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The Matouba Geothermal Prospect: a Newly-discovered Inferred Geothermal Resource on Guadeloupe Island, French West Indies

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ABSTRACT

Teranov and its partners in the GEOTREF research consortium have been exploring since 2015 the geothermal prospect of the Vieux-Habitants exploration license area, which encompasses 118km^2 on the West Coast of Guadeloupe (French West Indies, see Figure 1), between the Soufrière active volcano and the Bouillante developed geothermal field. This work involved a combination of geological, geochemical, and geophysical surveys with a strong R&D approach combined with a reliance on traditional methods.

A complete suite of surface geoscientific surveys was undertaken in an attempt to identify locations suitable for geothermal energy extraction. This included a surface geological reconnaissance, a structural study, the sampling and chemical analysis of known hot and cold springs over the license area, and the interpretation of pre-existing gas sample analyses from fumaroles located on the summit dome of the Soufrière volcano and around its base. Geophysical investigations included the reprocessing of 1970s gravity data with an up-to-date lidar-derived digital elevation model, the acquisition of 103 magnetotelluric (MT) soundings of adequate quality for inversion which were used to produce 1D and 3D resistivity models of the area explored.

MT results showed a doming conductive unit interpreted to indicate an underlying geothermal upflow centered close to the steam-heated thermal spring called “Bains de Matouba”. This upflow extends to the west. inside the Vieux-Habitants exploration license area and is clearly separate from that observed below the Soufrière volcanic chimney. The doming MT feature at Matouba aligns with a wide East-West faulted zone interpreted as a structural deformation corridor, and with the “Bains de Matouba” steam-heated feature. This corridor is interpreted to channel an outflow from the inferred reservoir to the west.

Although another area of widespread low resistivity was observed on MT contours to the north of the exploration area, the Matouba prospect is considered to be a much more promising exploration target because of the coincidence of positive geophysical, geochemical and structural indices of prospectivity.

Temperature estimates of the underlying inferred reservoir were derived indirectly, and therefore come with a relatively low level of confidence: a shallow conductor is present below the Soufrière dome, which extends continuously to the edge of the exploration license area. The Soufrière dome fumaroles are interpreted to be fed by a shallow thermal aquifer with a temperature estimated at 240°C. A continuity of shallow temperature contours matching that observed on resistivity models is postulated, which leads to our estimate of Matouba reservoir temperature of 240°C. A conceptual model of an inferred geothermal resource at Matouba was built to synthesize the geoscientific information gathered to date. An assessment of the inferred Matouba geothermal resource was then produced following the principles of the Australian Resources and Reserves Reporting Code (2nd edition).

A high enthalpy geothermal resource is inferred to be located in the Matouba area. A Monte Carlo simulation of the heat stored in the reservoir was run in order to account for uncertainties on key parameter values. On this basis, the inferred Matouba geothermal resource is interpreted to be able to sustain a power production potential of 61MWe (P50) over 30 years. The portion of the inferred resource accessible through wells entirely located within the limits of the Vieux-Habitant license area is interpreted to be able to sustain a power production potential of 38MWe (P50) over 30 years.

INTRODUCTION: TERANOV, VIEUX-HABITANTS AND THE GEOTREF PROJECT

Teranov is a geothermal power project development company currently focused on prospects in the Caribbean and south and central America.

Teranov also coordinates the GEOTREF[1] research consortium, which brings together 35 researchers from 10 French university groups and their doctoral candidates and postdoctoral staff. The consortium’s goal is to enhance geothermal exploration methods through research on a wide array of topics. Software tools integrating some of the resulting research are planned to be developed as plugins for the SKUA-GOCAD 3D geomodeller. Technical leadership and software integration responsibilities for GEOTREF rest with private company KIDOVA. GEOTREF is supported by ADEME (the French state agency for energy management) and the Future Investments Plan (PIA) of the French state.

Teranov’s industrial aim of exploring and developing a geothermal power project in the Vieux-Habitants area has partially supported the financing of studies providing valuable research data to the GEOTREF research consortium members. The consortium members have also been primary sources of such new data and interpretations, and were instrumental in the success of many of these surveys.

[1] GEOTREF: French acronym for « high energy geothermal in fractured reservoirs »

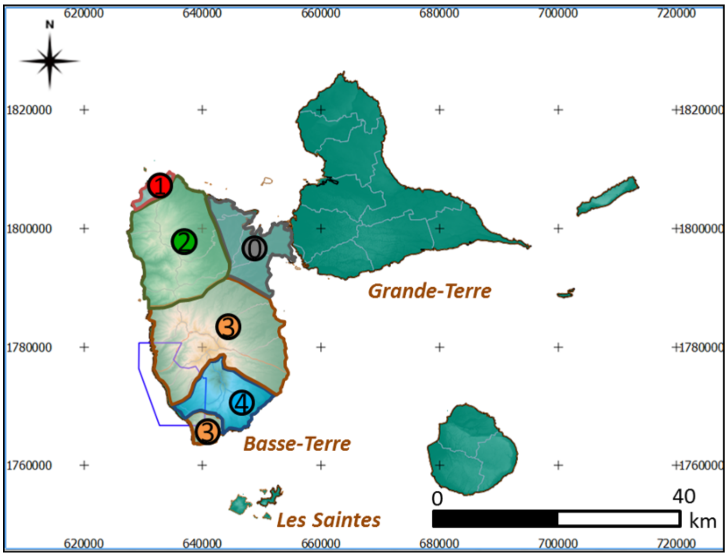
Some of the key issues that the GEOTREF project set out to investigate were:

- A need to better describe the relationship between the relatively old volcanic activity at Bouillante (last eruption dated at 600ka by Ricci et al. (2015)), the Bouillante geothermal field and the current volcanic activity at Soufrière, if any.
- A need to test the previously accepted interpretation that geothermal exploration results “do not allow for the identification of a potential deep geothermal resource” in the Vieux-Habitants area (Legendre et al. (2014)), in the light of newly-acquired geophysical data such as MT.
- Investigating the existence and relative importance of deep lateral circulations along subhorizontal flow pathways created by pressure-solution creep at depths nearing the brittle-ductile transition.
- Investigating the potential for making use of the concept of exhumed analogues in geothermal exploration: exploring the characteristics of a currently active geothermal field at depth by analogy with shallow observations in a nearby extinct geothermal system, as is commonly practiced in oil and gas exploration.
- Improving the methods to explicitly take uncertainties into account, in particular when building geomodels and flow models.
- Testing and calibrating new geothermometers, in particular based on lithium isotopes.
- Developing a drone-based magnetic surveying system.

These research topics are not detailed further in this paper, which focuses on the application of more standard exploration techniques for the identification, delineation and assessment of the Matouba prospect.

1. GEOLOGICAL SETTING

Guadeloupe is located on the volcanic arc of the Lesser West Indies. Its volcanism results from the subduction to the west of the north and south-American plates below the Caribbean plate (see Figure 2). The volcanism on Guadeloupe moved generally from the north to the south of Basse-Terre (the western lobe of Guadeloupe) along a N160 direction, and Soufrière is currently the only active volcanic center in the area explored. Four large scale volcanic units have been described and dated as shown in Figure 1.



	Age (ka)	
Unit Name	Start	End
Basal Complex	2 790	2 680
Northern Chain	1 810	1 150
Axial Chain	1 023	412
Grande-Découverte-Soufrière Complex	205	Now

Figure 1 Large scale volcanic units of Basse-Terre (left, after Samper et al (2007)) and their eruptive age ranges estimated using revised values of K/Ar ages based on the Cassignol-Gillot method, GEOTREF (2017) and Ricci et al (2017). The Vieux-Habitants exploration license area is shown with a blue outline. Unit number zero is an erosion plain composed of non-volcanic units.

1.1 Regional Tectonics

The island of Guadeloupe undergoes a regional transtensional geodynamic stress (GEOTREF (2017) and Figure 2) in which, at the level of the Vieux-Habitants exploration licence area, four principal fault directions are observed: SW-NE, E-W, NW-SE and N-S (Figure 5). Some of these features are likely to control seismicity, the upflow of magmatic fluids and also of geothermal fluids, as is the case with E-W faults at Bouillante (Bouchot et al, 2011). East-west (or WSW-ENE) faults are generally associated with normal displacements, they are the product of bookshelf faulting which can be traced over long distances regionally at sea (Legendre, 2018).

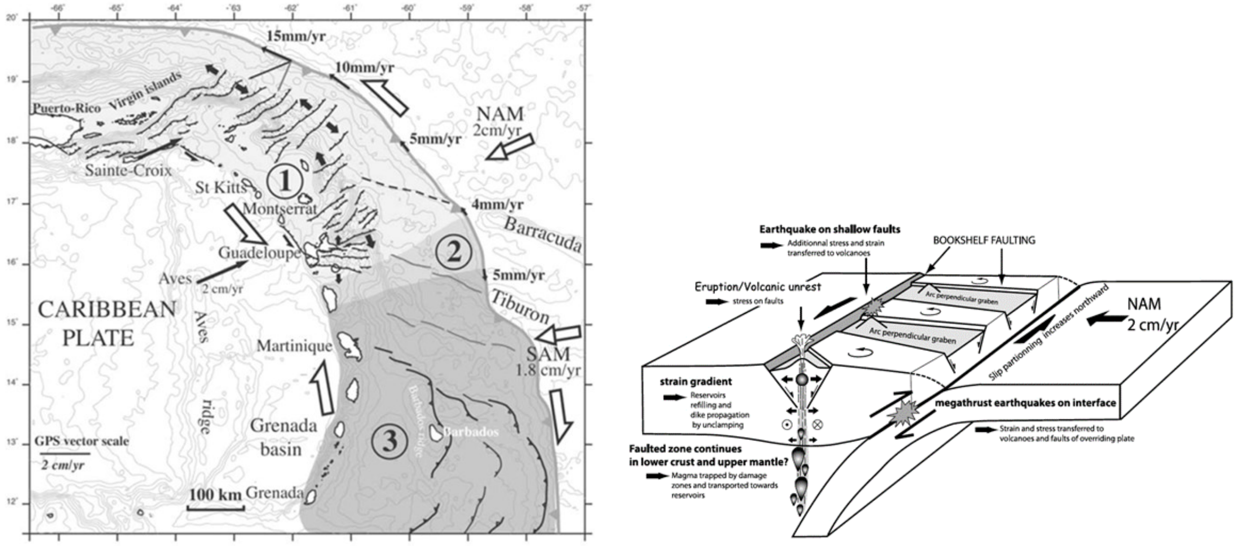


Figure 2 Tectonic model of the Lesser Antilles arc, Feuillet et al. (2002) (left); schematic zoning of structural features, volcanism and seismic activity along the Lesser Antilles volcanic arc, Feuillet et al. (2011).

1.2 Local Geology

Surface geological units in the area of primary interest near Matouba are of volcanic origin and include alternations of cohesive lavas and non-cohesive pyroclastics, lahar flows and debris flows. The lavas are predominantly andesitic as seen on the analysis of surface samples shown on Figure 3, but a wide range of compositions is nonetheless present. Subsurface geology in the Vieux Habitants area is hidden by surface units resulting from large scale sector collapses and smaller scale debris flows mapped on Figure 4. These imply a general absence of outcrops over a large part of the area of interest.

It is also possible that the sliding surfaces at the base of these debris flow units could be impermeable, and behave in much the same way as a hydrothermal clay cap such as that observed at Matouba (see paragraph 3.2).

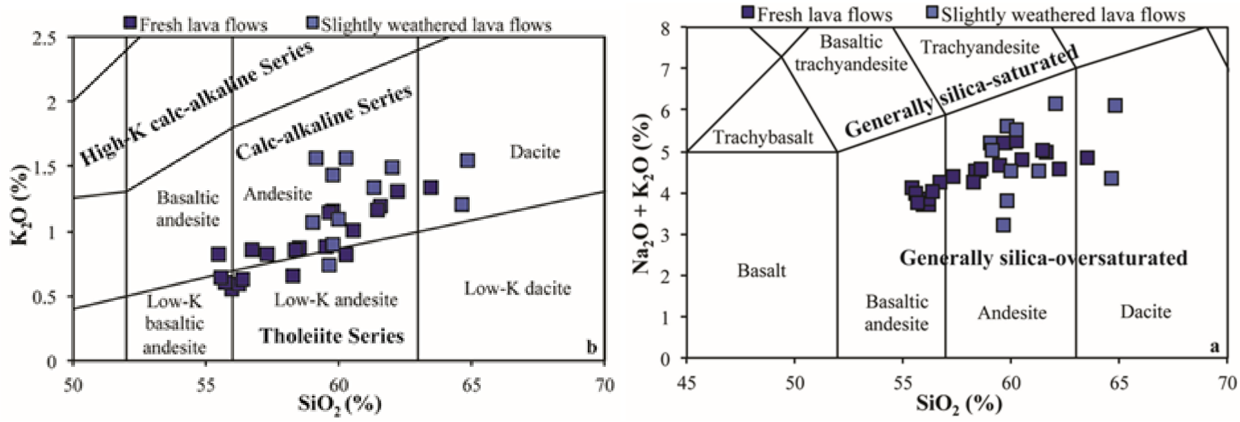


Figure 3 Geochemical characterization of surface lava samples obtained on Basse-Terre, after Navelot (2018). K_2O vs. silica at the left and total alkali versus silica at the right.

Petrophysical characteristics such as density, permeability, porosity, heat capacity and conductivity were measured on a wide array of surface samples in Navelot (2018) with the aim of investigating methods of constraining these parameters in the reservoir. The representativity of these measurements is however not established, so we instead relied on an average porosity derived from applying the Nettleton method to reprocessed gravity measurements in Teranov (2017), combined with solid phase density measurements from Navelot (2018). This yielded a value of 8.6% porosity which we used as a first approximation of bulk porosity for the purpose of resource estimation.

In the absence of direct investigation of deep permeability, surface investigations and measurements showed that pyroclastic units were generally very porous and permeable (Navelot (2018)). It is also likely considering past experience of drilling in similar fields that structural permeability within these units is high.

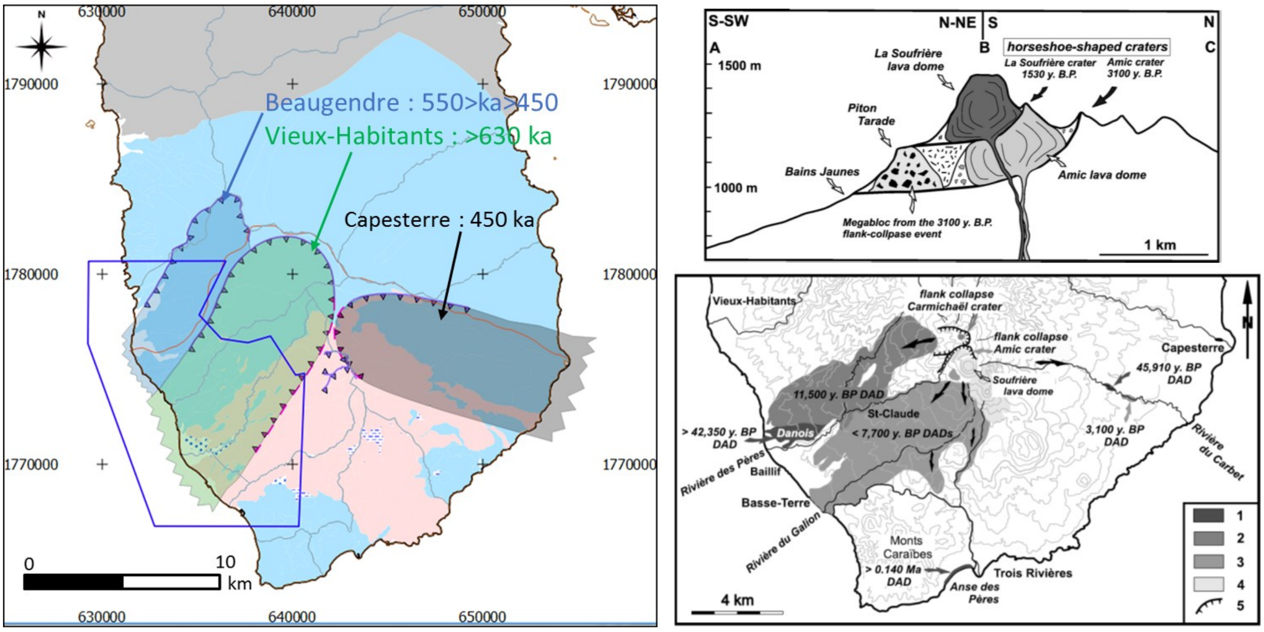


Figure 4 Large sector collapses and their estimated age (left, after GEOTREF (2017)), and smaller scale more recent debris flows and their estimated age, Boudon et al (2008) at top right and Boudon et al (2007) at the bottom right.

1.3 Structural setting

A detailed interpreted structural model was produced based on lineament analysis of orthophotos, a high resolution lidar-derived digital elevation model, faults interpreted from marine seismic data and field reconnaissance at the scale of the Vieux-Habitants exploration license area and at the scale of the Matouba prospect (Figure 5).

In the Matouba area, E-W and SW-NE faults clearly dominate the structural grain which – given the presence of debris flow obscuring old inactive structures – is interpreted as an indication that these two faults directions are also most likely to be currently active locally.

Deformation corridors were interpreted on the basis of the island-scale structural model (Figure 5), where wide faulted zones were observed. These corridors (especially those oriented east-west) are thought to be good conduits of vertical flow and may channel any geothermal upflow as was previously observed at Bouillante, eg. Bouchot et al (2010).

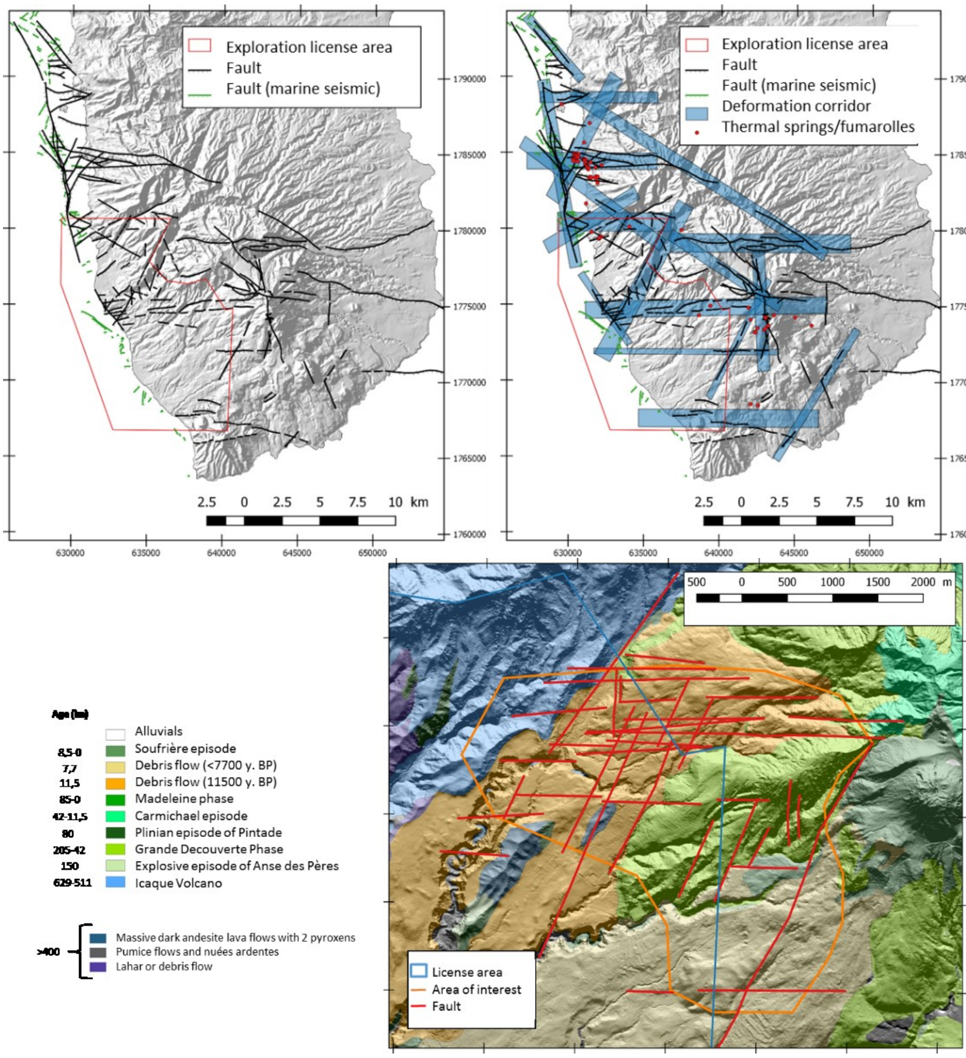


Figure 5 Structural analysis (top left) on the basis of lineaments analysis, field proofing and integration of faults interpreted from coastal marine seismic surveys - GEOTREF (2017); modelling of the resulting analysis as deformation corridors for flow modelling purposes (top right) and detailed structural analysis and geological map of the area of primary interest based on MT results (bottom).

1.4 Hydrology and recharge

An inventory of data in order to quantify hydraulic recharge in the south of Basse-Terre was undertaken by Armines, one of the partners in the GEOTREF consortium, in Barbé (2017). This shows a very high level of precipitations of the order of 4.5m/year over the Matouba area, rising to 8m/year at the Soufrière dome. A hydraulic mass balance on the Soufrière dome shows that a large share of the effective precipitation infiltrates at depth, and could reach deeper than the impermeable interface of the sliding surface located below the dome, via large faults like the “Faille du Ty”. This phenomenon could also occur at Matouba and is interpreted to provide the bulk of the recharge necessary to fuel the deep geothermal system.

On this basis, we interpret that there is little risk of a problematic lack of recharge at Matouba, but excessive inflow of cold fluids cooling the deep geothermal resource via subvertical faults may be an issue.

2. GEOCHEMISTRY

2.1 Surface thermal manifestations

An inventory of surface geothermal features of the exploration area and beyond (Bouillante) was undertaken, pre-existing geochemical analyses collated and new samples collected and analyzed in Teranov (2017a).

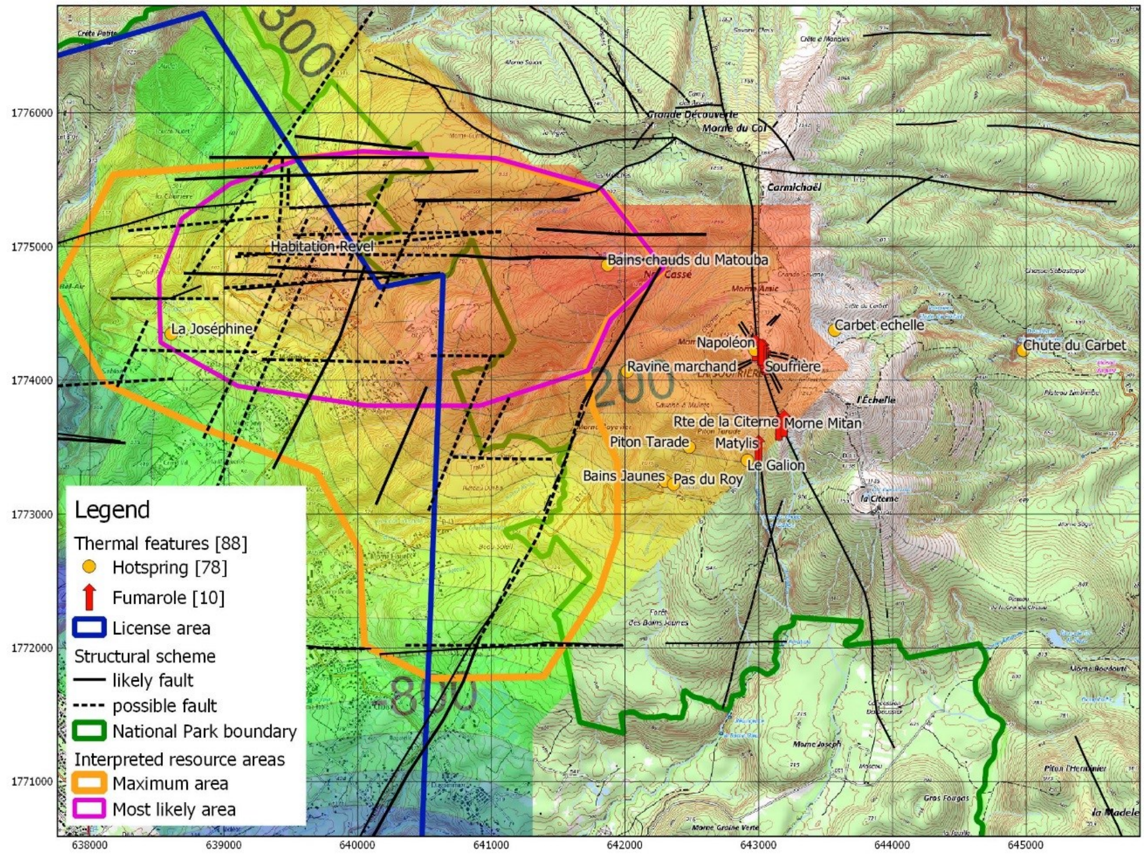


Figure 6 Surface thermal manifestation in the vicinity of the area of primary interest as defined by MT results

2.2 Gas analysis of fumaroles

We were only able to reference one data point which allowed for the application of the H2/CO2 geothermometer, as shown below.

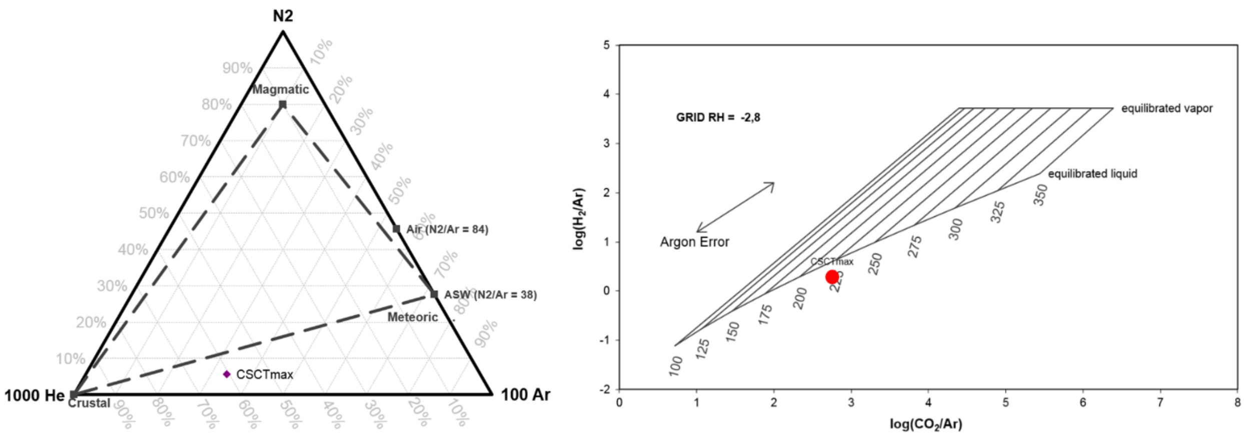


Figure 7 Ternary diagram of the gas analysis of the summit fumarole data (CSCTMax) and application of the H_2/CO_2 geothermometer to this data point, from Villemant et al (2014). Graphs produced on the model by Powell and Cumming (2010)

The He/N2/Ar ternary diagram shows that the magmatic component is low in the fumarole reviewed. This is interpreted as the clear indication that the Soufrière fumaroles are fed from an intermediary shallow aquifer. The temperature of this unit can be estimated from the application of the H_2/CO_2 geothermometer, which indicates 240°C (Figure 7).

2.3 Analysis of liquid springs

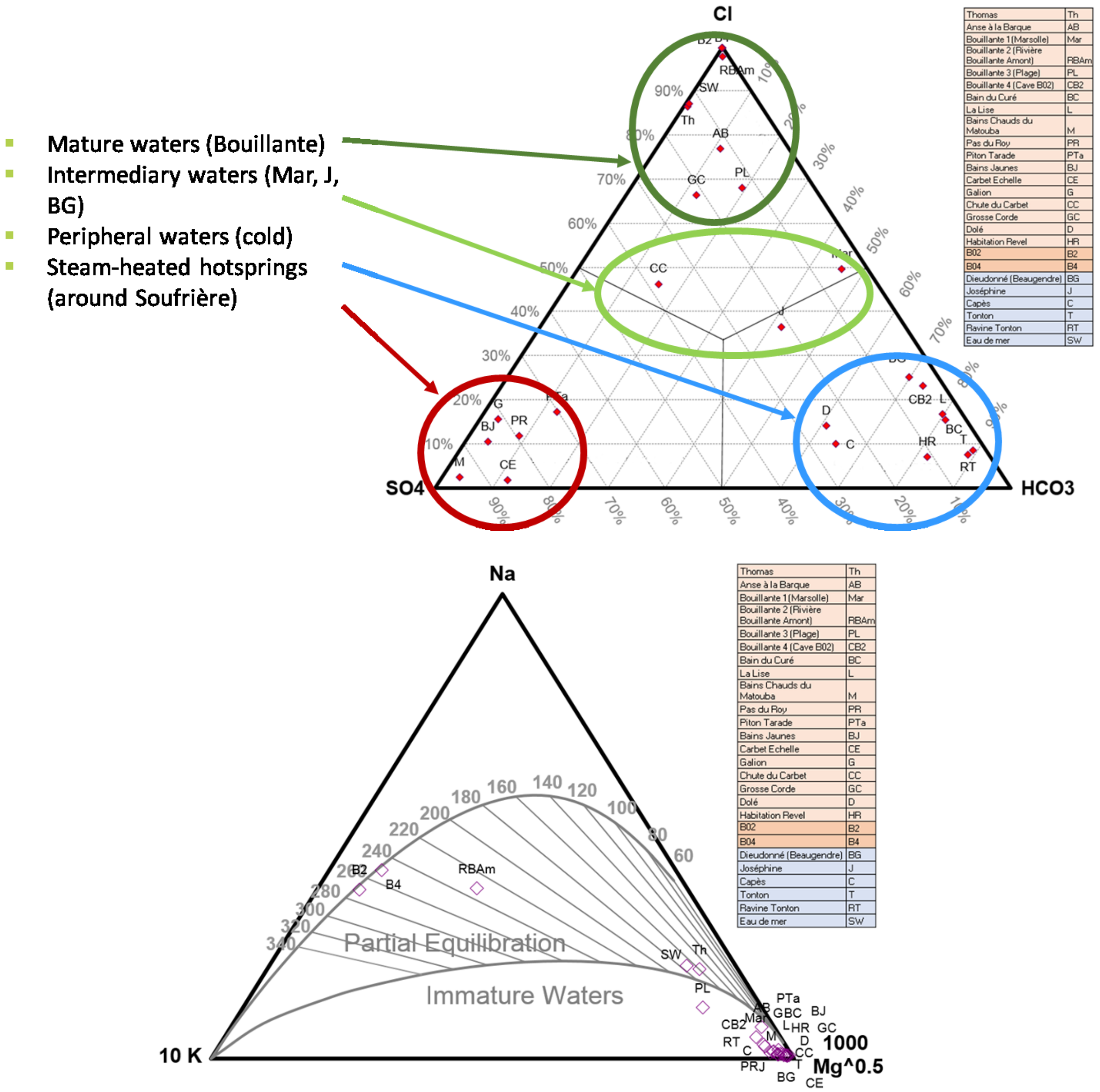


Figure 8 Ternary Giggenbach diagram including a compilation of 86 liquid springs analysed at and around Basse-Terre (sources: Brombach et al (2000), Traineau et al (1997), Sanjuan et al (1997), Tonani (1963), Gal et al (2014)), at the top; NaKMg ternary diagram and geothermometer which does not yield a reliable estimate of temperature for liquid springs in the Soufrière/Matouba area, bottom.

The gas and liquid analyses show that the surface features they represent can be categorized as such:

- A group of 7 fumaroles are found on top and on the immediate periphery of the Soufrière dome, with temperatures and compositions that have varied over time, are generally close to boiling point for depth at this altitude (95°C). One fumarole temperature was measured at 130°C in 2007, see Villemant et al (2014).

- A group of hotsprings with a NaCl / $NaHCO_3$ composition is found in the Bouillante area, for which a large proportion of the fluid comes from the "deep" geothermal reservoir.

- Three other types of spring compositions are observed: $CaSO_4$, $CaNaHCO_3$ and CaNaCl, which are present exclusively at the periphery of Soufrière. These springs have compositions that vary a lot depending on surface aquifer level, their pH is neutral to acidic. The former two types of spring compositions are interpreted to result from the heating of surface aquifers by volcanic gases (steam-heated groundwaters). The CaNaCl waters present at Grosse Corde and Chutes du Carbet show elevated chloride concentrations indicating mixing with a substantial portion of fluids coming from a deep geothermal resource, on top of the interaction with magmatic gases.

- A number of cold springs with compositions close to surface water have also been analysed. In the case of Ravine Tonton, the lithium isotope analyses show only a very small contribution of deep fluids, but that these would have been at equilibrium at a temperature of the order of 250°C.

The analyses show that none of the springs in the Matouba area (mainly steam-heated groundwaters) have enough of a deep geothermal character to yield a reliable evaluation of deep temperatures in a potential underlying geothermal resource. However, the Soufrière fumarole analysis indicates the presence of a shallow aquifer that feeds it with a temperature of 240°C. The MT results (section 3.2) show that a shallow conductive unit is present between Soufrière and the Bains de Matouba area, extending to the edge of the Vieux-Habitants license area. This also coincides with an area showing an elevated concentration of shallow microearthquakes (Ucciani, 2015) categorized as caused by hydrothermal activity. This shallow aquifer is clearly separate from the deep resource imaged at Matouba. However, given the lateral continuity in resistivity contours, and in the absence of a more direct means of evaluating deep temperature, we have used this value of 240°C observed in the shallow reservoir as a proxy for estimating an upper limit of temperatures in the deep resource at Matouba. It is clear that this value comes with a rather low level of confidence.

3. GEOPHYSICAL ACQUISITIONS AND INTERPRETATION

3.1 Gravity measurements

A suite of gravity measurements were obtained from The Bureau Gravimétrique International (BGI) – Coron et al (1975). These were reprocessed using a recent digital elevation model to derive a Bouguer anomaly map computed for a density of 2.67.

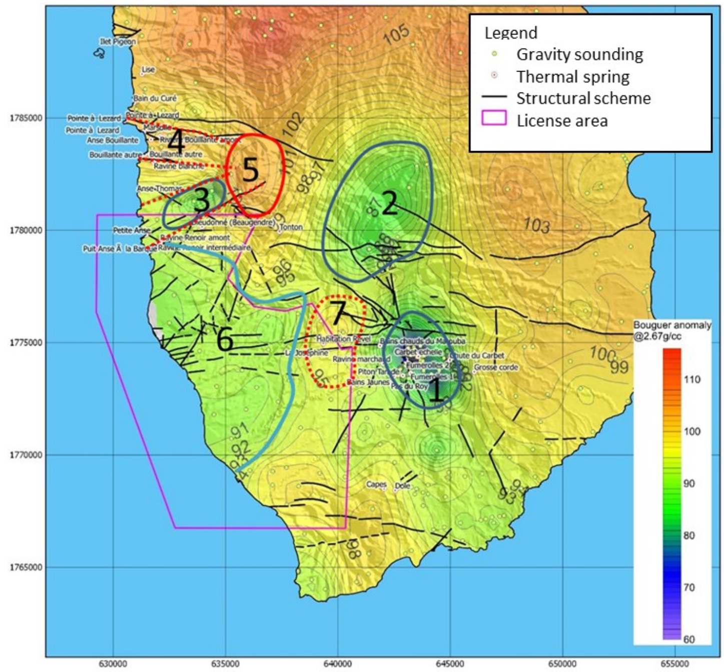


Figure 9 Bouguer anomaly map based on Coron et al (1975) data, reprocessed using a high-resolution DEM and a density value of 2.67g/cc

In the Matouba area, a mild gravity high (anomaly #7) is present, which coincides approximately with the presence of a deep resistive body that is clearly imaged on MT sections. The Soufrière volcanic vent exhibits an intense gravity low anomaly (#1). We estimate thus that the geometry of the volcanic chimney as defined by its gravity signature is a cone elongated in the N160 direction.

On the west coast, near the village of Vieux-Habitants (#6), density values are generally lower than on the axial chain, which can be explained by the layers of pyroclastics resulting from sector collapses and debris flows. These layers are interpreted to be several hundred meters thick on the basis of geomorphology, but no on-site evidence backs this up. Gravity results tend to reinforce this hypothesis.

3.2 Magnetotelluric (MT) results

Two magnetotelluric surveys were acquired by Teranov and Imagir (2015 and 2017) between Bouillante and the SW of Basse-Terre, providing 103 soundings of sufficient quality for modelling. The results were inverted in 1D and 3D (Imagir, 2017b) and jointly interpreted (Teranov, 2017) to define an interpreted surface corresponding to the base of the conductor (blue lines on Figure 11 cross-sections). They showed the presence of the typical resistivity signature of a hydrothermal clay cap below the Matouba area: a very conductive layer with resistivities <5Ω.m forming a dome shape and an underlying resistive unit. These are interpreted to be caused by a deep geothermal upflow with no direct surface outflow and is distinctly separate and offset from the magmatic chimney of Soufrière. The size of the interpreted reservoir was evaluated at 5.6km2 on the basis of resistivity contours.

The summit of the resistivity dome coincides approximately with the location of the Bains de Matouba hotspring.

In defining the extent of the most likely resource area, we also noted that the east-west elongation of the contours of the elevation of the base of the conductor coincides with a major east-west deformation corridor interpreted to exist in this area (see Figure 5). We interpret this feature as a mark of a preferential outflow direction to the west which follows the topographical gradient and the deformation corridor. An outflow is also interpreted to happen to the south-west on the basis of the shape of the elevation contours of the base of the conductor.

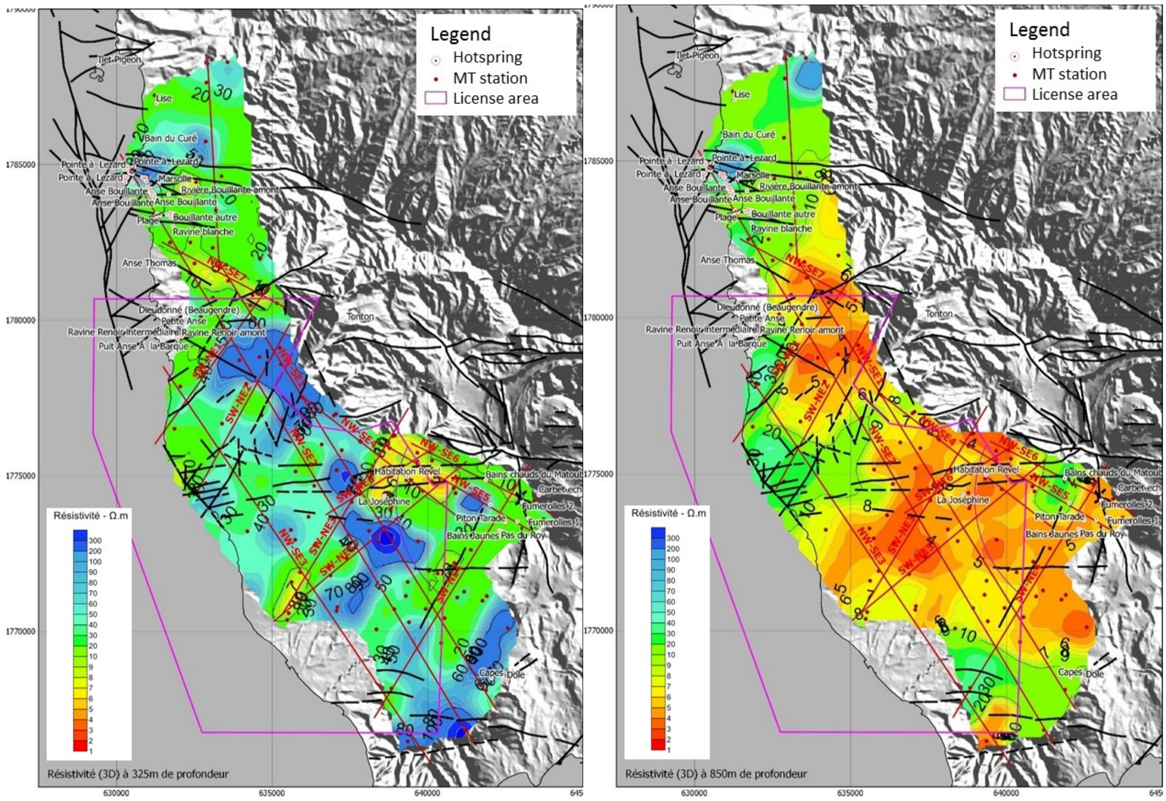


Figure 10 3D inverted resistivity contour maps at 325m below ground surface (left) and 850m below ground surface (right), contours in Ω.m.

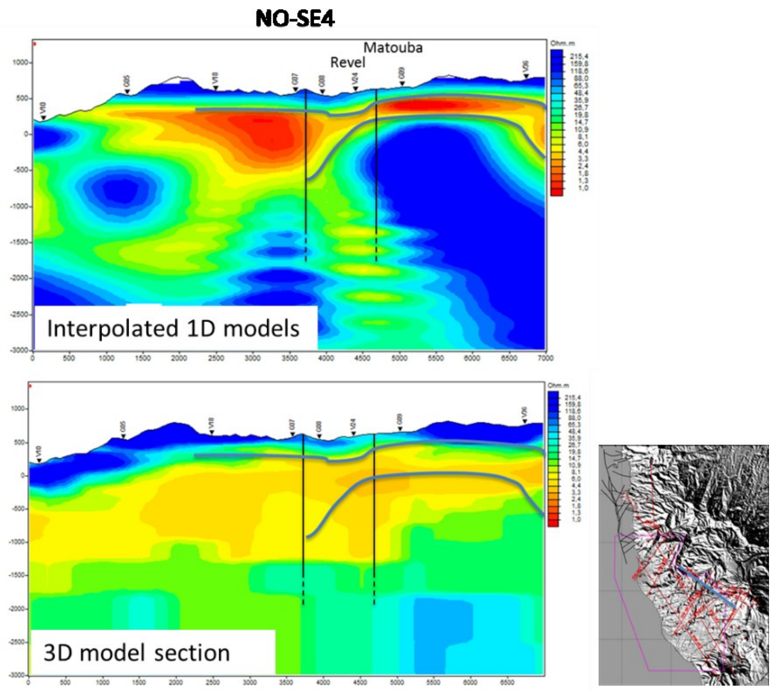


Figure 11 1D and 3D modelled resistivity cross-sections along a NW-SE profile through Matouba showing the base and top of the conductor interpreted based on the joint reliance on both sets of models.

4. CONCEPTUAL MODEL AND INTEGRATED RESOURCE ASSESSMENT

On the basis of the elements presented earlier, we interpret the presence of an inferred geothermal resource below the Matouba area. The resource is currently modelled with the following elements:

- The Soufrière volcanic chimney channels volcanic gasses and feeds a shallow intermediate aquifer with heat and gasses with an intensity that varies depending on the distance to the summit. This aquifer feeds indirectly the steam-heated groundwater springs and fumaroles encountered in the vicinity of Soufrière. We interpret that it reaches a temperature of 240°C based on the application of the H_2/CO_2 geothermometer to fumarole gasses. The temperatures and intensity of fumarolic activity are notoriously variable with time (Villemant et al (2014)) and it is also likely that conditions in this aquifer are quite heterogeneous.

- The interpretation of MT data shows the presence of a very conductive continuous shallow unit which is interpreted to coincide with the shallow thermal aquifer feeding the fumaroles.

- Below it is a wider very conductive zone with a slight dome shape, that becomes thinner towards the centre of the dome and thicker towards its edges. This is typical of the clay cap features that are well known to occur over geothermal upflows as a result of argillic alteration (and in particular the presence of smectites). It has also been shown that in such cases, the base of the conductor is often close to the 200°C isotherm (Ussher et al, 2000). So as a first approximation, we consider that temperatures in the deep reservoir are likely to be contained in the interval 200°C-240°C, although the level of confidence in these values (especially the upper bound) is rather low. In order to account for this uncertainty in the Monte-Carlo simulation, we used a trapezoidal distribution of temperature to increase the lower and higher bounds of the temperature interval by 20°C.

- Below this conductive zone is a deep resistive unit imaged on 1D and 3D sections, which also coincides with a gravity high anomaly. Such features are also commonly observed below hydrothermal clay caps, which reinforces the interpretation.

- It is possible that magmatic gasses coming from the Soufrière magmatic chimney or other related conduits have some influence on the Matouba geothermal resource, but it is difficult to assess the importance of this influence. This can be detrimental to a geothermal development through enhanced corrosion resulting from the contact with acidic fluids. This risk can only be properly assessed by exploration drilling.

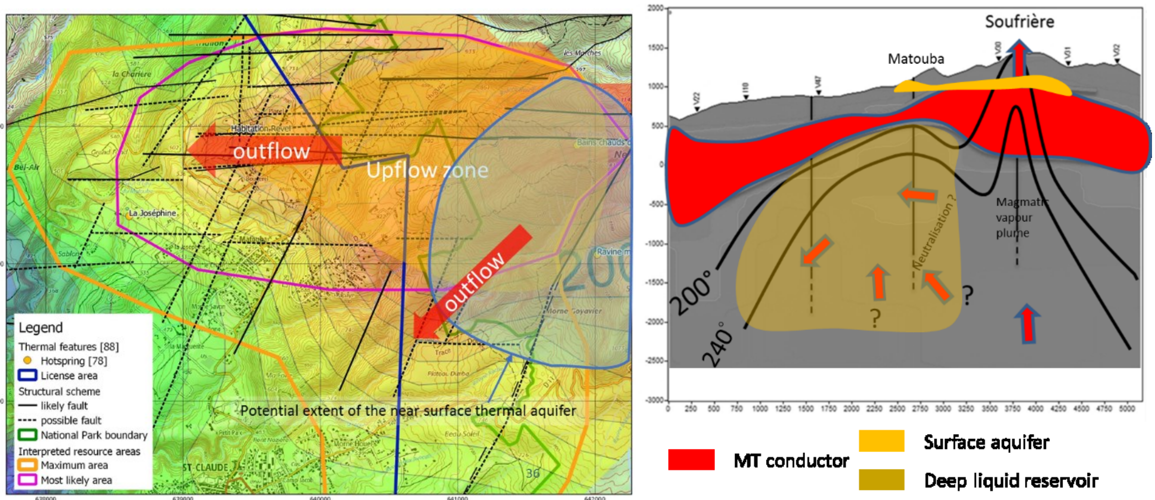


Figure 12 Conceptual model map (left) showing the elevation contours of the base of the conductor and structural model; NW-SE cross-section of the Matouba inferred geothermal resource (right)

An estimate of the power production potential associated with the Matouba inferred geothermal resource was produced following the principles of the Australian Geothermal Resources Reporting Code, 2nd edition – AGRCC (2010a and b). This assessment was undertaken using the stored heat method and a Monte-Carlo simulation to take into account the large uncertainty on certain crucial input parameters (Table 1).

The assumption of a binary development was made, and a 30 year running period was assumed. This yields a capacity to sustain a development with the following electric power values: 24.9MWe (P90) < 61 MWe (P50) < 100.1 MWe (P10) when taking the complete area of prospect into account and of 15.6 MWe (P90) < 38 MWe (P50) < 63 MWe (P10) when taking only into account the portion of the resource accessible from wells drilled within the exploration license area. This is done by taking a 300m buffer zone towards the outside of the exploration license area.

Table 1 Input parameters of the Monte-Carlo simulation used to calculate power production potential of the Matouba inferred resource using a binary plant over a period of 30 years

Parameter	Limit	Unit	Value
Reservoir area	Minimum	km²	0
	Most likely		5.6
	Maximum		11.3
Reservoir thickness	Minimum	M	1000
	Most likely		1300
	Maximum		1500
Porosity	Minimum	%	4.6
	Most likely		8.6
	Maximum		12.6
Temperature	Minimum	°C	180
	Lower limit of trapeze distribution		200
	Higher limit of trapeze distribution		240
	Maximum		260

Parameter	Limit	Unit	Value
Solid phase density	Mean value measured on surface andesites (GEOTREF, 2017)	-	2.75
Reservoir saturation	Fixed value	%	100
Rock heat capacity	Minimum	kJ/kg°C	0.927
	Most likely		0.946
	Maximum		0.954
Recovery factor (uniform distribution)	Minimum	%	8
	Maximum		14
Net conversion factor (including 10% de parasitic load)	Minimum	%	12
	Most likely		15.1
	Maximum		16.6
	Correlation used	-	SKM (reservoir temperature dependent, AGRRC (2010b)

CONCLUSIONS

Teranov and its partners in the GEOTREF project have identified an inferred geothermal resource at Matouba in Guadeloupe on the basis of surface exploration only, in accordance with the principles of the Australian Geothermal Resources reporting code. A stored heat evaluation of the power production capacity associated with it yields a P50 estimate of 38MWe when excluding the parts of the resource inaccessible to wells located strictly within the Vieux-Habitants exploration license area. This resource is close to the Soufrière active volcano but MT data shows that it is clearly distinct and that the upflow that feeds it is separate from the magmatic chimney. The summit of the upflow is located approximately 1.4km NE of the Soufrière summit. Although this prospect cannot exactly be called blind, there are few surface thermal features in the area and none in the immediate vicinity show the influence of a deep geothermal resource. Magnetotelluric survey results were therefore the key exploration tool that allowed for this prospect to be discovered.

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