la région de Bouillante-Vieux Habitants (Guadeloupe). Rapport géologique [Geothermal survey of the Bouillante-Vieux Habitants area (Guadeloupe)]. BRGM report No. 84 SGN 063 GTH, BRGM, Orléans, France
- Gandino A, Guidi M, Merlo C, Mete L, Rossi R, Zan L (1985) Preliminary model of the Ribeira Grande geothermal field (Azores Islands). Geothermics 14(1):91–105
- Genter A, Traineau H (2004) Synthèse méthodologique sur l'exploration géothermique haute énergie dans les DOM: approche géologique. [Methodological synthesis on high energy geothermal exploration in French overseas regions: geological approach]. GHEDOM project, BRGM report BRGM/RP-53130-FR, BRGM, Orléans, France, 86 pp
- Guillou-Frottier L (2003) Compilation et analyse des données thermiques sur le champ géothermique de Bouillante: premières interprétations pour le fonctionnement du champ géothermique [Compilation and analysis of the thermal data on the Bouillante geothermal field: first interpretations of the functioning of the geothermal field]. BRGM Report No. BRGM/RP-52452-FR, BRGM, Orléans, France
- Guisseau D, Patrier Mas P, Beaufort D, Girard JP, Inoue A, Sanjuan B, Petit S, Lens A, Genter A (2007) Significance of the depth-related transition montmorillonite-beidellite in the Bouillante geothermal field (Guadeloupe, Lesser Antilles). Am Mineral 92 (11–12):1800–1813
- Hulen JB, Anderson TD (1998) The Awibengkok, Indonesia, geothermal research project. 23rd Workshop on Geothermal Reservoir Engineering, Stanford Geothermal Program, Stanford, CA
- Ingebritsen S, Scholl M (1993) The hydrogeology of Kilauea volcano. Geothermics 22:255–270
- Kühn M, Stöfen H (2005) A reactive flow model of the geothermal reservoir Waiwera, New Zealand. Hydrogeol J 13(4):606
- Lachassagne P, Maréchal J (2004) Synthèse des connaissances hydrogéologiques, profondes et de subsurface, sur le champ géothermique de Bouillante [Synthesis of the deep and subsurface hydrogeological knowledge about the Bouillante geothermal field]. BRGM report No. RP-53404-FR, BRGM, Orléans, France
- Lachassagne P, Blavoux B, Livet M (2006) Généralités sur les eaux souterraines. 5. Aquifères volcaniques, chapitre I [Generalities on the aquifers. 5. Volcanic aquifers, Chap. I]. In: Roux JC (ed) Aquifères et Eaux Souterraines en France [Aquifers and Groundwater in France, vol 1]. BRGM, Orléans, France, pp 52–58
- Maréchal J-C, Perrochet P, Tacher L (1999) Long term simulation of thermal and hydraulic characteristics in a mountain massif: the Mont-Blanc case study, French and Italian Alps. Hydrogeol J 7:341–354
- Mas A, Guisseau D, Patrier Mas P, Beaufort D, Genter A, Sanjuan B, Girard JP (2006) Clay minerals related to the hydrothermal activity of the Bouillante geothermal field (Guadeloupe). J Volcanol Geoth Res 158(3–4):380
- Patrier P, Beaufort D, Mas A, Traineau H (2003) Surficial clay assemblage associated with the hydrothermal activity of Bouillante (Guadeloupe, French West Indies). J Volcanol Geoth Res 126(1–2):143
- Sanjuan B (2001) Champ géothermique de Bouillante (Guadeloupe): synthèse des travaux réalisés en géochimie avant 1999 [Bouillante geothermal field (Guadeloupe): synthesis of the geochemical studies performed before 1999]. BRGM report No. RC-51672-FR, BRGM, Orléans, France, 64 pp
- Sanjuan B, Brach M (1997) Etude hydrogéochimique du champ géothermique de Bouillante (Guadeloupe) [Hydrogeochemical study of the Bouillante geothermal field (Guadeloupe)]. BRGM report No. R39880, BRGM, Orléans, France
- Sanjuan B, Lasne E, Brach M (2000) Bouillante geothermal field (Guadeloupe). Geochemical monitoring during a thermal stimulation operation. 25th Workshop on Geothermal Reservoir Engineering, Stanford, CA, USA, 24–26 January 2000
- Sanjuan B, Lasne E, Brach M (2001) Bouillante geothermal fluid: mixing and water/rock interaction processes at 250°C. Proc. 10th Water-Rock Interaction (WRI-10), Cagliari, Italy, 10–15 June 2001, pp 911–914
- Sanjuan B, Le Nindre Y-M, Menjoz A, Sbai A, Brach M, Lasne E (2004) Travaux de recherche liés au développement du champ géothermique de Bouillante [Research studies linked to the development of the Bouillante geothermal field (Guadeloupe)]. BRGM Report No. RP-53136-FR, BRGM, Orléans, France, 166 pp
- Sanjuan B, Traineau H, Roig JY, Miché J, Cotiche C, Lachassagne P, Maréchal J, Fabriol H, Brach M (2005) Reconnaissance du potentiel géothermique du secteur nord de la baie de Bouillante, en Guadeloupe, par des méthodes d'exploration de surface [Survey of the geothermal potentialities of the Bouillante bay northern sector (Guadeloupe) by surface exploration methods]. BRGM report No. RC-53634-FR, BRGM, Orléans, France, 120 pp
- Smith WHF, Sandwell DT (1997) Global seafloor topography from satellite altimetry and ship depth soundings, Science 277:957–962
- Tamanyu S, Wood CP (2003) Characterization of geothermal systems in volcano-tectonic depressions: Japan and New Zealand. Bull Geol Surv Jpn 54(3–4):117–129
- Thinon I, Bitri A, Guennoc P (2004) Levé sismique et magnétique le long de la côte ouest de l'île de Basse Terre, Guadeloupe: apports à la compréhension du contexte structural du champ géothermique de Bouillante [Seismic and magnetic surveys along the western coast of the Basse Terre island (Guadeloupe): comprehension of the structural context of the Bouillante geothermal field]. BRGM report No. RP-53152-FR, BRGM, Orléans, France
- Traineau H (2001) Champ géothermique de Bouillante (Guadeloupe): synthèse des travaux réalisés en géologie avant 1999 [Bouillante geothermal field (Guadeloupe): synthesis of the geological studies performed before 1999], CFG report, CFG, Orléans
- Traineau H, Sanjuan B, Beaufort D, Castaing BMC, Correia H, Genter A, Herbrich B (1997) The Bouillante geothermal field revisited: new data on the fractured geothermal reservoir in light of a future stimulation experiment in a low productive well. 22nd Workshop Geothermal Reservoir Engineering, Stanford, CA, 27–29 January 1997
- Violette S, Ledoux E, Goblet P, Carbonnel J-P (1997) Hydrologic and thermal modeling of an active volcano: the Piton de la Fournaise, Reunion. J Hydrol 191(1–4):37–63
- Vosteen H-D, Schellschmidt R (2003) Influence of temperature on thermal conductivity, thermal capacity and thermal diffusivity for different types of rock: heat flow and the structure of the lithosphere. Phys Chem Earth 28(9–11):499–509
- Westercamp D, Traineau H (1987) Hydrogeologic and geothermal scheme of an insular arc stratovolcano: Mount Pelee, Martinique, French Antilles. Bull Soc Geol France 3(6):1063–1073
- Zarrouk S, Kaya E, O'Sullivan M (2006) A review of worldwide experience of reinjection in geothermal fields. 28th New Zealand Geothermal Workshop, Auckland, 15–17 November 2006